Climate - Change Ireland: The potential impacts of climate change on food safety from an island of Ireland perspective

be safe be healthy be well

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Foreword and acknowledgements

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Abbreviations

DON	Deoxynivalenol
EFSA	European Food Safety Authority
EPA	Environmental Protection Agency (Republic of Ireland)
EU	European Union
FAO	Food and Agriculture Organisation of the United Nations
FHB	Fusarium head blight
GTIS	Global Trade Information Services
HACCP	Hazard analysis critical control point
IoI	Island of Ireland
IPCC	United Nations Intergovernmental Panel on Climate Change
NI	Northern Ireland
NIV	Nivalenol
UK	United Kingdom

Executive summary

On the 11th of November 2013, the Intergovernmental Panel on Climate Change (IPCC) published a Summary for Policymakers of the Working Group I contribution to its Fifth Assessment Report, presenting the latest evidence for the Physical Science Basis of observed global warming. The thrust of this summary emphasised the increasing certainty of observed changes to the global climate and the contribution of anthropogenic drivers. The degree of certainty surrounding these observations and the precision of future climate prediction models have increased since the IPCC's Fourth Assessment Report in 2007.

Arguably the most fundamental impact of global climate change on human populations is, and will continue to be, upon food production systems. People need to eat. The ecological and social changes arising from global warming may be far reaching, but there is little hope of adapting to these changes if sustainable food supplies cannot be assured. The interface of climate change and food security (having "physical and economic access to sufficient, safe and nutritious food to meet dietary needs and food preferences for an active and healthy life", Food and Agriculture Organisation of the United Nations (FAO)) has understandably been the subject of much scrutiny. However, within this definition, the impacts upon food safety have received comparatively little attention.

The chemical, biochemical and microbiological safety of food is a vast field subject to myriad influences both natural and anthropogenic. Those influences may sometimes be global in their scope, but often will be highly localised, dependent upon changes in regional food production practices, legislation and microclimates. An increasing challenge to climate prediction scientists is to refine large scale predictions into progressively smaller regional scale predictions which can be integrated with truly localised conditions. This is not an easy task. As stated recently by the IPCC, "on regional scales, the confidence in model capability to simulate surface temperature is less than for the larger scales."

However, there is high confidence that regional-scale surface temperature is better simulated than at the time of the [Fourth Assessment Report]. There has been some improvement in the simulation of continental-scale patterns of precipitation since the AR4. At regional scales, precipitation is not simulated as well, and the assessment is hampered by observational uncertainties."

This difficulty in predicting regionalised changes from continental or global climate models has consequences. People think, and governments act, primarily on the basis of localised, personal threats. If the changing weather outside is shown to adversely affect the security and safety of the food on their table, people will be persuaded of the importance of both local and international mitigation and adaptation strategies in the face of climate change.

The island of Ireland (IoI) is a small geographical entity (population approximately 6.4 million in 84,421 km^2), residing in a temperate oceanic climate off the north-western fringe of continental Europe. It is characterised by lush vegetation, a product of its mild but changeable climate, which avoids extremes in temperature, due primarily to the warming effect of the North Atlantic Current. Only 11% of the land is forested, compared with the European average of 35%. It is a highly developed region yet its largest industry remains agriculture and therefore the effects of climate change on food production and food safety are of particular economic and public health relevance.

***safe*food** commissioned this review on the potential impacts of climate change on food safety from an IoI perspective. The review aimed to assess the potential effects of climate change on food safety and public health for the populations on the IoI and to highlight those areas of the food chain where impacts are most likely and to recommend steps to ameliorate those impacts. This has been completed and provides the most comprehensive assessment yet of the climate-related difficulties we face relating to the production of safe food on this Island.

Major findings and recommendations

Potential impacts of Climate Change on agriculture and food safety within the island of Ireland both internal and external

For the IoI, most of the insights into the likely consequences of climate change, particularly in the long term, are based on biophysical statistical and simulation models. The uncertainty associated with the predictions and conclusions of these models is often not fully appreciated: however our understanding of the likely response of our food production and safety systems to climate change must rely on these statistical and simulation models informed by our knowledge of the underlying biological processes.

It is established that there is a strong connection between local climate and local vegetation. We can therefore expect gross changes in local ecosystems. On the IoI, this will result in changes in land use, potentially agricultural land abandonment in some places and change of use in others from livestock to crops or vice versa. Beyond these general expectations, specific problems will arise. For example, it is highly likely that there will be novel pest species such as invasive insects, weeds or fungi to be dealt with.

Control responses may generate food safety problems due to the novelty of the pests in question and the unfamiliarity of farmers in dealing with them, using pesticides or other measures. Changes in weather patterns such as rainfall, seasonality and lengthening of the growing season are likely to entail changes in cropping shares and other adaptations.

Increased winter rainfall coupled with milder temperatures in some areas may result in greater use of anthelminthics as snail vectors multiply. Threat from mycotoxins may intensify as the climate becomes more suitable for disease development. Biosecurity measures will need to be stepped up as environmental change continues and pest and diseases continue to systematically move north. Particular vigilance is needed to detect emerging threats in nearby warmer countries from which these agents might spread, including the development of control measures and awareness of associated food safety hazards if they successfully invade.

The food industry and stakeholders on the IoI must cooperate to plan for climate change related emerging threats by setting in place monitoring and surveillance systems to identify problems before they become entrenched and so very expensive to fire-fight. Anticipating invasive species, pests and diseases before they arrive or eradicating rapidly should they do so is orders of magnitude more cost effective than waiting until it is too late.

Emerging pests and diseases should be identified before they arrive on the island. Such pests and diseases, where present in a potential donor country, should be assessed for consequences should biosecurity measures fail. An evidence-based approach using the latest epidemiological modelling techniques can help identify potential problems in advance and allow informed risk assessment.

The likely changes in land use, cropping and pest management should be anticipated in detail rather than broad brush, using the latest regional climate models and what is known about current climates analogous to that of the IoI's future.

The impact of climate change on mycotoxin contamination of cereal grains

Climatic conditions will subsequently determine a pathogen's establishment and growth. Projecting what we are likely to encounter in the coming decades is extremely difficult as there are many interactions that must be considered. These include not only variations in temperature, relative humidity and rainfall but also the frequency and intensity of extreme weather events, increasing atmospheric carbon dioxide, the crops that are cultivated and the pests and pathogens that attack these hosts. In certain geographical regions there may be reductions in some diseases, however, an overall increase in global plant disease is expected.

On the IoI there is no doubt that monitoring of cereal grains must be performed for the trichothecene mycotoxins such as deoxynivalenol, 3-acetyldeoxynivalenol, 15-acetyldeoxynivalenol, nivalenol (NIV), T-2 toxin, HT-2 toxin, neosolaniol and T-2 triol as these have all been detected in grains in the United Kingdom (UK) including Northern Ireland (NI). Other mycotoxins of importance include zearalenone which has seen increased incidences over the past decade, moniliformin which has been detected in barley, albeit at low levels and fusarenone-x, although again low incidences and low concentrations have been reported to date.Mycotoxins that may pose problems in the future included fumonisins (if maize becomes a viable crop) and ochratoxin A.

For the emerging mycotoxins fusaproliferin, beauvericin and enniatins and the masked mycotoxins, there is no legislation covering their control in food or feed and they are not routinely monitored as a result of this but yet contamination of grains is a growing concern with an increasing number of reports of contamination throughout the globe.

Specific recommendations for monitoring/risk analysis

Activity	Recommendations
Routine monitoring	• Implementation of routine monitoring for the mycotoxins detailed above • Development of improved methods of detection, in particular rapid screening assays • Development of molecular methods for the identification of pathogenic fungal species
Risk assessment	• Toxicokinetic studies are required for enniatins, beauvericin, fusaproliferin, moniliformin and masked mycotoxins • Toxicity data both *in vitro* and *in vivo* are required for enniatins, beauvericin, fusaproliferin, moniliformin and masked mycotoxins • Investigate the synergistic effects of emerging mycotoxins with others commonly produced in this geographical region

Agricultural adaptation to climate change will include the selection of different varieties and species of crops that are more suited to the environmental conditions, cropping and management practices will be modified, including possible investments in storage facilities and there will be a need for improved handling of pests and diseases.

Agronomic practice recommendations

Practice	Recommendations
Cultivation	• Ploughing should be used rather than direct drilling or minimal till to reduce • fungal infestation. • Crop rotation: Avoid growing wheat after maize.
Fertilizers	• Use of urea or nitrolime will reduce FHB symptoms.
Fungicides/pesticides	• Use of Metcanazole and tebucanzole reduce Fusarium infections and mycotoxin contamination. • Avoid azoxystrobin and glyphosphate-based weed killers.
Plant breeding	• Introduce resistant cultivars.

Post-harvest and processing recommendations

Handling	Recommendations
Post-harvest	• HACCP systems must be in place for all crops. • Analysis and rejection of contaminated grains (pre/during storage). • Grains must be cleaned and dried (<12% moisture content) prior to storage. • Storage silos must be clean and dry.
Processing	• By-products must be analysed for mycotoxin content prior to entry into the animal feed sector.

Finally, the development of predictive models for the IoI for the mycotoxins outlined above are required to help the food industry and food safety authorities in risk analysis, to focus monitoring and amelioration where risks are expected to be higher, to help producers on the use of fungicides and to reinforce that monitoring is of the utmost importance over the decades to come in order to identify the trends and to protect human and animal health.

Wetter soils and impacts on crops nutrition and toxicology

The key knowledge gap identified in this review was how soil Se behaves with respect to wetter soil conditions, and the resultant impacts on tissue Se concentration and speciation, as evidence points to the fact that grain Se is highly negatively correlated with soil wetness/compaction. Using state-of- the-art Se speciation, using ion chromatography ICP-MS, as well as synchrotron based studies of Se location and speciation in soil, along with characterizing key elements whose cycling regulates Se (C, O, S, Fe & Mn), it is possible to resolve how Se is immobilized or lost, potentially through biovolatilization, given that methodologies have now been developed to look at Se biovolatilization loses from soils. It is likely that strategies for manipulating C, O, S, Fe & Mn status of soil will be more successful, and economic, that Se fertilization per se, particularly as the fate of that fertilizers unknown (this could be investigated as well), and due t to fact that Se fortification itself raises issues. Also, grain survey of Se (i.e. Williams *et al.*, 2009), geographically over Ireland, and how this interacts with weather, is key to identifying and characterizing problems associated with grain deficiencies.

It is also clear that the impact of wetter soils and weather on crop quality (that is nutrient status, taste and physical appearance) have been understudied. As this crop quality may affect value and sustainability it is a priority that impact of a wetter climate on relevant parameters are studied to ascertain if this is a concern or not.

Potential Impacts of Climate Change on Veterinary Medicinal Residues in Livestock Produce on the Island of Ireland

Many factors influence the emergence of animal diseases and subsequent treatments which may lead to harmful drug residues in food. Climate change will continue to have a major impact on animal disease occurrence and prevalence. However, precise forecasting of disease emergence is problematic. Its status as an island may partially protect IoI from climate-driven changes to animal diseases, but this may simply be delaying the inevitable as global warming is likely to continue. Animal transportation (importation of diseased stock) will continue to be a major route for emerging infections.

Climate change on IoI is likely to increase the disease burden on some agricultural livestock. With the exception of parasitic helminth infections, there is little published data on the subject. Administration of veterinary medicines to food animals is likely to increase, encroaching drug resistance may lead to administration of greater quantities of medications or alternative drugs being used inappropriately. There is the potential for more and different residues of veterinary medicines to appear in locally produced foods. Existing food safety control measures on IoI will need to be sufficiently flexible to identify changes in the profile of veterinary residues and preclude their entry into the marketplace.

A range of mitigation and adaptation strategies can be implemented locally to ensure that predicted climate change on IoI does not adversely affect food safety via increasing veterinary drug residues.

<u>Mitigation: reducing veterinary drug use</u>

Reducing the use of veterinary drugs is the most effective way of guarding against climate change-driven increases in harmful residues in food.

Developing alternatives to existing drug treatments will pay long-term dividends. Primary examples include production of vaccines against helminth infections and bacteriophage therapy as an alternative to livestock antibiotics.

Educating farmers and producers: Livestock management practices which reduce drug usage should be promoted to primary producers. Examples include in refugia and grazing strategies to control helminth infections. The message of appropriate use of effective veterinary medicines must continue to be driven home to avoid unnecessary administration of drugs which can lead to animal welfare issues, greater residues in food and increasing drug resistance.

<u>Adaptation: enhancing residues monitoring</u>

To ensure climate change does not adversely affect our food safety, sufficient resources must be in place to expand the scope of residue testing on the IoI. Testing schemes must encompass relevant new and emerging veterinary drugs and take account of the possibility of increased usage of existing drugs as disease loads on livestock increase as a result of climate change. With changes imminent to EU legislation, it is likely that National Residues Surveillance Schemes will be adapted to a more targeted, risk-based sampling approach. Should risk assessment become integral to our food safety testing regimes, the risks associated with climate change must be taken into account and resources made available to gather the necessary data.

Adaptation: filling the knowledge gaps

Veterinary drug use: There is a need for reliable, quantitative, local data defining the types and amounts of veterinary medicines used in food production on IoI. Currently only limited sales or questionnaire figures are available.

Veterinary drug residues in the environment: There is a need for comprehensive research to measure residues in the environment and the extent to which they are recycled into the food chain.

Environmental residues and resistance: There is a need for fundamental research on the relationship between veterinary residues in the environment and the occurrence on IoI of drug resistant target species to determine if there is a link, if there are critical threshold concentrations and if the link can be circumvented.

Effect of climatic changes on prevalence of harmful algal blooms and the implications to aquaculture food safety

For seafood security both for consumer and industry there should be enhanced monitoring of different factors that are involved in the HAB ecosystem. This should include:

- Further investigations into related ecosystem communities and interactions with HABs
- Improved monitoring of phytoplankton in the marine environment with enhanced molecular detection to identify arrays of species particularly those not identified using microscopy.
- Expansion of toxin monitoring to include emerging toxins and other seafoods based on HAB and toxic species identified.
- Improved monitoring of climatic conditions from regional locations by adding a buoy to the Northern Irish East coast.
- Monitoring of freshwater environments for both HAB species and toxins and to examine bioaccumulation of identified toxins in plants and animals.
- Mapping and correlation of factors to build a robust model to develop risk management strategies that can be implemented when conditions prevail.

The apparent increase in the occurrence of HABs and the recognition that changes in climate may be creating a marine environment particularly suited to HAB-forming species of algae underline the need for regulators to ensure that existing risk management measures are adequate and are in line with international recommendations.

Current and adaptive strategies to combat climate change should be considered such as regular monitoring of the water quality as an early warning tool and to comply with legislation on food hygiene and safety the cultured product should also be tested for human health risks. However, the erratic and sporadic occurrence of HABs requires for monitoring systems that provide continuous and co-located time series of physical, chemical, and biotic properties with at least daily observations of phytoplankton species and concentration, nutrient and water chemistry profiles (CO_2 and O_2), temperature and salinity profiles, toxins, surface winds, and solar radiation. Nevertheless, if all this information can be connected using predictability modelling to additional data from surveillance of HAB-related contamination in products, and illness in animals and humans the generation of qualitative predictions of climatic conditions to HAB risks to food safety could be performed. Managers could then be forewarned, operate at a heightened level of caution and implement mitigation strategies to respond rapidly if HAB risks are "high to prevent food safety issues.

Pathogens across the Food Chain: Local impacts of climate change

We are already beginning to feel the adverse effects of climate change on food safety. The aim is to prevent, detect and control foodborne illnesses but this is challenging because of the complex and continually evolving production and processing developments, the extensive food distribution network involved, the lack of traceability of individual food components, the influence of consumer preferences and activities, and the presence of foodborne hazards.

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 bionetwork and behaviour of foodborne pathogens. Research is required to better understand microbial interactions, pathogen survival, colonisation, attachment, stress adaptation and proliferation of foodborne pathogens in food, crops, livestock and the environment. 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 transmission of pathogens in order to decrease potential risks as heavy rainfalls flooding and overflows are expected to be more frequent. The structure and capability of local water treatment plants will need to be assessed to determine their capability to buffer the effects of climate change and the ability of the aging water infrastructure on the IoI to manage the extra capacity predicted will need evaluated.

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. Information sharing of surveillance data between industry and governmental agencies is essential. Rapid, sensitive and cost effective technologies are required to detect multiple pathogens, to enable differentiation of pathogenic from non-pathogenic organisms, and to 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 nutritional or safety issues that arise. An expanded and co-ordinated surveillance system incorporating animal health, environmental health, public health and food safety would enable a broader view of pathogens across the food chain and help with risk assessment. Cooperation, interagency collaboration and standardisation of methods and procedures between public health, veterinary health, crop health and food safety, international surveillance and scientific research are crucial to this global problem (Tirado *et al.*, 2010) with good agricultural and manufacturing practices, improved traceability and application of hazard analysis and critical control point programs underpinning prevention strategies.

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 leading to better control and validation processes and facilitating the development of new innovative production processes and products. Foodborne diseases will need to be 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 food-borne 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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1.1 Introduction

In an increasingly interconnected and changing world, effective food safety and security is ever more important. Globalisation and the consequent exponential growth in food chain complexity has inflated enormously the potential for the importation of undesirable food components and the establishment of novel agricultural pests and diseases from new sources (Sutherst 2004; Work *et al.* 2005; Hulme 2009). In addition, global environmental change, particularly climate change, acts in synergy to exacerbate risk: the combination of increased globalisation and environmental change is potentially greater than either component alone (Sala *et al.* 2000; Tilman *et al.* 2001; Foley *et al.* 2005; Foley *et al.* 2011). The penultimate report of the IPCC reviews the potential development of climate change in detail (Solomon *et al.* 2007). The latest available report on global Climate Change (summary for policymakers: IPCC5 2013) emphasises the likelihood that the earth's climate will continue to change and that higher temperatures and increased variation in climate for most parts of the world are to be expected. Many aspects of food safety and security are in turn likely to be affected by this, ranging from spoilage organism prevalence, changes in existing plant and animal pathogen epidemiology, and migration, introduction and invasion of novel pests and diseases.

Recommendations on food safety from climate change analyses are typically general and geographically large-scale in scope, yet policymakers and scientists are often constrained to act more locally to gather evidence and deal with the consequences of environmental change within their remit. Weighed against this is the recognition that extra-jurisdictional drivers of change, most obviously climate, are often dominant and do not respect borders. This chapter will deal with some of the main climate change related processes likely to affect food safety and security, with an emphasis on the IoI. We err towards a longer term perspective whilst recognising that some threats are immediate, following from the climate change that has already taken place in the latter half of the 20th century, but others will likely develop in severity and importance over the decades to come.

The challenges presented by climate and environmental change has resulted in thousands of scientific publications over the last few years (17844 hits for the decade ending 2012: Thomson- Reuters Web of Science search with terms "climate" and "change" in the title; search date 26/11/2013). However, integrative publications on climate change and food safety are much scarcer. Adding the terms "food" and "safety" reduces this to 10 hits in the last decade, suggesting the relevant literature is scattered widely and is multidisciplinary in nature.

1.2 Current and future Climate Change within the island of Ireland

Ireland has an archetypal oceanic climate, caused by its position at the edge of the western Atlantic Ocean, with relatively small differences between summer and winter temperatures, high precipitation levels and westerly winds. Hard frosts and snow at low elevations are relatively infrequent compared to similar latitudes in continental Europe (Rohan, 1986). This damp, temperate climate lends itself to production of crops requiring moderate temperature regimes and particularly to livestock production where soil conditions are suitable. Most of Europe experienced increased temperatures in the 20th century, averaging 0.8 Celsius (Alcamo *et al.* 2007).

The latest IPCC report, the fifth Assessment Report (IPCC5 2013), builds on and for the most part reiterates previous conclusions regarding global-scale warming in the past few decades, particularly from the 1970s onwards (Fig. SPM 1 in IPCC5 2013). The authors conclude that (i) the period1983–2012 was likely (in their terms) to have been the warmest 30-year period of the last 1400 years in the northern hemisphere (ii) that changes in extreme weather events have been observed since the middle of the 20th century, including fewer cold and more warm days and nights, and an increased frequency of heat waves in Europe, Asia and Australia. Precipitation is inherently more variable than temperature, but globally it is likely that heavy precipitation events have increased in frequency (IPPC 2013). The projections for global rise in temperatures are for approximately in the two to four degrees Celsius per century range, depending on emission and economic development scenarios.

Local projections, covering Europe for example, are made using regional simulations calibrated using coarser-scale global circulation models. The currently available regional projections are based on the previous generation of global circulation models – updated versions are not currently available. For Ireland, these regional climate models suggest longer growing seasons, a further 2.5 Celsius increase in July temperatures by 2050, with a reduction in summer rainfall, increase in winter precipitation, milder winters and a bias towards the south east in warming (e.g. Dunne *et al.* 2009).

1.3 Small changes in averages produce big changes in extremes

An increase of one or two degrees Celsius, such as expected in Ireland and elsewhere in the next few decades, is obviously small compared to the magnitude of seasonal temperature change or indeed within-day variation, but it is the long term consequences of temperature (and other components of climate) that matter. The soil, vegetation and communities of animals present and their interconnection into functioning ecosystems reflects these long term ecological processes operating over centennial and millennial time scales. Additionally, small to moderate movements in average conditions typically result in disproportionate changes in the frequency of extreme or marginal conditions (Figure 1.1): as the average conditions change, the proportion of extreme values above an arbitrary threshold grows rapidly (and the opposite tail shrinks similarly). This is a general argument applicable to many phenomena. For example, the threshold could apply to a temperature limit above which conditions are suitable for cultivation for particular crops, for example sowing thresholds, (Olesen *et al.* 2012) or above which toxigenic fungi grow rapidly, or the area of land currently suitable for production of some kind. Changing the average conditions changes this marginal area disproportionately.

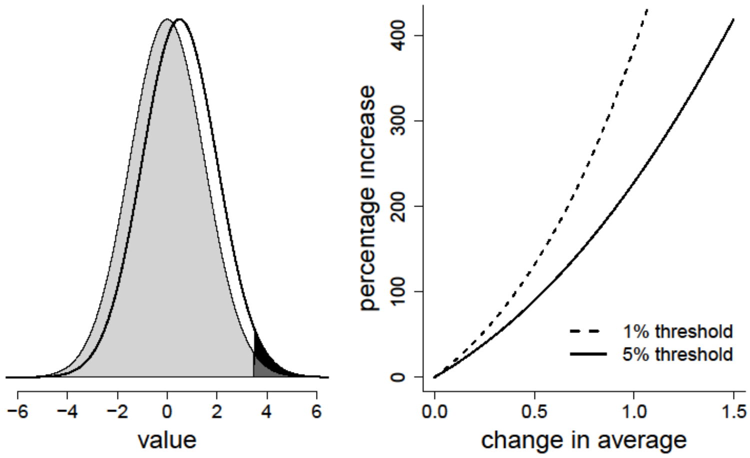


Figure 1.1: Changes in average environmental conditions magnify changes in marginal conditions. Movement of the mean conditions in time results in the rapid increase in the frequency of conditions beyond a threshold (left panel: black area shows growth of marginal conditions over previous frequency, shown in dark grey). The rate at which extreme conditions become commoner is seen in the right panel. If the threshold is set such that 1% of all events are in the tail, these grow more quickly than if it is set such that 5% are in the tail.

1.4 General challenges

The IoI faces a number of general challenges to food safety and security as a consequence of climatic and other forms of environmental change in common with many parts of the world. Specific concerns and local considerations are based around the particular circumstances of geographic isolation, local climate, biogeographic history and context, and socio-economic, political and regulatory norms. Some issues following from climate change are causally more immediate, such as the spread of a single toxigenic fungus or parasite as it tracks the local environment becoming more favourable for its survival. Others, what we might call ecological issues, are longer term and/or the chain of causation leading to consequences for food safety and security is more complex. These ecological processes lead to a transformation of the operation of the local ecosystem and wholesale changes in the environment in which food production takes place. A few degrees temperature rise does not mean that conditions are simply warmer in essentially the same landscape or agricultural environment – it means that the landscape changes, potentially dramatically, in response. Moreover, there is considerable uncertainty in the route these changes will take, and indeed in their end-points (Scheffer *et al.* 2001). This point regarding uncertainty applies in particular to all prognostications based on models, particularly those models that take other models outputs as inputs, generating a cascade of uncertainty.

The scope of this chapter is limited to climate change, food security and food safety, with a bias towards longer term systemic changes in the productive environment. We focus on terrestrial systems and highlight threats specific to the IoI, where attributable. The topics we cover below are (i) novel pests and diseases, (ii) mycotoxins, (iii) changes in climate affecting production, (iv) impacts on the general operation of ecosystems, and (v) potential economic impacts. Climate change and spoilage organisms, water quality, chemical contamination and marine food safety issues are covered in accompanying chapters of this report.

1.5 Current and Future Concerns for the island of Ireland

A. Climate change and invasive species, pests and diseases

Plant health is crucial for global food security (Flood 2010; Newton *et al.* 2011). A recent paper found that pests and diseases are systematically shifting polewards (Bebber *et al.* 2013). In a meta-analysis of hundreds of pathogens and pests the authors detected a systematic shift towards the poles of 2.7 Km per year since 1960, suggesting that, at the time of writing, an expected movement of greater than 100 Km north (or south). This matches the magnitude of similar systematic movements of many species of plants and animals in recent decades (Parmesan & Yohe 2003). At the same time, there have been reports of large numbers of fungal and fungal-like diseases causing major impacts, including extinction, on natural populations of plants and animals (Fisher *et al.* 2012). The authors argue that the numbers of emerging infectious diseases seen is unprecedented, at least partly caused by human activity (see also Anderson *et al.* 2004) and increasingly jeopardises food security.The spread of novel agricultural pests and diseases has much in common with invasive species, discussed below.

Biogeography matters for invasion potential: landlocked countries, isolated countries, and temperate rather than tropical countries all face different problems contingent on their local environment and biogeographic history. The IoI is in a unique position with regard to its relative isolation at the edge of continental Europe. Following the end of the last glaciation, Europe was gradually recolonized by southern species, with the most northerly and most isolated regions occupied more slowly and more recently. What is now the IoI was connected to mainland Europe by a land bridge (severed approximately 12000 years ago) but the re-colonisation process was incomplete at this point. Ireland is relatively poor in biodiversity for its area and the main reason for this is likely to be that this post-glaciation re-colonisation process is still underway: many European species that could potentially survive here have simply not reached the island yet. The natural barrier of the Irish Sea still keeps out many species present a few tens of kilometres away in the UK. It also keeps out or reduces the ingress of potentially harmful pests, diseases and their vectors. Legislative biosecurity barriers also operate to reduce exposure, simplified by this isolation.

These biogeographic process and principles apply generally, hence the widespread problem of invasive species. Invasive species are organisms that proliferate when given the opportunity to fill vacant niches in a previously isolated environment (Mack *et al.* 2000). Such invasive species fall into two overlapping classes depending on their limiting factors: those that are invasive due to breaching of a dispersal barrier, and those successfully invasive because the invaded environment has become suitable due to environmental change i.e. the barrier was environmental rather than simply isolation by distance. Both mechanisms are involved in the potential for pest/pathogen introduction and subsequent food production and safety considerations. For the first, the IoI is more fortunate than landlocked countries as mentioned above. For the second, no action is possible beyond a very small contribution to global reduction in greenhouse gas emissions.

The tally of species undergoing expansion of their poleward latitudinal limits has grown rapidly in recent decades and there is little doubt that we are seeing a concerted biological response to warmer conditions. Invasive species worldwide cause enormous damage both ecological and economic (e.g. $120 billion for the United States, Pimentel *et al.* 2005).The current economic cost of invasive species for NI has been estimated at £46.5 million and for the IoI £161 million (Kelly *et al.* 2013). It can be difficult to predict invasion success in advance given a set of candidate species, although some species' traits are suggestive of likely candidates (Kolar & Lodge 2001). Recommendations for limiting the likelihood and success of biological invasions on the IoI are set out in Stokes *et al.* (2006). Successfully invasive invertebrates in the IoI are overrepresented by cryptic, damp-loving species such as slugs and flatworms which can have negative impacts on food production and safety, rather than diurnal warmth-loving species such as dragonflies, butterflies and bees. Already-present agriculturally invasive plants such as sterile brome Anisantha sterilis, wild oat Avena fatua, Italian ryegrass Lolium multiflorum, and common field-speedwell Veronica persica typically have relatively incomplete coverage of the countryside in the

IoI compared to the UK. This may indicate that they have not yet completed their spread due to dispersal limitation or that the unoccupied environment is climatically or otherwise unsuitable. If it is climatic unsuitability, then there is the possibility that climate change will open up more of the landscape for these species, as well as allowing higher abundances of agricultural pests in general. For other agriculturally important invasives, the barrier was clearly isolation by distance: The New Zealand flatworm Arthurdendyus triangulatus was first recorded in NI in 1963 and spread onwards to and the south of the island and central Scotland. Records are concentrated around urban areas but only in NI is it frequent in agricultural areas; it is possibly under-recorded in the south but with numerous foci of additional introductions. Arthurdendyus kills earthworms causing soil damage and thus lowers yields, preferring cool wet conditions typical of the IoI. Climate envelope models applied to the Scottish invasion found that the potential distribution is ultimately restricted by low soil pH but potentially could occupy 37% of Scotland's land area (Boag *et al.* 1998); a similar application to the IoI is desirable.

The case of Bluetongue virus (BTV) exemplifies how disease can be driven by climate change. This particular disease-vector-host system neatly illustrates the role of climate change in generating novel threats. BTV causes an untreatable disease of ruminants transmitted by blood-feeding midges of theCulicoides genus. It also infects wild ruminants such as red deer. In sheep the disease can cause acute symptoms with high morbidity but mortality overall is generally low, and cattle can be asymptomatic – however the disease is of great economic important in mainland Europe with millions of ruminants lost to production (Guis *et al.* 2012). Legislative restrictions on animal movement and vaccination programmes have ensued. At the time of writing the IoI remains BTV free but there is an ongoing and growing threat of contamination. The disease is seasonal in Mediterranean countries, subsiding as winter weather kills the midge vectors but the virus apparently overwinters in an as yet unidentified host or hosts (but see Takamatsu *et al.* 2003). It has only recently (in 2006) spread to central and north west Europe (European Commission 2006). The IoI is susceptible to BTV either by direct importation of infected animals or by migration or transportation (perhaps more likely) of infected midges from continental Europe (Napp *et al.* 2013). The BTV-Culicoides-ruminant-climate interaction in Europe has been modelled with a view to understanding the epidemiology of the system and the likely spread in response to dispersal and above all, climate change (Guis *et al.* 2012). This study found that the widespread outbreaks of BTV in Europe are well explained by the parallel increase in temperatures in the last few decades. The modelling results suggest that future increases in BTV prevalence and continued spread to north-west Europe are likely if the disease is given a foothold; the modelled secondary infection rate parameter is predicted to increase by 4.3% per decade in northwest Europe, including the IoI.

Other pests and diseases have climatic constraints and thus likely climate-change linkages. Gastrointestinal helminth loads in cattle are potentially linked to climate (Bennema *et al.* 2010); their distribution, abundance and seasonality has responded to climate change in recent decades (van Dijk *et al.* 2010). The continuance of these trends will probably cause an increase in the dosage or frequency of use of anti-helminthic agents with attendant implications for residue levels. Similarly, an increase in crop pest burdens are usually met with increased use of pesticides, again with potential consequences for elevated residues in the food chain. A pest does not have to be a direct feeder on a crop to casue harm– this is exemplified by the case of the Asian Harelquin ladybird Harmonia axyridis. This species has been introduced or spread widely throughout the world (Evans *et al.* 2011), possibly originating in China. It is predatory on a wide range of insects and as a consequence it has disrupted the biological environment (local food webs) in which production occurs; it is particularly problematical for horticultural production. Analysis of Harmonia spread and potential for future invasion suggests that it is far from its maximum range (Poutsma *et al.* 2008; Bidinger *et al.* 2012) and further spread on the IoI should be expected. Similarly, analysis of the agricultural pest the grey field slug Deroceras reticulatum predicts northwards range expansion in the UK (Willis *et al.* 2006) into climate space similar to that in the IoI, where increased prevalence/abundance should be expected in many areas. However, the consequences of climate change for some crop pests is not always harmful: while cereal aphids are expected to shift distributions, they are forecast to decline in southern UK (Newman 2005; Newman 2006).

If climate change, as predicted, tends to produce more intensive agriculture, then minimising pesticide use is a worthwhile way of increasing food safety. More widespread us of biological control methods applied to emerging insect pest problems is one route; recent developments in control agents are encouraging (Lacey *et al.* 2001).

B. Climate change and mycotoxins

Climate change is expected in general to increase the prevalence of contaminants in the biosphere, both natural and as a consequence of food production (Noyes *et al.* 2009). Mycotoxins are a particularly important biologically-derived source of food contamination (Miraglia *et al.* 2009). Mycotoxins are secondary metabolites (notably aflatoxins, fumonisins, deoxynivalenol, zearalenone and ochratoxin A) produced by fungi such as Aspergillus and Fusarium species both pre-harvest and in storage where environmental conditions are suitable, particularly temperature and humidity. The full spectrum of deleterious effects on human and animal health is only now being uncovered but includes cancer, immune system depression and developmental abnormalities (Wild & Gong 2010). In animal feed, mycotoxin contamination typically reduces yields through chronic rather than acute mechanisms (Bryden 2012). Low level contamination is commonplace (Schatzmayr & Streit 2013).

A number of studies have assessed evidence for climate change increasing the risk of contamination (Magan *et al.* 2011). In general, it is argued that warming conditions in cool or temperate climates increase risk of mycotoxin production and contamination (Paterson & Lima 2010), while changes in precipitation are less straightforward in their consequences (Paterson & Lima 2011). The regional climate model projections for warmer but drier summers within the IoI may be congruent with the notion that mycotoxin risk will increase, but only if the increase in temperature outweighs the decrease in precipitation. An additional complication is changes in cropping species identity or mixtures in response to climate change (e.g. Elsgaard *et al.* 2012). Much hinges on the precise pattern of precipitation – when it occurs relative to crop phenology – which is particularly important for Fusarium development and inoculum production on cereals (Schaafsma & Hooker 2007). Dynamic risk assessment forecasting models using physiological/statistical sub-models for fungal environmental niche constraints and growth rates, dispersal rates and past weather and weather forecasts are now being applied to give farmers an early warning system for the likelihood of an outbreak (Maiorano *et al.* 2009). Similar models with longer-term scope also indicate an increase in Fusarium Ear Blight of wheat in UK in the next few decades (Madgwick *et al.* 2011; West *et al.* 2012).

Changes in production, discussed below, may lead to change in risk due to the varying levels in prevalence of toxigenic fungi on different crop species. It has been argued that generalised "early warning systems" (not necessarily the forecasting approach mentioned above) are desirable as a means to identify potential risks from natural disasters and extreme climatic events (Marvin *et al.* 2013). This would involve improved environmental monitoring, data collation and expert input in preparation for unforeseen events.

C. Climate change effects on production

Modes of production have implications for food safety; the potential for climate change to have deleterious consequences for agriculture and food security was recognised decades ago (Adams *et al.* 1990). Changes in agricultural and biosphere productivity in general are expected as a consequence of climate change (Nemani *et al.* 2003). Historically, in the three decades from 1980 global wheat and maize yields fell as a consequence of climate change (Lobell *et al.* 2011). Globally, a reduction in crop yields caused by water stress is predicted to outweigh the contribution higher temperatures makes to productivity, but the fertillisation effect of CO_2 in increasing productivity may not compensate for this reduction (Long *et al.* 2005). Changes in crop phenology are underway and are expected to continue (Cleland *et al.* 2007). Projections of climate change driven variation in cropping shares (proportions) of maize, wheat and oats in Europe in the decades to 2040 suggest an increase in the north of wheat and maize, but little change in oat cropping (Elsgaard *et al.* 2012). Projections for the 2070-2100 period indicate an acceleration of these trends (Olesen *et al.* 2007). Within the IoI it is likely that conditions suitable for maize cropping will become more frequent, particularly in the south east. If this proves to be economically viable, food safety problems associated with maize production, such as Fusarium toxin contamination, may become more challenging.

A study of how climate might drive land use in the 21st century suggests that a widespread reduction will occur of land in agricultural use in Europe overall (-13.1% using HadCM3, B2 scenario) but with considerable variation between and within countries (Schroter *et al.* 2005). According to this analysis the IoI is expected to lose relatively little agricultural land compared to elsewhere in Europe. However, the implications for intensification of production as an adaptive response are not clear. It is possible that the loss of more marginal agricultural land will shift the balance towards greater intensification of the remainder, with consequent implications for food safety risk (e.g. elevated use of pesticides, nitrates in water supply, and so on) and biodiversity loss (Stoate *et al.* 2001).Modelling of animal production specifically, both globally and locally, is difficult and uncertain (Vermeulen *et al.* 2012).

D. Climate change and ecosystem-level effects

Food production is embedded within, and now constitutes, a major part of the earth's ecosystems; the type of production possible is constrained strongly by local climate, soil type, water availability and other ecosystem services, which in turn has implications for food safety in numerous ways. It is a central lesson from ecology that the biocomplexity (biodiversity in all its guises) that results from the strong coupling of the biotic and abiotic parts of the biosphere means that agriculture and safe food delivery cannot be treated in isolation (Foley *et al.* 2011). Given that it is argued that we are now living through the world's sixth mass extinction event, driven by human population growth, habitat destruction and energy use (Barnosky *et al.* 2011; Bellard *et al.* 2012) there is considerable cause for concern. There is now strong empirical evidence that biodiversity loss leads to major ecosystem change (Thomas *et al.* 2004; Hooper *et al.* 2005; Hooper *et al.* 2012). Current global declines in keystone pollinators such as bees will have major effects on production and ecosystem functioning if not reversed (Potts *et al.* 2010). Hoverflies have declined in parallel (Biesmeijer *et al.* 2006). Effects of bee colony diseases such as Varroa destructor mites are most obvious on horticultural businesses with an immediate dependency on insect pollination, such as orchards and honey producers. The decline of pollinators may be caused by a number of factors including habitat loss and pathogens; it is connected with climate change potentially via phonological changes in flowering times (Memmott *et al.* 2007; Potts *et al.* 2010).

Climate envelope models applied to Irish plants suggest that moisture-critical taxa such as mosses and liverworts will undergo range contractions while other species may respond more idiosyncratically (Coll *et al.* 2012). Mapping likely changes at the landscape scale of climate expected to develop in Europe, Gallardo *et al.* (2013) found large changes in local climates categorised using the Koppen Trewartha system. While changes in central Europe were most extreme, the west coast of the IoI is predicted to change from its current "temperature oceanic" category to that of "subtropical humid", a climate now present in the north of Spain and Portugal. Similar, if less dramatic, changes might be expected throughout the island. Since it is axiomatic in biogeography that climate is a strong determinant of the dominant type of vegetation present and the ecological operation of biomes and ecoregions, we must expect large changes in species composition and functioning to match this altered climate. These wholesale transformations are likely to be much more important than the sum of individual species movements tracking climate change as identified in piecemeal studies, and will likely throw up novel and unforeseen challenges for food security and safety.

E. Climate change and trade networks

The globalisation of trading networks against a background of climate change has generated problems for long-term economic planning. From a policy perspective, it would be immensely useful strategically if governments could anticipate changing agricultural viability by knowing which types of production are likely to become uneconomic. Unfortunately in international trade, agricultural commodity and food staple prices, like company stock/share prices, often fall into the difficult-to- impossible category of prediction feasibility, despite the immense financial rewards available for success. When it is attempted, the time horizon is often too short to be useful but highly complex longer-term models with dozens of parameters have been developed (Ramirez and Fadiga 2003; Rosengrant *et al.* 2012). Consequently, predicting the viability of particular agriculture products from a particular location such as the IoI against a global market background, with or without the complication of environmental change, is immensely challenging from the outset.

However, there are sources of local and global trade data that allow at least a coarse overview of network topology, at least, between countries (e.g. Eurostat 2013, Global Trade Information Services (GTIS) 2013). In principle, it is possible to construct analytical models using these data whilst incorporating the likely consequence of changing yields following environmental change in import countries of origin. In practice, there are numerous hurdles to overcome, not least the unpredictable dynamics of the global financial system including shifting exchange rates, volatile energy prices, political influence and "black swan" events potentially drowning out any signals attributable to environmental change (Lipton-Lifschitz 1999; Nag & Mitra 2002; Challet & Marsili 2003). In addition, it is possible that causality operates in both directions: economic growth rates have been hypothesised to depend partly on climate (Masters & McMillan 2001).

Notwithstanding these problems with predictability caused by cascades of uncertainty, it is nonetheless desirable that jurisdictions keep track of trading networks with a view to establishing a baseline vulnerability to change. There is an analogy with financial investments and the inherent trade-off between reward and risk: from a particular jurisdiction's perspective, current trade networks may be rewarding but rather too vulnerable to losses in export revenue, import biosecurity and food safety if the risk were objectively assessed, insofar as it is possible. While integrative modelling approaches have been developed to forecast future land use under different climate change and social scenarios (van Meijl *et al.* 2006; Verburg *et al.* 2008), it is difficult to know how much reliance is optimal on results from integrative modelling given their complexity in terms of numbers of parameters, assumed functional relationships between sub-processes and overall inherent uncertainty (Beale & Lennon 2012). For the IoI, perhaps the best that can be done is an exploration of simple models of likely market change given climate change in countries of origin while bearing in mind the considerable challenges inherent in such an undertaking.

F. Conclusion

For the IoI, most of the insights into the likely consequences of climate change discussed above, particularly in the long term, are based on biophysical statistical and simulation models. The uncertainty associated with the predictions and conclusions of these models is often not fully appreciated (Beale & Lennon 2012). That said, our understanding of the likely response of our food production and safety systems to climate change, insofar as it is possible to say anything useful, must rely on these statistical and simulation models informed by our knowledge of the underlying biological processes. Sometimes these models have a relatively rapid development- testing cycle, such as crop disease weather forecast models where the timescale is days or weeks. More often, models refer to decades in the future. Nonetheless, if climate change produces the temperature increases forecast by our current simulation models then the linkage with some consequences is more or less certain given what we know from many sources about the connection between vegetation, habitats, and ecosystems. The first of these is the principle of general ecosystem transformation. It is long established that there is a strong connection between local climate and local vegetation (Prentice *et al.* 1992). We can therefore expect gross changes in local ecosystems. On the IoI, this will result in changes in land use, potentially agricultural land abandonment in some places and change of use in others from livestock to crops or vice versa. Beyond these general expectations, specific problems will arise. For example, it is highly likely that there will be novel pest species such as invasive insects, weeds or fungi to be dealt with. Control responses may generate food safety problems due to the novelty of the pests in question and the unfamiliarity of farmers in dealing with them, using pesticides or other measures. Changes in weather patterns such as rainfall, seasonality and lengthening of the growing season are likely to entail changes in cropping shares and other adaptations. Increased winter rainfall coupled with milder temperatures in some areas may result in greater use of anti-helminthics as snail vectors multiply. Threat from mycotoxins may intensify as the climate becomes more suitable for disease development. Biosecurity measures will need to be stepped up as environmental change continues and pest and diseases continue to systematically move north. Particular vigilance is needed to detect emerging threats in nearby warmer countries from which these agents might spread, including the development of control measures and awareness of associated food safety hazards if they successfully invade.

Future changes in the wider world are uncertain and recent thinking on human transformation of the biosphere throughout the coming century points to concerns about environmental stability in the broadest sense, and the foreseeability of sudden and large step changes in the environment (Scheffer *et al.* 2001). In economic terms there are potentially large consequences for trade with other countries as they adapt in similar ways to environmental change, particularly when the trading partner is more strongly affected. This is a step up in complexity and a challenge to understand for reasons discussed above. Nonetheless, to the extent that such economic consequences can be anticipated, they should be, using the tools and data currently available. The food industry and stakeholders on the IoI can cooperate to plan for climate change related emerging threats by setting in place monitoring and surveillance systems to identify problems before they become entrenched and so very expensive to fire-fight (Pimentel *et al.* 2005). Emerging pests and diseases should be identified before they arrive on the island. Such pests and diseases, where present in a potential donor country, should be assessed for consequences should biosecurity measures fail. Anticipating invasive species, pests and diseases before they arrive or eradicating rapidly should they do so is orders of magnitude more cost effective than waiting until it is too late. An evidence-based approach using the latest epidemiological modelling techniques can help identify potential problems in advance and allow informed risk assessment. Similarly, the likely changes in land use, cropping and pest management outlined above should be anticipated in detail rather than broad brush, using the latest regional climate models and what is known about current climates analogous to that of the IoI's future.

2 The impact of climate change on mycotoxin contamination of cereal grains

2.1 Introduction

It is now broadly accepted that global climate change is occurring and its impact on agriculture and food production systems throughout the world over the forthcoming decades will be widespread and extremely complex (Sheffield and Landrigan, 2011). Policymakers and food producers must be prepared to adapt to the changing environment that will undoubtedly affect crop yield, prices, quality and safety and be able to develop and implement mitigation strategies to respond to these scenarios. The risks associated with agriculture include heat stress, water stress, flooding, pests and diseases, contamination of agricultural land, groundwater and surface water, heavy metals, agricultural residues and hazardous waste, all of which will impact on food safety and ultimately food security (Vermeulen *et al.*, 2012; Tirado *et al.*, 2010; Miraglia *et al.*, 2009). It is recognized that global climate change will alter the degree of human exposure to food contaminants whether the effects are direct, for example through acute poisoning or indirect due to changes in the food supply (Balbus *et al.*, 2013). This is simply because crop pathogens and pests influencing environmental contaminants are enormously affected by temperature and humidity. The relationship is complicated and it is unknown how their latitudinal shift in response to environmental change will affect the safety of our food (Bebber *et al.*, 2013; Juroszek and von Tiedemann, 2013). Major concerns over our future food safety will necessitate scientific research to assess the impacts of climate change as accurately as possible and through policy changes, regulatory guidelines and monitoring schemes to ascertain occurrence of contaminants and enable risk assessments to be completed; countries should be able to respond to any health threats posed by increased contamination of foodstuffs (Lake *et al.*, 2012; Boxall *et al.*, 2009).

2.2 Climate change predictions

According to the Intergovernmental Panel on Climate Change (IPCC, 2007) climate change is indisputable and the projections for increases in average global temperatures for this century range from 1.8ºC to 4ºC. Within Europe climate related hazards will increase although such events will depend on the geographical region but it is expected that winter floods are likely to increase in maritime regions, the number of flash floods events will grow and coastal flooding related to increasing storminess and sea-level rise is likely (IPCC, 2007).

Ireland's climate is classified as temperate oceanic, i.e. there are no extremes of temperature and there is abundant moisture and precipitation resulting in warm summers and mild winters and in fact much warmer than most places at this latitude. This is caused by Ireland's position in the eastern Atlantic and the thermohaline system ("Gulf Stream"). Regional climate model predictions for Ireland (EPA climate change regional models) have indicated that Ireland will be warmer by 1.25°C to 1.5°C and most of the warming will be observed in the south and the east. The largest temperature increases will be during the month of July. Drier summers and wetter winters (June and December specifically) are forecast. In the southern half of Ireland the climate will become drier especially in June with a 10% decrease in precipitation while an increase in precipitation of 25% in the northwest is likely.

Variable weather patterns such as heavy, unseasonal rains; drought; increased humidity; warmer winter seasons; an increase in severe or intense weather events such as hurricanes, cyclones, storms and floods in addition to increased carbon dioxide in the atmosphere will have a direct influence on the epidemiology of plant disease (Luck *et al.*, 2011; Garrett *et al.*, 2011; Bunyavanich *et al.*, 2003). Therefore the distribution, abundance and performance of crop pathogens responsible for the production of food contaminants may be affected and will subsequently influence agricultural practices through the types of pesticides, herbicides and fungicides used (Lake *et al.*, 2012; Luck *et al.*, 2011).

2.3 Potential Impacts of climate change on cereal production

Agricultural productivity can be significantly affected by increased temperatures. In mid to higher latitudes the type of cereals that may be grown will change. Maize, sunflower and soya beans that are predominantly produced in southern Europe may become more viable in more northern regions thus bringing with it different pests and diseases and perhaps different risks to consumers (Gornall *et al.*, 2010). These weather cycles may contribute to increased contamination of crops with mycotoxins with drought weakening the kernels of the plant which increases susceptibility to fungal contamination and flooding promoting fungal growth (Bunyavanich *et al.*, 2003).

The IoI, a net importer of cereal grains also produces grain for the home market. Spring barley is the most popular cereal crop grown by farmers and is used for the malting, seed and feed industries in the country. Winter and spring wheat, winter barley and winter and spring oats are the other important grain crops produced for the agri-food industry. Another cereal produced on a smaller scale is maize. Due to significant livestock farming a strong domestic feed market exists with approximately 75% of domestic cereals production going to this market, while the remainder is a valuable raw material for Ireland's brewing, distilling and flour milling industries (Ireland's Cereal Sector, 2009). Ireland's cereal yields are among the highest internationally, with winter wheat yields among the highest in the world, due to the suitable climate and soils, along with the expertise of the growers (Ireland's Cereal Sector, 2009). Climate change will have an enormous impact on agriculture not only with variations in the growing seasons and the crop varieties that can be grown but also in terms of contamination of crops by naturally occurring toxins. Current risks to cereal production on the IoI include the damp weather conditions that can exert adverse effects on disease levels, harvest moisture and quality in addition to the fact that often there is continuous cereal cropping and the absence crop rotation. There are also likely to be some benefits from climate change. In the case of barley it will be grown in the same geographical locations, but yields are expected to increase on average by 2 t/ha, particularly in western regions due to elevated atmospheric carbon dioxide levels. Holden *et al* (2003) also concluded that it will remain a viable crop, harvesting will occur earlier in the year and therefore increased rainfall during autumn and winter should not affect the yield. In addition the authors suggested that by 2055 it could be in competition with maize as a forage crop.

2.4 Fusarium head blight and mycotoxin production

The Fusaria fungi are probably the most damaging toxigenic fungi affecting small cereal grains and maize throughout the globe and typically one or more species may infect a plant at one particular time (Imathiu *et al.*, 2013). Fusarium head blight (FHB), one of the most important diseases associated with this fungal genus causes yield loss, a reduction in grain and seed quality in addition to the production of mycotoxins which pose health risks. Wheat, barley and maize comprise two thirds of the world's cereal production and are often affected by these fungal pathogens. Other cereal crops such as oats and rye have been reported to be contaminated with Fusarium mycotoxins (Miller, 2008). Fusarium species are found in all

European cereal-growing regions and affect small- grain cereals and the most commonly found species include F. graminearum, F. culmorum and F. avenaceum. Table 2.1 outlines the major species affecting grain in Europe.

Table 2.1: Fusarium species isolated in Europe and the mycotoxins they produce

Fusarium species	Grain	Mycotoxins produced
F. graminearum	Wheat, oats, barley, rye, maize	DON, NIV, ZEN, AcDON, FUS-X
F. culmorum	Wheat, oats, barley, rye, maize	DON, ZEN, ZOH, NIV
F. avenaceum	Wheat, oats, barley, rye, maize	MON, BEA, ENS
F. poae	Wheat, oats, barley, rye, maize	NIV, BEA, DAS, FUS-X, ENS,T2, HT2
F. langsethiae	Wheat, oats, barley, rye	T2, HT2, NEO, DAS
F. sporotrichiodes	Wheat, oats, barley, rye, maize	T2, HT2, T2ol, NEO
F. crookwellense	Wheat, oats, barley, rye, maize	DON, NIV, ZEN, FUS-X
F. acuminatum	Maize	T2, NEO
F. equiseti	Wheat, oats, barley, rye, maize	DAS, ZEN, ZOH
F. cerealis	Wheat, oats, barley, rye	NIV, FUS-X, ZEN, ZOH
F. tricinctum	Wheat, oats, barley, rye	MON
F. subglutinans	Wheat, maize	FB, MON
F. verticilliodes	Maize	FB
F. proliferatum	Maize	FB

DON: deoxynivalenol; NIV: nivalenol; ZEN: zearalenone; AcDON: acetyldeoxynivalenol; FUS-X: fusarenone-x; ZOH: α-zearalenol/β-zearalenol; MON: moniliformin; BEA: beauvericin; ENS: enniatins; DAS: diacetoxyscirpenol, T-2: T-2 toxin; HT-2: HT-2 toxin; NEO: neosolaniol; T2ol: T-2 triol; FB: fumonisins.

The pathogens are saprophytes, surviving in wheat, maize and other species. Ascospores and/or macroconidia are produced and dispersed by the wind, insects and the rain and infect wheat at anthesis. Warm and wet weather at anthesis causes major yield and quality losses of the crop including the production of mycotoxins (Prandini *et al.*, 2009) and the production of these toxins increases with high levels of rainfall and raised relative humidity. The pathogens can survive winters on or within plant residues therefore minimal tillage has resulted in a significant increase in infection of crops (Osborne and Stein, 2007), however, weather is the most important factor associated with the pathogens. Therefore with climate change there is the potential of an increase in the risk of FHB in wheat and barley resulting from an increase in the production of maize (longer growing season), particularly when maize and wheat are grown in rotation with no tillage (Garrett *et al.*, 2011).

Insects and pests can help the colonisation of crops by toxigenic fungi by lowering the plant's resistance to stress or through mechanical damage (particularly on the kernels) and therefore give rise to greater mycotoxin contamination (FAO, 2008). Petzold and Seaman (2005) determined that the effect of climate change on insects and pathogens was uncertain but all the evidence suggests that there will be an increase in a wider variety of insects (FAO, 2008). Dispersal of Fusarium inoculum may be transferred by insects such as mites, thrips, housefly, beetles, grasshoppers and weevils. In particular a study has shown that wheat midges are capable of transferring F. graminearum and other Fusarium species to wheat spikes and another research group reported that mites have transferred F. poae to wheat glumes in South Africa (Parikka *et al.*, 2012).

In terms of food safety these toxigenic fungi produce a range of mycotoxins (Table 2.1) such as DON, NIV, T-2 toxin and HT-2 toxin in addition to zearalenone and fumonisins, all of which are regulated within the European Union as they are known to pose a risk to public health. Further evidence has shown that emerging toxins produced by such species include fusaproliferin, beauvericin, enniatins and moniliformin (Stenglein, 2009; Parikka *et al.*, 2012; Jestoi, 2008) (Table 2.1). Climatic conditions affect the severity of FHB in the production phase of the crop but the effects are observed right through the production chain. The disease also affects barley and a reduction in the quality of the grain has proved disastrous for the malting and brewing industries (Schwarz *et al.*, 2006). Moreover, deoxynivalenol (DON) has been carried through the brewing process and into the final beer product (CAST, 2003) and currently no European Union regulations exist for these products (Schwarz *et al.*, 2006; Sarlin *et al.*, 2005). This disease will ultimately have an effect on whiskey production on the IoI. Contamination of barley with Fusarium fungi has been shown to have marked effects on germination, soluble nitrogen, free amino acid, wort colour and β-glucan levels which may consequently affect the final product (Schwarz *et al.*, 2006). In relation to mycotoxins they are low- volatile compounds and therefore will not distill into the final product.

Masked mycotoxins are a growing area of concern. A comprehensive review on these mycotoxins has been published recently by Berthiller *et al* (2013). These compounds are extractable conjugated and bound mycotoxins that are not currently regulated by legislation anywhere in the world nor are they routinely monitored yet they may be a potential risk to consumer health (Berthiller *et al.*, 2013). Masked mycotoxins have been identified for the trichothecenes, zearalenone and its metabolites, α-zearalenol and β-zearalenol, ochratoxin A, fumonisins and patulin. The masked mycotoxins and the cereals in which they have been detected are detailed in Table 2.2 (Berthiller *et al.*, 2013).

Table 2.2: Masked mycotoxins and the cereals in which they were detected

Masked mycotoxins	Cereals affected
Trichothecenes:	
deoxynivalenol-3-β-D-glucopyranoside	Wheat, maize, oats, barley
nivalenol-glucoside	Wheat
fusarenone-x-glucoside	Wheat
3-O-glucosides of T-2 toxin and HT-2 toxin	Wheat, oats
Zearalenone, α-zearalenol, β-zearalenol	
zearalenone-14-*O*-glucoside	Wheat, maize
zearalenone-14-sulphate	Wheat, maize
α-zearalenol-14-β-D-glucopyranoside	Not reported
β-zearalenol-14-β-D-glucopyranoside	Maize

	Ochratoxin A:
ochratoxin α	Wheat, maize
(4R)-4-hydroxy-ochratoxin A	Wheat, maize
(4S)-4-hydroxy-ochratoxin A	Wheat, maize
β-glucosides of (4R)-4-hydroxy-ochratoxin A	Wheat, maize
β-glucosides of (4S)-4-hydroxy-ochratoxin A	Wheat, maize
Fumonisins	Maize

Many publications have focused on deoxynivalenol-3-β-D-glucopyranoside. It has been detected in malt and beer (Zachariasova *et al.*, 2008) often at higher levels than DON and Kostelanska *et al* (2009) reported that a survey performed on 176 commercial beer products from Europe and North America showed that this masked mycotoxin had occurred universally in addition to DON and its acetylated derivatives. These conjugated mycotoxins are formed as part of the detoxification process in plants and therefore it seems reasonable to assume that they will exert a lower toxicity compared to the parent mycotoxins, however limited data has been presented for toxicological studies. No bioavailability studies and only a few metabolism studies have been performed for masked mycotoxins (Berthiller *et al.*, 2013).

2.5 Impacts of Climate Change on Mycotoxin Production

Mycotoxins will continue to pose safety risks to humans and animals under differing climatic conditions. In addition, substantial harvest losses due to contaminated grains will have huge consequences for food security (Vermeulen *et al.*, 2012). Environmental factors, in particular, temperature and rainfall have an enormous impact on the growth of fungi and thus raise the possibility of the production of mycotoxins posing a health risk to consumers. In addition these parameters may increase the plant's susceptibility to pest infestations, again raising the probability of fungal infection and the production of mycotoxins (Tirado *et al.*, 2010; Garrett *et al.*, 2011).

Environmental change will affect the pathogenic fungi in specific geographical regions (Vermeulen *et al.*, 2012; Tirado *et al.*, 2010). Increases in temperature may eradicate toxigenic fungi (Russell *et al.*, 2010) producing certain mycotoxins from tropical areas however climate change could result in the colonisation of these mycotoxin producers in more temperate climates. For example, in Italy, since 2003, the summers have been hotter and drier and as a result there have been increased amounts of aflatoxin contamination of grain due to the conditions being ideal for the growth of Aspergillus flavus which until then had been uncommon in Europe and normally confined to more tropical regions. A similar trend has been reported in the United States of America (FAO, 2008; Lake *et al.*, 2012). Growing seasons and crop varieties will be altered according to the environment thus new mycotoxins posing a serious health risk may emerge as a result of this (Miraglia *et al.*, 2009; Balbus *et al.*, 2013). Additionally, deterioration of soil quality may result through loss of minerals by leaching and erosion and so crop yield will be impacted upon, exacerbated by plant disease (Miraglia *et al.*, 2009). In terms of harvest, storage, processing and distribution of cereal crops, climatic conditions also play an important role. Weather conditions at the time of harvesting of cereal crops, such as wet weather or high temperatures are well-known to affect mycotoxin contamination for example DON is generally produced when water availability is high and on the IoI this can be the case before harvest. Any delay in harvest due to wet weather can increase the DON contamination significantly. Optimal growth of Fusarium species and subsequent production of mycotoxins is governed by temperature and water availability and in general at temperatures below 12ºC or above 32ºC, all mycotoxin concentrations are decreased (Chakraborty and Newton, 2011). Table 2.3 outlines typical conditions required by species of importance to the IoI.

Table 2.3: Optimum growth temperature and water availability conditions for Fusarium species

Species	Optimum growth conditions		Reference
	Temperature (ºC)	Water availability (Aw)	
F. graminearum	24 - 28	0.96 – 0.98	Doohan *et al.*, 2003; West *et al.*, 2012; Bottalico and Perrone, 2002
F. culmorum	20 - 25	0.96 – 0.98	Doohan *et al.*, 2003; West *et al.*, 2012; Bottalico and Perrone, 2002
F. avenaceum	20 - 25	0.96 – 0.99	Doohan *et al.*, 2003; Bottalico and Perrone, 2002
F. poae	20 - 25	0.96 – 0.99	Doohan *et al.*, 2003; Bottalico and Perrone, 2002
F. langsethiae	20 -30	0.93 – 0.99	Imathiu *et al.*, 2013; Medina and Magan, 2011

Storage conditions are paramount in the control of mycotoxins. Drying is the most effective method of preventing fungal growth and therefore production of mycotoxins and provided grain is stored at a moisture content equivalent to $\leq$0.70 water activity (Aw) no spoilage should occur (Magan *et al.*, 2003).

2.6 Pathogenic fungal genera of importance to the IoI

As a result of climate change, significant effects on crop production are expected, including advanced anthesis and maturity and increased frequency of plant disease such as FHB. The two species of most importance are F. graminearum and F. culmorum as they produce mycotoxins that pose a threat to public health. DON and zearalenone are two mycotoxins produced by the above Fusarium species but other toxins such as HT-2 toxin and T-2 toxin are produced by other species i.e. F. poea and F. langsethiae (West *et al.*, 2012). Moreover, in warmer climates these toxins can be produced by various strains or species and so mycotoxins will remain a major concern in food safety. F. graminearum is commonly found in the moist, warm climates of central and south-eastern Europe with F. culmorum and F. avenaceum occurring in maritime and cooler European regions however shifts in the regional profile of these pathogenic fungi have been reported in many areas in the past decade (Bottalico and Perrone, 2002). In France, The Netherlands, Belgium, England and Scotland the most common Fusarium species associated with disease of cereals is F. culmorum, F. graminearum, F. poae and F. avenaceum and in the UK wheat surveys indicated the causal species for FHB to be F. graminearum and F. culmorum. In the last decade, the incidence of FHB has been sporadic but increasing within the UK and in 2008 there was a serious epidemic with associated DON contamination. Similar changes have been noted for maize (West *et al.*, 2012). F. graminearum was the predominant species responsible for FHB however there has been a shift from this species to F. verticilloides, F. proliferatum and F. subglutinans which produce several mycotoxins (West *et al.*, 2012). Evidence for the effects of climate change on FHB in wheat production has already been noted. Higher temperatures in England, Wales, Germany and The Netherlands have seen a shift in the dominant fungal species infecting the crop (Chakraborty and Newton, 2011). Fusarium head blight of wheat in England and Wales has been associated with F. culmorum, F. poae, F. avenaceum and Microdochium nivale with F. culmorum being the most important in terms of mycotoxin production and yield loss (Jennings *et al.*, 2004). However from 1998 an increase in the pathogen F. graminearum was observed year on year until it out-competed F. culmorum; a trend that had also been observed in Germany and The Netherlands (Jennings *et al.*, 2004; FAO, 2008). A change in farming practices has also been attributed to this trend, particularly cropping systems, in addition to F. graminearum having adapted to the environment and becoming more aggressive (Bateman *et al.*, 2007). This pathogenic fungus can produce DON and zearalenone or NIV and zearalenone depending on the isolate infecting the grains. In addition, DON is produced via either the 15-acetylated or 3- acetylated precursor, again depending on its geographical position. F. culmorum produces deoxynivalenol, 3-acetyldeoxynivalenol and zearalenone (Bottalico and Perrone, 2002). Studies in the UK have shown that both DON and NIV have been present in harvested grain and both DON and NIV chemotypes are present in F. culmorum (Bottalico and Perrone, 2002). In the south-west of England and south Wales, the predominant pathogenic species found is F. graminearum however the isolate has been chemotyped as the DON producer, therefore the NIV has been produced from F. culmorum, NIV chemotype. If the trend for an increase in F. graminearum continues then perhaps the UK will experience a reduction in NIV contamination in the future. Yet a study has also shown that the NIV chemotype of F. graminearum is also present in England and Wales but that the DON chemotype was by far the most prevalent. F. culmorum NIV chemotypes were found in the south-west while 3-acetyldeoxynivalenol chemotypes were found in the east, no such regional variation was seen for F. graminearum chemotypes. Therefore with this high proportion of the NIV chemotype present, contamination with NIV may actually increase in the future (Jennings *et al.*, 2004).

F. poae and F. sporotrichiodes produce trichothecenes, a few isolates of F. poae can produce small amounts of T-2 toxin and HT-2 toxin but mainly NIV is produced. F. sporotrichiodes and F. poae have been reported to cause contamination in Norwegian cereals by T-2 toxin and HT-2 toxin, while F. acuminatum has reportedly caused T-2 toxin and neosolaniol contamination. F. sporotrichiodes, a producer of T-2 toxin, HT-2 toxin, neosolaniol and diacetoxyscirpenol is uncommon in northern regions and while it used to be relatively common in Denmark, this is no longer the case (Parikka *et al.*, 2012). F. poae has been implicated in FHB of small grains worldwide and the mycotoxins produced from this fungus including the trichothecenes are fusarenone-x, aurofusarin, beauvericin, butenolide, culmorin, cyclonerodiol, enniatins, fusarin and moniliformin. In cereal surveys in England, Wales, Ireland, South America, Canada and many other countries within Europe F. poae has been one of the most frequently isolated fungal pathogens (Stenglein, 2009). It affects wheat, barley and oats, but has a preference for the latter (Parikka *et al.*, 2012). Production of beauvericin has been reported in Finnish grains and beauvericin along with enniatin A, B and B1 has been reported in maize kernels infected with F. poae. This fungal pathogen is on the increase in Austria, France and has been the predominant species found in contaminated Finnish, Norwegian, Swedish and Japanese grains. It predominates in England, Wales, Ireland and Slovakia and has been confirmed in wheat samples in Argentina (Stenglein, 2009). Normally associated with cooler conditions it has been associated with dry, warm conditions whereas F. graminearum prefers warmer, humid conditions while F. avenaceum and F. culmorum prevail in cooler, wet, humid conditions. In Scandinavian countries F. culmorum has been the main producer of DON however increased incidences of F. graminearum have been noted as with other European regions (Parikka *et al.*, 2012). Another European species F. langsethiae, first found in Norway has also been isolated in the UK and has been responsible for the infection of wheat, oats and barley with oats being the more susceptible grain (Bottalico and Perrone, 2002; Medina and Magan, 2011; Imathiu *et al.*, 2013). Over the past twenty years in northern Europe contamination of oats with T-2 toxin and HT-2 toxin has increased as a result of this pathogen and this species has become prevalent, not only in Scandinavia and the UK but also in France and Slovakia, particularly on barley (Parikka *et al.*, 2012). Detection of contamination is made more difficult by the fact that often this pathogenic fungus has been isolated from oats and wheat that do not appear to be infected (Medina and Magan, 2011). This species and F. poae are morphologically very similar and both are weak pathogens when compared to F. graminearum and F. culmorum. Unlike F. poae, F. langsethiae can produce high levels of T-2 toxin and HT-2 toxin, similar to F. sporotrichiodes (Parikka *et al.*, 2012). Both F. langsethiae and F. poae infect the plants during flowering (especially oats) and it is thought that they are competitors (Yli-Mattila, 2010). Two other noteworthy Fusarium species are F. avenaceum and F. tricinctum that are commonly found in Scandinavian regions. They have been isolated from wheat, oats and barley and although they do not produce trichothecenes, other so called emerging mycotoxins such as enniatins, moniliformin and beauvericin have been observed (Parikka *et al.*, 2012). Table 2.4 ranks the Fusarium species as high or low risk for the IoI.

Table 2.4: Fusarium species of risk of occurrence on the IoI

High risk	Low risk
F. graminearum	*F. sporotrichiodes*
F. culmorum	*F. acuminatum*
F. poae	*F. verticilliodes**
F. avenaceum	*F. proliferatum**
F. langsethiae	*F. subglutinans**

*These species infect maize therefore if grain maize becomes a viable crop through global warming, their risk of occurrence will increase.

Edwards investigated Fusarium mycotoxins in UK barley (and NI), including their distribution, the relationship between the mycotoxins, seasonal and regional variations and considered conventional versus organically grown barley over a four year period. The results highlighted that moniliformin was not an important mycotoxin at that time and the maximum concentration found was 45 µg/kg and only 2% of samples analysed (n = 239) had concentrations above 10 µg/kg. Similarly for zearalenone, it was rarely detected and the maximum concentration found was 44 µg/kg which is below the European legal limit. Again only 2% of the samples demonstrated levels above 10 µg/kg. All trichothecenes with the exception of diacetoxyscirpenol and neosolaniol were found in varying concentrations with DON, NIV and HT-2 toxin all demonstrating concentrations above 100 µg/kg. DON was the most prevalent occurring in 57% of samples tested, although only one sample was found to exceed the regulatory limit of 1250 µg/kg and in addition this was the only sample where the acetyl derivatives of DON were detected. T-2 toxin and HT-2 toxin were reported in 12% and 36% of samples and the highest combined concentration was 138 µg/kg. NIV was reported in 25% of the samples, the highest concentration found being 157 µg/kg while fusarenone-x, a mycotoxin that had not been reported in UK cereals previously had an incidence rate of 0.7%, all samples having low concentrations. Finally T-2 triol was found as a co-contaminant of HT-2 toxin and T-2 toxin in one sample and detected just above the limit of quantification. The results highlight that mycotoxin contamination of barley during those harvests, although present, was relatively low and that there was no significant difference between conventionally grown barley compared to organically produced barley. A weak relationship was shown for HT-2 toxin and T-2 toxin but no relationship was found between DON or NIV against HT-2 toxin and T-2 toxin or for DON and NIV. Year and region had a significant effect on DON, HT-2 toxin and T-2 toxin (Edwards, 2009a).

In a similar study as described in Edwards (2009a), the author investigated wheat contamination by Fusarium mycotoxins. DON, 15-acetyldeoxynivalenol, NIV, HT-2 toxin and zearalenone were found at concentrations above 100 µg/kg. T-2 toxin, T-2 triol and 3- acetyldeoxynivalenol were detected below this. Again DON was the predominant mycotoxin, found in 86% of the samples tested and usually present in higher concentrations. 2.4% of samples exceeded the regulatory limits over the 5 year period. NIV was present in 67% of wheat samples, the highest concentration reported as 430 µg/kg. Although HT-2 toxin and T-2 toxin were detected in 31% and 16% of samples respectively, the levels were generally low however 0.5% of samples exceeded the discussion limit of 100 µg/kg. Zearalenone was more prevalent, in 39% of the samples analysed with 19 of samples exceeding 10 µg/kg and 3.1% being above the recommended levels permitted. The acetyl metabolites of DON and T-2 triol were detected in a small number of samples and at low concentrations while fusarenone-x, diacetoxyscirpenol and neosolaniol were not present in any sample. Of all the mycotoxins determined in the samples only DON and zearalenone showed any correlation. No significant differences were seen between contamination levels of DON or zearalenone in conventional or organic wheat however organic wheat had significantly lower concentrations of HT-2 toxin and T-2 toxin. The region and year were significant for all mycotoxins produced (Edwards, 2009b).

A further investigation of Fusarium mycotoxins was performed in conventional and organically grown oats in the UK (again including N. Ireland). Analyses were conducted for DON, NIV, 3-acetyldeoxynivalenol, 15-acetyldeoxynivalenol, fusarenone-x, T-2 toxin, HT-2 toxin, diacetoxyscirpenol, neosolaniol, T-2 triol, zearalenone and moniliformin. As no moniliformin was detected in the first two years of the study, this analysis was discontinued. Zearalenone was found at very low concentrations during the same time period and therefore the number of samples analysed reduced with 296 samples being tested over four years. Of these 5% were above 3 µg/kg (limit of quantification) and the highest concentration detected was 29 µg/kg. For the trichothecenes, DON, NIV, HT-2 toxin, T-2 toxin, neosolaniol and T-2 triol were detected above 100 µg/kg. DON was present in 32% of the samples tested and the maximum concentration determined was 282 µg/kg; well below the regulatory limits. High contamination of HT-2 toxin (92%) and T-2 toxin (84%) was reported with a maximum combined concentration of 9990 µg/kg detected. 72% of the samples contained NIV with the highest concentration found being 847 µg/kg. Neosolaniol and T-2 triol were both present in 41% of samples at maximum levels of 189 µg/kg and 263 µg/kg respectively while 3-acetyldeoxynivalenol was present in 0.2% of samples with a maximum concentration of 26 µg/kg. No fusarenone-x, diacetoxyscirpenol or 15-acetyldeoxynivalenol was detected. Concentrations of HT-2 toxin correlated well with T-2 toxin, T-2 triol and neosolaniol. Again the year and region were highly significant as was the difference between contamination levels of HT-2 toxin and T-2 toxin in organically grown oats compared with those conventionally grown. Combined concentrations of these toxins in organic oats were approximately 5 times lower. Taking the European Union discussion levels for oats intended for human consumption (500 µg/kg) into account, between 0 –22% of organic oats and 18 – 50% of conventional oats exceeded this level between 2002 and 2005 (Edwards, 2009c).

In Scotland, Fusarium Head Blight is common with 70-95% of grain samples being contaminated, albeit at very low levels (<5%), however the fact that the Fusarium species produce mycotoxins makes the situation more complicated. Generally Microdochium nivale is the most prevalent species found in grain samples (a non-toxigenic species), but F. culmorum is found frequently and F. graminearum and F. avenaceum found infrequently to date (The Scottish Agricultural College, 2007). F. graminearum poses the greatest threat in terms of mycotoxin production and with increases in temperature maize may be a grain of choice in the future. This poses as additional threat as growing maize in rotation increases the risk of infection and therefore production of mycotoxins.

Zearalenone is another mycotoxin produced by Fusarium species, with F. graminearum being the responsible species for high levels in harvested cereal grains. Other species that produce this toxin are F. culmorum, F. crookwellense, F. equiseti, F. pseudograminearum and F. semitectum. Infection is dependent on weather conditions before and during flowering and therefore in northern Europe this period is usually June/July. Zearalenone is heterogeneously distributed within the grain and predominates in the bran fraction of wheat. Contamination concentrations for zearalenone are limited. DON is more of an issue in cereals in Europe and therefore zearalenone is not tested for as frequently. Increasing incidence of F. graminearum has been reported over the last decade and as a consequence of later, wetter harvests, the risk of zearalenone contamination is greater. Since 2001, monitoring of wheat in the UK for this toxin has been performed and results highlight that the toxin has been found every year and in 2008, 29% of the samples tested were found to be above the regulatory limit (Edwards, 2011).

As already stated the fungal genus Fusarium is capable of producing other toxic metabolites, i.e. emerging mycotoxins known as fusaproliferin, beauvericin, enniatins and moniliformin that may contaminate small grains and therefore pose a risk to human and animal health if these contaminated grains are consumed. Risk assessments have not been completed for these mycotoxins since there is a lack of toxicity, occurrence and contamination data available in addition to sensitive methodologies to determine concentrations, yet in order to obtain such information regular surveillance is required to clarify the risk. Various Fusarium species have been shown to produce these emerging mycotoxins including F. avenaceum, F. langsethiae, F. poae and F. culmorum and maize has been reported as the most common host for such mycotoxins (Jestoi, 2008). Although limited information is available, these toxins have been reported worldwide in wheat, barley, oats, rye and maize and co-occur with other mycotoxins, reiterating that detailed investigations including toxicology studies and monitoring to ascertain contamination levels and global distribution are urgently required. The European Commission has requested scientific opinions on the risks for animal and public health related to the presence of beauvericin, enniatins and moniliformin in food and feed. Originally these reports were expected by January 2012, however the deadline has been extended and the European Food Safety Authority (EFSA) will report at the end of September 2014 (http://www.efsa.europa.eu/).

F. avenaceum has been shown to have the ability to produce moniliformin and enniatins in vitro and moniliformin has been reported as a contaminant of wheat infected with this fungal species. In maize, the same species has also produced beauvericin (Logrieco *et al.*, 2002). Wheat samples from four different areas in Finland, affected by head blight were collected at harvest and tested for beauvericin and enniatins in addition to the fungal strain being identified. The predominant species reported was F. avenaceum being present in 91% of the wheat samples however F. culmorum, F. tricinctum and F. poae were determined in 4%, 3% and 2% of the samples. Beauvericin was detected in all samples; the highest concentration found being 3.5 µg/g. Of the enniatins, enniatin B was the most frequently reported (in 92% of samples); enniatin A1 was present in 77% of samples and enniatin B1 was found in 62% of samples. The maximum concentrations determined were 4.8 µg/g, 6.9 µg/g and 1.9 µg/g, respectively (Logrieco *et al.*, 2002). It is understood that FHB can be caused by several species depending on the climatic conditions and geographical region therefore it is important that research is undertaken to establish if synergistic effects exist between these toxins and others produced by Fusarium species such as the trichothecenes and moniliformin (Logrieco *et al.*, 2002).

More recently in a study by Serrano *et al* (2012), contamination of unprocessed maize, wheat and barley and breakfast cereals in Spain and Morocco has been reported and in particular infant cereals have been shown to contain enniatin B1 and enniatin A1. In this study infant formula and follow-up infant formulas derived from wheat, corn, rice, oat, barley, rye, sorghum and millet flour and whole cereals were analysed for the presence of the Fusarium mycotoxins beauvericin, enniatins and fusaproliferin. Enniatins (ENA, ENA1, ENB and ENB1) were detected in 21 of the 45 samples tested. Enniatin A and Enniatin B were found in only one sample each at concentrations of 150 mg/kg and 39 mg/kg respectively. The frequency of contamination with enniatin A1 ranged from 0% to 22% with a mean concentration of 47 mg/kg and a maximum concentration of 102 mg/kg. Enniatin B1 was the most frequently found mycotoxin ranging from 10% to 60% depending on the type of sample tested and the maximum level detected was 42 mg/kg. Fusaproliferin was found in 20% of the samples analysed and the maximum concentration determined was 1.7 mg/kg. This research demonstrates that cereal-based infant formulas do contain these toxic secondary metabolites and should serve to demonstrate the need for more research in this area to protect public health (Serrano *et al.*, 2012).

Jestoi (2008) and Santini *et al* (2012) have comprehensively reviewed the natural occurrence of fusaproliferin, beauvericin, enniatins and moniliformin in grains and grain-based foodstuffs. Fusaproliferin has been detected in maize, wheat, barley oats and rye in Italy, Finland, USA, South Africa, Slovakia, Spain, Tunisia and Spain with concentrations ranging from <0.001 – 500 mg/kg. The natural occurrence of beauvericin in maize, wheat, barley, oats, rye and rice in Poland, Italy, USA, South Africa, Switzerland, Argentina, Croatia, Finland, Slovakia, Norway, Denmark, Spain, Morocco and Tunisia has been reported, the highest concentration of 520 mg/kg being detected in maize from Italy. Fewer studies have been conducted for enniatins, however, they have been observed in wheat, barley, oats, rye, maize, sorghum and rice from trace levels to 813 mg/kg. The countries included Finland, Italy, Norway, Denmark, Spain, Morocco and Tunisia. According to Jestoi (2008), moniliformin has been studied more extensively than the others possibly because of its higher acute toxicity. Again it has been detected in the cereals and grains mentioned above in South Africa, Germany, USA, Canada, UK, Poland, China, Austria, Switzerland, Norway, Finland and Italy and the highest concentration found has been 425 mg/kg in maize from Poland.

Penicillium verrucosum is a fungal species that inhabits temperate climate zones and is responsible for the production of the mycotoxin ochratoxin A (Patterson and Lima, 2010). It has been detected in a variety of products such as cereals, coffee, grapes and beans but has been particularly prevalent in Scandinavian barley (Sweeney *et al.*, 2000). The fungus grows in a temperature range of 0ºC to 31ºC, the optimum being 20ºC but ochratoxin A can be produced over the entire temperature range with the optimum temperature for production being 20ºC (Sweeney *et al.*, 2000). While there has been no evidence of this species contaminating cereals or fruits in the UK and Ireland, monitoring the situation including testing for ochratoxin A would be pertinent.

Little information is available for the natural occurrence of masked mycotoxins in cereals and foods, however deoxynivalenol-3-β-D-glucopyranoside has been reported in wheat, maize, barley, malt and beer, zearalenone-14-β-glucopyranoside has been detected in wheat, barley and maize, zearalenone-14-sulphate in wheat and maize commodities and masked fumonisin in maize commodities. To date, no studies have been performed to indicate if ochratoxin A masked mycotoxins occur in naturally infected cereals (Berthiller *et al.*, 2013). This highlights the need for research in this area.

Table 2.5 outlines the mycotoxins presently posing a problem in this geographical region and those that may pose a risk in future years as a result of a warming climate.

Table 2.5: Mycotoxins risks to the IoI

Legislated mycotoxins		Non-legislated mycotoxins		
Present high risk	**Predicted**	**Present high risk**	**Present low risk**	**Predicted**
Deoxynivalenol	Fumonisins* (low risk)	Nivalenol	15-Acetyldeoxynivalenol	Enniatins
Zearalenone	Ochratoxin A (low risk)	HT-2 toxin	3-Acetyldeoxynivalenol	Beauvericin
		T-2 toxin	Moniliformin	Fusaproliferin
		Fusareone-X	Masked ochratoxin A** (low risk)	

	T-2 triol	Masked fumonisin** (low risk)
		Neosolaniol
		Masked trichothecenes
		Masked zearalenone

*If grain maize becomes a viable crop
**See Table 2.2 for the full list

2.7 Mitigation strategies

Food safety issues are extremely complicated and require control procedures throughout the production chain to minimize risk (Pitt *et al.*, 2013). Climate change has been determined as one of the major causes of pre-harvest contamination of cereal grains by pathogenic fungal and the subsequent production of toxic metabolites that pose a risk to the health of both humans and animals. However, the entire cropping system may also play an integral role in infection levels (Champeil *et al.*, 2004). These environmental changes may see the cultivation of cereals being shifted to more northerly or southerly areas and populations of the pests associated with these crops are expected to move with them. Therefore no major changes are envisaged in relation to plant protection, but it is unknown in the new geographical location how severe the damage may be (Juroszek and von Tiedemann, 2013). Moreover it has not been determined how farming practices and climate change will affect the virulence and toxin biosynthesis of the Fusarium genera (Kazan *et al.*, 2012). Fusarium mycotoxins are ubiquitous in the field and can therefore never be totally eradicated however the aim is to reduce levels of mycotoxins as much as possible by adopting agronomic practices that enable this. Since climate change has only been slight over the past decades, other factors may contribute to the severity of infection (West *et al.*, 2012). These include crop rotation, control of pests in the field and planting of resistant cultivars or less susceptible cultivars (West *et al.*, 2012; Imathiu *et al.*, 2013).o

A. Agronomic practices

Good agricultural practice will remain the foundation of management strategies to tackle the effects of climate change and revision of guidelines for particular crops may be required to improve production and minimise the risk from mycotoxins (FAO, 2008).

Infection of cereal crops by toxigenic fungi ultimately results in reduced yield and milling and malting quality and the possible presence of mycotoxins. Edwards (2004) reviewed the relevant literature on FHB infection with respect to agricultural practices. The general consensus is that crop rotation plays an important role in the control of infection for example if wheat is grown after maize then the risk of FHB infection by F. graminearum and F. culmorum is increased (Parikka *et al* 2012), the risk being increased more after grain maize than forage maize and the lowest levels of contamination were observed when wheat followed soya bean (Edwards, 2004). Ploughing, minimum tillage and no-till cultivation methods have also been shown to affect infection rates (West *et al.*, 2012). If infected residues are removed or buried then the inoculum is reduced for the next crop however it has been reported that if minimum tillage is used after maize then there could be a significant increase in DON contamination of wheat. Also direct drilling after maize or wheat resulted in increased DON contamination when compared to ploughing. It was also found that if the previous crop was soya bean and no-till cultivation methods were employed, no effect was observed. Parikka *et al* (2012) reported that using direct drilling and wheat as a pre-crop to wheat, increased incidences of FHB and DON contamination were observed when compared with reduced tillage or ploughing. Yli-Mattila (2010) reported that tillage together with ploughing was shown to increase infection with F. poae but infection with F. langsethiae decreased when compared to direct drilling. Following a two-year study in the UK by Bateman *et al* (2007) investigating the risk of FHB and production of mycotoxins by F. graminearum, they concluded that increased disease and contamination by mycotoxins was exacerbated by minimal tillage and maize cropping. Cropping systems were also researched by Champeil *et al* (2004). The authors evaluated four different cropping systems on the severity of infection by Fusarium species and the contamination levels with respect to mycotoxins. They found that the level of mycotoxin contamination was dependent on the year and the cropping system and in agreement with other studies, direct drilling resulted in higher levels of contamination. If wheat was grown directly after maize, then again levels of mycotoxin contamination were increased. Maize is grown from temperate to tropical regions (FAO, 2008) but with climate predictions for northern Europe and suggestions of extended growing seasons and milder winters, grain maize may be introduced as a crop (Parikka *et al.*, 2012). Therefore crop rotation will be an important factor to consider in the future. In fact the production of maize has become more common in Denmark and central Europe resulting in the occurrence of F. verticilloides and fumonisin mycotoxins (Yli-Mattila, 2010) but due to the high temperature required for growth, we should not expect to see these fungi dominate in northern latitudes (FAO, 2008).

The use of fertilizers can have an impact on fungal attack by changing the rate of residue decomposition, stressing the plant or by alteration of the crop structure. Fertilizers have been shown to increase the incidence of FHB infections but it depends on the form of nitrogen applied (FAO, 2008). Use of urea compared with ammonium nitrate resulted in a reduction of FHB symptoms and nitrolime application saw reductions of 31 – 59% when compared with calcium ammonium nitrate (Edwards, 2004). Fungicides are an important control measure for FHB and therefore subsequent mycotoxin contamination (Parikka *et al.*, 2012) but again care must be taken to select the most appropriate dose as it has been reported that some fungicides at sub-lethal concentrations can stimulate the production of mycotoxins. Metconazole and tebuconazole have been used successfully to reduce Fusarium infections and reduce mycotoxin contamination whereas azoxystrobin, while it reduces FHB, reductions in DON contamination are not observed (Edwards, 2004). Another measure to reduce infection and mycotoxin production could be biological control but further work is required. Glyphosphate-based weed killers have been associated with an increase in FHB in wheat in Canada. Insect control may help in the reduction of some FHB infections, depending on the invasive species, however there is a lack of evidence in the literature. Caution must be exercised with increased use of fungicides/pesticides as this may lead to greater chemical contamination of crops that may enter the food chain posing an additional threat to public health. That said, recent European legislation has dictated the use of fewer fungicides for the control of FHB therefore we may see increased infection rates in the future (West *et al.*, 2012).

Plant breeding will allow the adaptation of crops to increased growing seasons, elevated temperatures and drought while new cultivars could be introduced, however, as plants adapt to the changing environment, so too do plant pathogens necessitating assessment of new pathogens or more aggressive ones (Luck *et al.*, 2011). Breeding for resistance has been successful for spring and winter wheat and in barley while there are differences in resistance; opportunities exist for the breeding of resistant cultivars. Unfortunately the situation for oats is that in commercial cultivars there is not much resistance, however using oat wild-types in Norway, resistance has been found to F. langsethiae (Parikka *et al.*, 2012). The recommendations are outlined in Table 2.6.

Table 2.6: Agronomic practice recommendations

Practice	Recommendations
Cultivation	Ploughing should be used rather than direct drilling or minimal till to reduce fungal infestation. Crop rotation: Avoid growing wheat after maize.
Fertilizers	Use of urea or nitrolime will reduce FHB symptoms.

Fungicides/pesticides	Use of Metcanazole and tebucanzole reduce Fusarium infections and mycotoxin contamination. Avoid azoxystrobin and glyphosphate-based weed killers.
Plant breeding	Introduce resistant cultivars

B. Post-harvest storage and processing

Post-harvest handling is important in the control of mycotoxin contamination. Cleaning, drying and restricting water availability in storage will reduce the likelihood of further contamination. Therefore investment in infrastructure may be required to ensure these factors are controlled (FAO, 2008).

Pests in grain silos may multiply under increased temperatures due to climate change, thus increasing water produced and therefore making conditions conducive to fungal growth and the possibility of contamination with mycotoxins. F. langsethiae infection of oats and barley may not be visible under inspection and therefore it is more difficult to determine where contamination has occurred. Post-harvest management must therefore ensure a hazard analysis critical control point (HACCP) system is in place to deal with such scenarios. Predictive increases in atmospheric carbon dioxide may not be an issue to fungi as a study has shown that they can withstand high concentrations of the gas. Temperature and water availability are two of the most important factors affecting germination, growth, sporulation and mycotoxin production (Magan *et al.*, 2011). A moisture content of 12% has been set for the storage and transport of grain. If at harvest the moisture content exceeds this one option is to delay harvest until it has reached an acceptable level or drying can be applied at an additional cost. DON concentrations can increase during storage if the moisture is not kept at or below 10-11% (Chakraborty and Newton, 2011). Ochratoxin A occurs post-harvest during the drying stage. The fungus is a xerophile and therefore is able to grow under storage conditions with little water and so mycotoxin concentrations may increase (Pitt *et al.*, 2013), therefore analysis of contaminated batches must be performed to determine if the grains are safe for human and animal consumption. During processing, many methods are employed to ensure that the final product will be safe for the consumer (Pitt *et al.*, 2013) for example milling can reduce the levels of DON or NIV in grains as the toxin is produced in the germ (Pitt *et al.*, 2013). Vaclavikova *et al* (2013) studied the fate of enniatins during processing (brewing and bread making) of barley and wheat. The results demonstrated that milling reduced the levels of contamination but 40% of enniatins remained in the wheat flour. Baking of bread reduced the levels further to 30% in the final product. In contrast, malting of barley decreased the concentrations of these toxins to 30% of the initial content and complete removal occurred during the wort production, therefore these toxins were not present in the final product. The spent grains from this process contained high levels of the mycotoxins and are therefore care should be taken if this by- product is destined for animal feed. Table 2.7 highlights the recommendations.

Table 2.7: Post-harvest and processing recommendations

Handling	Recommendations
Post-harvest	HACCP systems must be in place for all crops. Analysis and rejection of contaminated grains (pre/during storage). Grains must be cleaned and dried (<12% moisture content) prior to storage. Storage silos must be clean and dry.
Processing	By-products must be analysed for mycotoxin content prior to entry into the animal feed sector.

C. Regulatory limits and surveillance

Regulatory limits are currently enforced in many countries in order to limit human exposure to these natural toxins and therefore monitoring programmes have been established to monitor concentrations in crops, although this is not the case for all countries. Tables 2.8 and 2.9 outline the EU regulations for the mycotoxins of interest to the IoI in food and feed.

Table 2.8: EU regulatory limits for cereals and cereal-based food (Commission Regulation (EC) No 1881/2006)

Mycotoxin	Food stuff	Max. levels (µg/kg)
Deoxynivalenol	Unprocessed cereals other than durum wheat, oats and maize	1250
	Unprocessed durum wheat and oats	1750
	Unprocessed maize, with the exception of unprocessed maize intended to be processed by wet milling	1750
	Cereals intended for direct human consumption, cereal flour, bran and germ as end product marketed for direct human consumption	750
	Pasta (dry)	750
	Bread (including small bakery wares), pastries, biscuits, cereal snacks and breakfast cereals.	500
	Processed cereal-based foods and baby foods for infants and young children.	200
	Milling fractions of maize with particle size > 500 micron	750
	Milling fractions of maize with particle size $\leq$ 500 micron	1250
Zearalenone	Unprocessed cereals other than maize	100
	Unprocessed maize with the exception of unprocessed maize intended to be processed by wet milling.	350
	Cereals intended for direct human consumption, cereal flour, bran and germ as end product marketed for direct human consumption.	75
	Refined maize oil	400
	Bread (including small bakery wares), pastries, biscuits, cereal snacks and breakfast cereals, excluding maize snacks and maize-based breakfast cereals.	50
	Maize intended for direct human consumption, maize-based snacks and maize-based breakfast cereals.	100
	Processed cereal-based foods (excluding processed maize-based foods) and baby foods for infants and young children.	20
	Processed maize.	20
	Milling fractions of maize with particle size > 500 micron.	200
	Milling fractions of maize with particle size $\leq$ 500 micron.	300
Ochratoxin A	Unprocessed cereals	5
	All products derived from unprocessed cereals, including processed cereal products and cereals intended for direct human consumption.	3

	Processed cereal-based foods and baby foods for infants and young children.	0.5
	Dietary foods for special medical purposes intended specifically for infants.	0.5
Fumonisins B1& B2	Unprocessed maize, with the exception of unprocessed maize intended to be processed by wet milling.	4000
	Maize intended for direct human consumption, maize-based foods for direct human consumption.	1000
	Maize-based breakfast cereals and maize-based snacks.	800
	Processed maize-based foods and baby foods for infants and young children.	200
	Milling fractions of maize with particle size > 500 micron.	1400
	Milling fractions of maize with particle size > 500 micron.	2000

Table 2.9: EU Regulatory limits for animal feed (Commission Recommendation 2006/576/EC)

Mycotoxin	Products intended for animal feed	Max. levels (µg/kg)
Deoxynivalenol	Complementary and complete feeding stuffs.	5000
	Complementary and complete feeding stuffs for pigs.	900
	Complementary and complete feeding stuffs for calves (< 4 months), lambs and kids.	2000
Zearalenone	Complementary and complete feeding stuffs for piglets and gilts (young sows).	100
	Complementary and complete feeding stuffs for sows and fattening pigs.	250
	Complementary and complete feeding stuffs for calves, dairy cattle, sheep (including lamb) and goats (including kids).	500
Ochratoxin A	Cereals and cereal products.	250
	Complementary and complete feeding stuffs for pigs.	50
	Complementary and complete feeding stuffs for poultry.	100
Fumonisin B1& B2	Complementary and complete feeding stuffs for pigs, horses.	5000
	Complementary and complete feeding stuffs for poultry, calves (< 4 months), lambs and kids.	20000
	Complementary and complete feeding stuffs for adult ruminants (> 4 months).	50,000

Any changes in the occurrence, distribution and toxicity of mycotoxins will be of interest to monitoring bodies and policy makers at all levels. It will be necessary for these stakeholders to ascertain if existing monitoring schemes are robust enough to protect public health in the future and to evaluate the consequences of increased or altered mycotoxin risks in our food supply (Lake *et al.*, 2012; Balbus *et al.*, 2013). Visual inspection of grains, mycotoxin analyses and subsequent rejection of non-compliant batches forms the basis of meeting regulatory requirements in many countries (Pitt *et al.*, 2013). Improved methodologies for the determination of mycotoxin contamination in commodities and the use molecular methods for the routine identification, detection and quantification of Fusarium species such as micro-array methods will be of use in identifying risks associated with these pathogenic fungi in the future (Yli-Mattila, 2010). Clearly research needs to be focused on the development of rapid methods to detect mycotoxins in complex samples and this will enable a rapid response to results generated from the surveillance and monitoring programmes (FAO, 2008). Table 2.10 outlines the recommendations.

Table 2.10: Specific recommendations for monitoring/risk analysis

Activity	Recommendations
Routine monitoring	Implementation of routine monitoring for the mycotoxins outlined in Table 2.5. Development of improved methods of detection, in particular rapid screening assays. Development of molecular methods for the identification of pathogenic fungal species.
Risk assessment	Toxicokinetic studies are required for enniatins, beauvericin, fusaproliferin, moniliformin and masked mycotoxins. Toxicity data both *in vitro* and *in vivo* are required for the above mycotoxins. Investigate the synergistic effects of emerging mycotoxins with others commonly produced in this geographical region.

D. Mycotoxin exposure through consumption of contaminated animal products

The half-life of most mycotoxins and their metabolites is short (a few days) (EFSA, 2009; Volkel *et al.*, 2011). They are generally not accumulated in muscle and excretion occurs through the urine and faeces however there can be carry-over into the eggs of poultry and milk of mammals. In the case of eggs, very low carry-over (0.6 – 0.001%) has been found for ochratoxin A, T-2 toxin, DON, zearalenone and fumonisin B1. In milk the mean carry-over was found to be 0.05% for fumonisin B1 and T-2 toxin while ochratoxin A and DON have only be carried through to milk upon experimental administration of milligram quantities. For these reasons these mycotoxins are not considered a risk in these products (EFSA, 2009). Ochratoxin A is the only mycotoxin regulated in animal products since it has an extended half-life in pigs and in Denmark regulations have been put in place to safeguard consumers. If concentrations are found to be above 25 µg/kg the whole carcass is condemned. At concentrations between 10 µg/kg and 25 µg/kg, the kidneys and liver are discarded while if concentrations below 10 µg/kg are detected only the kidneys are rejected (Volkel *et al.*, 2011). Zearalenone is metabolized rapidly and therefore is not considered a risk through consumption of animal products (Volkel *et al.*, 2011). There are no specific recommendations for use of detoxifying agents for animal feed as the risk of carry-over into animal products for human consumption is low.

E. Predictive models

Prediction of FHB and mycotoxin contamination is important to reduce the risk not only to consumers but also to the producers. To protect Public Health and for economic reasons there is a clear need to be able to predict the level of contamination. Various computer models to predict FHB and DON contamination of wheat have been designed and are based on temperature, rainfall and humidity. These models have been successfully developed in Argentina, Belgium, Canada, Italy and The United States and while they have proven to be useful, limitations exist and improvements are required (Prandini *et al.*, 2009). While predictive models developed to forecast infection due to Fusarium species certainly are useful, the ability to project mycotoxin contamination offers a more robust estimation of risk to consumers especially as severity of disease symptoms does not always reflect toxin contamination concentrations (Schaafsma and Hooker, 2007). In Canada, a predictive tool known as 'DONcast' has been used by growers and crop advisors in Ontario since 2000 and allows decisions to be made on the application of fungicides to reduce mycotoxins entering the food chain or if highly contaminated, removal of contaminated wheat from the food chain. Successful validation and calibration has led to its use in the United States, the Canadian prairies, Uruguay and in France. Other models exist and use similar variables to DONcast, however improvements are required before the models can be available for use by producers and governments (Schaafsma and Hooker, 2007).

Much research has been performed by many groups on the factors that most affect DON accumulation in wheat. The general consensus is that weather conditions, wheat variety and agronomic practices all contribute to the levels of DON contamination but that climatic variables such as rainfall, temperature and humidity play a significant role. In one particular study, the weather accounted for 48% of the variability in DON over a four year period while wheat variety accounted for 27% of the differences and other agricultural practices such as tillage systems accounted for <5% of the variability in DON (Schaafsma and Hooker, 2007). When the model was applied to the contamination of DON and fumonisin (FB1) in corn, one study observed that the corn hybrid used accounted for 25% of the variation of DON and FB1 accumulation over a seven year period. Weather conditions only accounted for 12% and 19% of the variability for DON and FB1 respectively and when weather and hybrid information were combined still only 42% of the variability of both toxins was explained. Another study using data from Argentina and the Philippines incorporated climate patterns, insect damage and hybrid information to determine fumonisin concentrations in corn at harvest. Variability of the toxin concentrations was attributed to the weather (47%), insect damage (17%), hybrid (14%) and genetically modified hybrids (11%) and overall 82% of the differences in fumonisin concentrations were explained by the model. The authors concluded that due to the complexities of Fusarium infection and mycotoxin contamination in maize, commercialization of a model for forecasting contamination may be very slow to emerge if at all (Schaafsma and Hooker, 2007).

Using models, the risk from FHB has been projected to increase in areas of South America due to increased rainfall at critical stages in growth. This approach was used to determine if FHB infections and mycotoxin contamination would increase across the UK by the 2050s. The predictions were based on weather alone and failed to include changes in the atmospheric conditions, yet increases in atmospheric carbon dioxide have been shown to increase FHB and the pathogen retained its ecological fitness (Chakraborty and Newton, 2011).

All fungal species have their optimum temperatures and water availability for growth and infection of grains with mycotoxins. Therefore changes in climate will undoubtedly alter fungal distribution and mycotoxin occurrence on a regional basis. To be able to predict which mycotoxins will be of interest in the future requires knowledge of the relationship between toxin formation and weather conditions conducive to this. In a study van der Fels-Klerx *et al* (2012a) collected information on mycotoxin contamination of wheat, barley, maize, oats and rye destined for human food production and for use in animal feeds from Finland, Norway, Sweden and The Netherlands for the period 1999 – 2009. Historical weather observations relating to the specific regions including daily temperature, rainfall and relative humidity were also collated. The information highlighted that DON was analysed for most frequently and the other mycotoxins monitored included NIV, T-2 toxin, HT-2 toxin, zearalenone, 3-acetyldeoxynivalenol, ochratoxin A, diacetoxyscirpenol, moniliformin, aflatoxins, fumonisins and sterigmatocystin. Levels of aflatoxins, fumonisins, sterigmatocystin, diacetoxyscirpenol and ochratoxin A all fell below their respective limits of detection while for moniliformin concentrations ranging from 50 µg/kg to 421 µg/kg were observed in wheat, oats and barley from Norway. DON showed the highest incidence of positive samples at 46% and was predominantly found in wheat, oats and maize. Samples found to be positive for 3- acetyldeoxynivalenol accounted for 13%, with the highest concentrations being found in Finnish oats. The prevalence of HT-2 toxin and T-2 toxin were 27% and 12% respectively and contamination was reported most often in oats. Barley was also found to contain levels of these mycotoxins but the majority of wheat samples did not contain them. Zearalenone was reported in 8% of samples tested and found in wheat and oats and the highest concentrations were observed maize. NIV contamination was seen in wheat, oats and barley with the highest concentrations being detected in oats. Co-occurrence of DON and 3-acetyldeoxynivalenol was prevalent in oats, DON and zearalenone in wheat and maize and T-2 toxin and HT-2 toxin in oats. Climatic conditions were highlighted to be important for the production of mycotoxins, for example at periods of increased temperatures, relative humidity and rainfall during flowering, contamination levels of DON and zearalenone in wheat increased but levels of NIV were low. Overall, the study revealed that mycotoxin contamination of grain has increased in all four countries with the exception of HT-2 toxin in oats (van der Fels-Klerx *et al.*, 2012a).

In another study by this research group they used predictive modeling to assess how changes in climatic conditions would influence the occurrence of DON in wheat in north-western Europe. Final model variables of flowering date, time between flowering and full maturation, cultivar resistance, relative humidity, temperature and rainfall during critical development stages were used. The projections for 2040 indicated that the time of wheat flowering and wheat maturation would occur 1 – 2 weeks earlier depending on location and the climate change scenario used and the results were similar with other studies in England and Wales (Semenov, 2009). DON contamination was also found to increase in this study, with higher estimated levels in spring wheat compared with winter wheat (van der Fels-Klerx, 2012b).

Climate models, crop phenology models and mycotoxin prediction models were used to investigate the impact of climate change on DON contamination in wheat in north Europe (van der Fels-Klerx *et al.*, 2012c). Flowering and full maturation of spring and winter wheat varieties was advanced with the results being more pronounced for spring wheat. Cropping frequencies for maize and wheat were predicted to increase in Scandinavia, Scotland and Poland. Large changes were noted for maize in England, Germany, Poland and southern Scandinavia. With such increases in cropping, particularly with maize and wheat in rotation which has been shown to be more conducive to Fusarium infection, then projected DON contamination could increase significantly. However crop breeding and use of fungicides may reduce contamination in the future. With respect to flowering, full maturation and Fusarium susceptibility, using new varieties may also have an effect that cannot be predicted at this stage (van der Fels-Klerx *et al.*, 2012c).

These studies highlight that further development of models will serve to help the food industry and food safety authorities in risk analysis, that predictive models may be useful to focus monitoring and amelioration where risks are expected to be higher, in addition to helping producers on the use of fungicides and that monitoring is of the utmost importance over the decades to come in order to identify the trends and to protect human and animal health (van der Fels-Klerx *et al.*, 2012a; 2012b; 2012c).

Specific recommendations would be for the development of predictive models for the IoI for the high risk mycotoxins that are present currently and for predicted mycotoxins (outlined in Table 2.5) as a result of climate change.

F. Conclusions

Climatic conditions will subsequently determine a pathogen's establishment and growth. Projecting what we are likely to encounter in the coming decades is extremely difficult as there are many interactions that must be considered. These include not only variations in temperature, relative humidity and rainfall but also the frequency and intensity of extreme weather events, increasing atmospheric carbon dioxide, the crops that are cultivated and the pests and pathogens that attack these hosts. In certain geographical regions there may be reductions in some diseases however an overall increase in global plant disease is expected.

On the IoI there is no doubt that monitoring of cereal grains must be performed for the trichothecene mycotoxins such as deoxynivalenol, 3-acetyldeoxynivalenol, 15-acetyldeoxynivalenol, NIV, T-2 toxin, HT-2 toxin, neosolaniol and T-2 triol as these have all been detected in grains in the UK including NI. Other mycotoxins of interest include zearalenone which has seen increased incidences over the past decade, moniliformin which has been detected in barley, albeit at low levels and fusarenone-x, although again low incidences and low concentrations have been reported to date. For the emerging mycotoxins fusaproliferin, beauvericin and enniatins and the masked mycotoxins, there is no legislation covering their control in food or feed and they are not routinely monitored as a result of this but yet contamination of grains is a growing concern with an increasing number of reports of contamination throughout the globe.

Agricultural adaptation to climate change will include the selection of different varieties and species of crops that are more suited to the environmental conditions, cropping and management practices will be modified, including possible investments in storage facilities and there will be a need for improved handling of pests and diseases.

For local decision making in terms of adaptation, climate models must be developed. Research areas include harmonization and improvement of monitoring methodologies especially rapid methods, toxicological studies on emerging and masked mycotoxins and investigation of the synergistic effects, if any, between the emerging mycotoxins and others produced by Fusarium species. Estimating the impact of increased atmospheric carbon dioxide and developing specific models for the early prediction of contamination would be beneficial.

3 Wetter soils and impacts on crops nutrition and toxicology

3.1 Introduction

Ireland, along with the rest of the British Isles, and north western Europe, has been experiencing a shift in weather patterns leading to increased periods of enhanced precipitation, as outlined in the introductory chapter of this review (Chapter XX). This will have profound effects on crop quality and quantity, not only because wetter weather coincides with lower spring-autumn temperatures and decreased light intensity, both impacting yield, and potentially quality, but will also lead to greater periods of soil waterlogging (Gobin, 2010). In particular, winter waterlogging is thought to be an increasing major problem (Dickin *et al.*, 2009). Modeling the impact of climate change on Belgian crops it was estimated that projected losses due to this type of agronomic flooding would be 5-12% in winter cereals (Gobin, 2010). Similar results were found for winter barley, potatoes and sugar beet.

Waterlogging profoundly alters soil chemistry by driving soil redox anaerobic as oxygen perfuses much more rapidly in air (104) that it does in water (Armstrong Drew, 2002). What oxygen is present in soil pore waters under flooded conditions is rapidly utilized by soil microbes and plant roots, exacerbating oxygen depletion (Marshner, 2012). As many metal(loid)s in soil are sensitive to redox, waterlogging can lead to their immobilization/mobilization greatly affecting the availability of primarily trace micronutrients (i.e. B, V, Cr, Mn, Fe, Co, Ni, Cu, Zn and Se) and non-essential toxicants (i.e. Al, As, Cd, Sb, Hg and Pb). For example, it is well known that Mn causes toxicity problems on crops grown on waterlogged acid soils (Hernandez-Soriano *et al.*, 2012).

Anaerobism also effects the function of plant roots and may lead to deceased effectiveness of macro-element (N, Na, Mg, Si, P, S, K & Ca) assimilation by affecting their root membrane transport due to general metabolic impairment of root function altering energization , or permeability, of membranes, which is also true for essential trace element transporters (Kupier *et al.*, 1994, Shabala, 2011). A wider systemic impact on plant function can be stimulated by initiation of anaerobic metabolism (i.e. catabolism) in roots, such as ethylene production and its subsequent impacts (Shabala, 2011).

Prolonged waterlogging will also lead to increased soil compaction, as flooded soils are more prone to vehicular (tractors) and animal (i.e. cattle) damage (Zhao *et al.*, 2007), accentuating anaerobism through further decreases in oxygen permeation. Additionally, tillage of waterlogged soils was found to damage soil structure (Birkas *et al.*, 2009).

The primary focus of this review will be to consider how increased waterlogging and increased soil wetness affects the nutritional, taste and toxicant status of edible crop parts, with respect to human and livestock consumers, of Irish arable produce. Yield and breeding/selecting waterlogging tolerant cultivars will also be considered, where these are intimately related to food quality. Field management strategies, besides drainage (which should be optimized on a farm by farm basis), will be discussed. This chapter will not explicitly discuss fungal spoilage (due to enhanced dampness) as this will be dealt with in Chapters xx.

This review will restrict itself to literature relevant to western European agronomic ecosystems and crops (or analogues elsewhere) as these will be most relevant to Irish scenarios. Key gaps in our understanding with respect to Irish agriculture will be highlighted, as will suggestions for future study.

3.2 The biogeochemistry of flooded soils

Once O2 is depleted in soils, through microbial and/or root consumption, microbial successions will then utilize other terminal electron acceptors in the sequence of nitrate, Mn4+, Fe3+, sulphate, and then carbon dioxide, with soil redox effectively clamped to a potential dependent on what chemical is being utilized as the terminal electron acceptor (Marshner, 2012). Increasingly negative redox potentials have major implications for elemental nutrition, leading to mobilization/immobilization of nutrients: i.e. denitrification which can lead to decreased nitrogen (nitrate) ions in the soil solution, increasingly negative soil porewater redox potentials lead to the mobilization of Mn (reduction of insoluble MnO_2 to soluble Mn2+); then mobilization of Fe (insoluble $Fe(OH)_3$ converted to soluble Fe_2^+); and then loss of soluble sulphate to insoluble sulphide (Marshner, 2012). As trace- and macro- element biogeochemical cycles are intimately interlinked, it is more than just N, Mn, Fe and S availability affected by this redox cascade. For example, Zn was found to increase 18-fold in soil porewaters subjected to waterlogging, with the mechanism responsible for this increase thought to be dissolution of Zn associated with Mn/Fe oxides (van Laer *et al.*, 2012). Like Zn, any inorganic elements are co-precipitated with iron and manganese oxides/oxyhydroxides under oxic conditions, but are mobilized on dissolution of these oxides/oxyhydroxides when soil porewaters an anoxic, most notably for P (Marshner, 2012, Meharg and Zhao, 2012). Many sulphides are insoluble and elements such as Fe, Zn, Cu and Cd, precipitate under redox conditions were suphate is the terminal electron acceptor (McKee and McKelvin, 1993), reducing their availability to the plant root. The effects of redox change are dynamic and will change from soil to soil, for example, Fe mobilizes under moderately reduced conditions, but is relatively unavailable under oxic and highly anoxic conditions, interacting strong with the S-cycle of any given soil. Furthermore, Mn2+, Fe2+ and S2- are highly phytotoxic (Marshner, 2012, Armstrong and Drew, 2002). Leaching of nutrients, such as phosphate, also occurs during waterlogging due both to waterlogging and to hydrological connectivity and flow paths (Jensen *et al.*, 1999).

Soil redox will vary spatially and temporally (Setter and Waters, 2003). Spatially anaerobism varies from the micro to the field scale. At the micro-scale matters such as soil pore structure, soil organic matter availability (as microbial utilization of organic matter depletes O2), active root density (as roots consume O2), soil profile position etc. will interact. At a field scale, topology (i.e. depressions will flood first and persist longest) and soil profile and type (both of which can vary across a field), drainage/soil structure and position of water table are key divers. Temporal drivers are the extent and nature of flooding, as well as preceding and proceeding weather patterns. Thus, nutrient and toxicant dynamics, as driven by waterlogging, within a soil profile are highly dynamic over a growing season, and the final elemental composition of a harvested crop will integrate this variation.

3.3 Plant responses/adaptations to waterlogging

Most crop species bred for European climes must have a degree of resistance to waterlogging as they, and their progenitors, cannot avoid this phenomenon if they are to prevail in temperate climes (Dickin *et al.*, 2009). Setters and Waters considered the traits needed in barley, wheat and oats to enable selection/breeding of cultivars for soils prone to water logging and these were: a) phenology, (b) morphology, (c) nutrition, (d) metabolism including anaerobic catabolism and anaoxia tolerance and (e) post oxic damage recovery. The primary responses of many plants subjected to root anoxia initiated by waterlogging is to induce aerenchymae, air channels connecting shoots to roots that allow for exchange of gasses, and to minimize the loss of oxygen from roots through radial oxygen loss (ROL), with both these responses thought to be important traits with respect to breeding waterlogging resistant crops (Garthwaite *et al.*, 2003). Other key traits are ability of roots to withstand high levels of toxic ions, primarily species of Al, Fe and Mn, mobilized under reduced soil conditions (Marshner, 2012, Khabaz-Saberi *et al.*, 2012), and the ability to recover from anaerobic catabolism and its toxic metabolites, such as ethylene (Shabala, 2011). Anaerobic metabolism leads to reduced energy levels, an along with disruption of cell metabolism caused by inorganic ions and anaerobic metabolites, as well as inhibition of root growth. Thus, there is a systemic reduction in the ability of roots to assimilate plant nutrients, having major consequences for the plant. Alteration of flavonoid (Khan *et al.*, 2011a), oil content (Boem *et al.*, 1996, Leul and Zhou, 1998), toxins such as glycosinolates (Khan *et al.*, 2011b), glycoalkaloids (Papathanasiou *et al.*, 1999), reduction in macro-and trace element content, and excess As, Fe and Mn accumulation (Zhao *et al.*, 2007, Stieger and Feller, 2008), could all impact on both the flavor and nutrition of crop edible parts; either making the product less palatable or valuable as a nutrient source, or actually making the product a potential health risk through the enhanced accumulation of toxins.

A. Grain crops

A UK field trial study on wheat found strong interactions between irrigation and soil compaction by tractor passes with respect to grain As and Se (Zhao *et al.*, 2007), with the authors discussing these findings in the context that soil compaction leads to anaerobism and, therefore, to differential mobilization of these elements. For both years of this study grain Se was lowest in well-irrigated soils (as opposed to intermediate and no irrigation), with this reduction either greatly or slightly enhanced, dependent on year, with increasing compaction. The difference between no irrigation and irrigation in grain Se was dramatic, decreasing by 10-fold in irrigated treatments. Given that there is wide Se deficiency in Western European due to low Se in grain staples (Zhao *et al.*, 2007), these very large drops in grain Se in wetter soils will be problematic if wetter climatic conditions persist. The authors offered three explanations for the decrease in grain Se: (a) growth dilution as irrigated plants yielded twice as much, but noted that this could not account for the bulk of the 10- fold differences in irrigation water treatments, (b) that S was added in irrigation water and this may compete with Se for uptake, though levels of S and its speciation, as well as levels of Se and its speciation, in soil pore or irrigation waters were not ascertained, so this is just a hypothesis, and (c) that Se could have been leached to sub-soils where it was not root available under irrigation, though this was not explicitly tested. As Se speciation is dynamic, and the interaction of these species with soil complex (Carey *et al.*, 2012), understanding the dynamics of Se in soil pore waters under different irrigation regimes, explicitly waterlogging of crop field, is a priority if the impact of increased soil wetness on crop nutrition is to be understood and improved. In the same study (Zhao *et al.*, 2007) grain As was more variable between years than Se in that irrigation produced the most grain As in 2003 and the least in 2004, with variable interaction with compaction that was not clearly interpretable. In cases compaction led to up to 3-fold increases in grain arsenic in no irrigation treatment in 2003, while the same treatment led to a slight decrease in grain As the following year. No clear conclusions on As can be drawn from this study except that differential irrigation and compaction can result in up to a 3-fold variation in wheat grain As levels.

With respect to other elements in grain under flooding it was found that waterlogging at anthesis, and maintained through maturation, impacted the grain nutrient content to wheat grain, decreasing K, P and Mg, as well as reducing grain yield (Stieger and Feller, 2008). Mn and Fe accumulation in shoots, K, P and Mg decreased, with Ca and Zn unchanged, under waterlogging.

For oats, waterlogging increased Mn and Fe in all plant parts except for grain, while Cu, Cd, Pb and Zn decreased in shoots (Bjerre and Scierup, 1985). It was found that waterlogging severely effected N assimilation by wheat when this treatment was applied 22 d after sowing for a 14 d period (Robertson *et al.*, 2009). Recovery of shoot N was rapid, but tiller growth and tiller number were impeded, leading to a 37% reduction in shoot dry weight at harvest, which resulted in grain yield reductions of 32%. However, application of N fertilizer after waterlogging was relieved allowed the plants to recover grain yield. In contrast, high N fertilizer application was found to exacerbate yield loss on post-anthesis waterlogging (Jiang *et al.*, 2008). Again, waterlogging was found to reduce N assimilation into shoots. When grown on acid soils, wheat cultivars with known Al, Mn and Fe tolerance dispositions grew better than sensitive cultivars when gown on waterlogged soils (Khabaz- Saberi *et al.*, 2012). Waterlogging (42 d, imposed 21 d after seeding) lead to massive increases in shoot Al, Mn and Fe, by 5-, 3- and 9- fold, respectively. Less insensitive cultivars took up less of these metals compared to sensitive cultivars. In hydroponics, simulating iron mobilization under waterlogging, excess Fe2+ in solution lead to enhanced Fe assimilation by shoots and lead to concurrent decreases in Ca and Mg (Khabaz-Saberi *et al.*, 2010). No information was given on grain nutrition. Macronutrients (N, P, K, Ca, Mg and Na) where all decreased in shoots by waterlogging, at various stages of plant development, in winter Rye (Stepniewski and Przywara, 1992). Protein and proline content of wheat grain decreased systematically with increasing period of waterlogging (Olgun *et al.*, 2008).

Winter oats flooded from mid-January to mid-April had a reduced grain yield of 9%, mainly through fewer grains per panicle (Cannell *et al.*, 1985). Waterlogging, for 8 d after heading, applied to wheat causes sustained damage to wheat (Triticum aestivum), reducing both root and shoot growth (Akaki *et al.*, 2012). Finnish barley cultivars were found to be sensitive to excessive rain early in the season (Hakala *et al.*, 2012). There was genetic variability in how barley responded to rain 3-7 wks after planting, and it was suggested that this variability could be exploited to breed plants more resistant to this waterlogging. QTLs identified for waterlogging tolerance in barley (Zhou and Zhou, 2011), while Zhou (2007) found high variability in waterlogging tolerance in Chinese barley. Waterlogging just before anthesis enhanced resistance to waterlogging post anthesis (Li *et al.*, 2011). Differences in waterlogging tolerance was found for UK wheat at seedling stage, but screening did not find consistent relationships between flooding tolerance at seedling sage to grain yields at maturity (Dickin *et al.*, 2009). Cultivars with the largest yields were the most flooding sensitive, while those with lowest yields were most flooding insensitive. It was concluded that waterlogging tolerance was near optimal in British wheat due to past breeding/cultivar selection, and that there was little diversity in this character.

B. Dicotyledons

Oilseed rape is relatively sensitive to waterlogging (Voesenek *et al.*, 1999). There was significant genetic variance found in waterlogging tolerance in Brassica napus breeding lines (Cheng *et al.*, 2010), suggesting that this crop could be optimized for climatic conditions where more frequent/prolonged waterlogging was occurring. A pot experiment was conducted on oilseed rape to ascertain the impact of both winter and spring flooding on yield, seed oil content and shoot biomass nutrient status (Boem *et al.*, 1996). Seed yield was reduced during winter flooding, with 30% yield reduction being recorded after 3 d of waterlogging, reaching a maximum of 50% decrease in yield by 10 d for winter flooding. Spring waterlogging lead to 10 and 30% reduction in yield after 3 and 7 d respectively. The oil content of the seed was barely impacted by flooding, only decreasing slightly in spring 14 d waterlogged plants. N, P, K and Ca content of above ground biomass were all severely impacted by flooding (note seed was not measured separately), by up to 50%, while sodium content increased 8-fold in spring waterlogged plants, but was for the same for these treatments in the winter crop.

Flavanoids in broccoli (B. oleracea) were studied under waterlogging. The only flavonoid found was kaempferol and this did not alter in content after 1 wk of waterlogging but increased significantly after 2 wk of this treatment (Khan *et al.*, 2011a). Glucosinolates were found to be non responsive to water logging in this species (Khan *et al.*, 2011b).

Cold and wet conditions were thought to be responsible for higher glycoalkaloid levels in potato, particularly high rainfall near harvest. Papathanasiou *et al.* (1999) , conducted (in Belfast) a study on Irish suitable potato varieties (early maturers Home Guard, Rocket; British Queen, late maturer) were subject to a waterlogging treatment (a permanent 30 - 50 mm head of water in pot) 30 d into tuber initiation. At the first harvest, after 20 d of waterlogging, there was no impact on tuber weight or glycoalkaloid concentration. Waterlogging for 62 d (which is highly excessive in terms of time period) did reduce tuber weight, but this was thought to be due to rotting of tubers. Only one cultivar, British Queen, had substantially higher glycoalkaloid, but still lower than control treatment at first harvest, under prolonged waterlogging.

The effect of waterlogging on soils contaminated with Cu, As and Pb was investigated on the uptake of these elements by radish and silver beet, but no discernable effect of waterlogging was found for any element (Merry *et al.*, 1986).

3.4 Field management

Rao and Li (2003) discuss a range of strategies to counteract negative impacts of waterlogging on horticulture. One obvious approach is to try and time planting to avoid periods of probable waterlogging, but this (a) may not be practical and (b) is subject to the vagaries of weather patterns. They also suggest ridging and furrowing or the use of raised beds to elevate the crop higher above flood level. The use of N fertilization to ameliorate the negative impact of flooding on the availability of this element, hormonal (cytokinin) sprays to ameliorate negative impacts of anaerobism on plant physiology and the spraying of fungicides (as fungi will proliferate under damp conditions) were all suggested.

Application of the plant growth regulator (PGR) uniconazole was found to ameliorate the negative impacts of root anaerobism caused by waterlogging in oilseed rape when added at the seedling stage before flooding, ultimately increasing yield and oil production (Leul and Zhou, 1998). There was also a rise in the monounsaturated omega-9 fatty acid erucic acid content of seeds with PGR application. This protection of the plant through PGR application was thought to be due to modification of GA(3), zeatin, ABA and ethylene levels on waterlogging, helping the plant to combat waterlogging induced chlorosis. Foliar spays of nitrogen and mixatol (a mixture of aliphatic alcohols) was found to help restore seed yield in oilseed rape when applied post waterlogging treatment removal.

3.5 Overview

Besides the impacts of wet weather during growth and at harvest on crop spoilage by fungi (see Chapter 2), there is relatively little systematic work on impacts of flooding on the quality of temperate crops. Understanding of impact on yield is better, including breeding/cultivar selection for enhanced yield under waterlogging. A Belgian study modeled impacts of winter flooding to lead to circa. 10% fall in production of relevant crops (Gobin, 2010). Whether this percentage is relevant to Ireland, or whether it is subject to change to alteration due to climate change, has to be ascertained. Dickin *et al.* (2009) have suggested that crop cultivars (wheat in their study) are relatively optimized to UK (and by inference Ireland) climatic conditions when it comes to yield with respect to being subjected to waterlogging, and that there was little further genetic diversity to be exploited with respect to significantly improving waterlogging resistance. In cases, waterlogging impacts can be managed by high N fertilization as N deprivation seems to be a main impact in terms of subsequent biomass production following root anaerobism (Robertson *et al.*, 2009).

Though studies were limited in number, there is not a lot of evidence that waterlogging impact toxic plant secondary metabolites (Khan *et al.*, 2011ab, Papathanasiou *et al.*, 1999), or on oil content of seeds (Boem *et al.*, 1996), though some effects were found on elemental nutritional content (Zhao *et al.*, 2007, Stieger and Feller, 2008). The relatively low impact of waterlogging on crop edible components inorganic and organic status, with the exception of perhaps As and Se (as Se and As are naturally low in crops, and readily perturbed by waterlogging, these elements show the greatest fluctuations), is probably due to the fact, by nature, that crops that survive waterlogging and reach market have only been subjected to a defined and limited period of field saturation. That is, if waterlogging is too severe or prolonged, it will lead to crop failure or spoilage and thus nutritional/toxin/taste concerns are irrelevant. Also, if waterlogging occurs early in the crop cycle then contaminants in edible tissue will decrease due to growth dilution. Similarly, if waterlogging occurs near harvest, the edible crop biomass will be reaching maximum and, therefore, contaminant contribution, or nutritional status perturbation, is relatively minor.

Perhaps the element of most toxicological concern under waterlogged conditions is As as it is readily mobilized and assimilated by crops under flooding (Meharg & Zhao, 2012). However, in a UK context, even on the most As contaminated of agricultural soils, wheat and barley assimilate levels of As not overly concerning with respect to human nutrition (Williams *et al.*, 2007). The same was found for a wide range of fruit and vegetables as growth on highly contaminated by As agronomic soils as crop As levels were not elevated to levels of concern (Norton *et al.*, 2012). As these studies were conducted in the extensive mining regions of SW England where As is highly elevated they represent the worst case scenario, and it is unlikely that As pollution of Irish agriculture soils is of the same extent, both geographically and with respect to pollution concentrations.

The key issue raised here with respect to British Isles crop production under waterlogging/compaction/anaerobic soil conditions was the Se content of grain (Zhao *et al.*, 2007). Grain Se content is problematic throughout Western Europe due to universal inherently low levels in grain staples (Williams *et al.*, 2009, Zhao *et al.*, 2007), and Se is the micro-nutrient that s most deficient in the European diet, thought to be linked to a range of chronic illnesses such as cancers (Finlay, 2007). The fact that wetter soil conditions systematically considerably lowered grain Se content of wheat, by 5-fold in cases (Zhao *et al*, 2007) is, therefore, of considerable concern. Se dynamics and speciation in soils is complex, redox sensitive and interacts strongly with other biogeochemical cycles and the form of Se grain is essential in Se's health properties (Carey *et al.*, 2012). The soil biogeochemical factors underlying decreases in Se under wetter soil conditions were not identified (Zhao *et al.*, 2007) and without this knowledge strategies for amelioration cannot be identified.

3.6 Priority for future research

The key knowledge gap identified in this review was how soil Se behaves with respect to wetter soil conditions, and the resultant impacts on tissue Se concentration and speciation, as evidence points to the fact that grain Se is highly negatively correlated with soil wetness/compaction (Zhao *et al.*, 2007). Using state-of-the-art Se speciation, using ion chromatography ICP-MS, as well as synchrotron based studies of Se location and speciation in soil, along with characterizing key elements whose cycling regulates Se (C, O, S, Fe & Mn), it is possible to resolve how Se is immobilized or lost, potentially through biovolatilization, given that methodologies have now been developed to look at Se biovolatilization loses from soils (Winkel *et al.*, 2010). It is likely that strategies for manipulating C, O, S, Fe & Mn status of soil will be more successful, and economic, that Se fertilization per se, particularly as the fate of that fertilizers unknown (this could be investigated as well), and due t to fact that Se fortification itself raises issues (Finlay, 2007). Also, grain survey of Se (i.e. Williams *et al.*, 2009), geographically over Ireland, and how this interacts with weather, is key to identifying and characterizing problems associated with grain deficiencies.

It is also clear from this review that the impact of wetter soils and weather on crop quality (that is nutrient status, taste and physical appearance) have been understudied. As this crop quality may affect value and sustainability it is a priority that impact of a wetter climate on relevant parameters are studied to ascertain if this is a concern or not.

4 Potential impacts of climate change on veterinary medicinal residues in livestock produce on the island of Ireland

4.1 Introduction

Chemical contamination of food is a wide ranging topic encompassing many exogenous chemicals which may or may not be harmful to the consumer. Broadly speaking, contaminants may be categorised as agrochemicals (primarily residues of veterinary medicines and pesticides), environmental contaminants (primarily heavy metals, persistent organic pollutants and natural toxins) and processing contaminants (from cooking, processing or packing).

A meaningful review of such an amorphous field and its interaction with climate change and food safety with a specific IoI perspective must necessarily focus on the most relevant threats to the consumer of foods originating on IoI, considering which chemical contaminant threats may reasonably be expected to have a predictable climate related function, which are most relevant to the agri-food industries as practiced on the island, and which may be amenable to intervention strategies at the local level.

Climate impacts associated with natural toxins in aquaculture and crop production, and heavy metals in crops are addressed elsewhere. This chapter addresses the major agri-food livestock sectors on IoI and assesses how the chemical safety of our livestock produce may be affected by climate change. It focuses specifically on the classes of veterinary medicinal drugs which are widely administered and are integral to our livestock systems and whose potentially harmful residues in food are currently controlled by European Union (EU) regulations.

There is a general move within the EU towards reducing veterinary drug use (routine use for growth promotion is banned), accompanied by growing organic and extensive production systems and improving biosecurity and vaccination programmes. However, the use of medicines to maintain animal health and welfare, thereby improving production, remains a necessity. Controlling residues of these medicines in food continues to be important for consumer safety.

The effect which climate change in the 21st century may have on veterinary drug residues in food is primarily a question of how climate change will affect diseases of farm animals which necessitate administration of those drugs. Several published reviews of climate change and food safety suggest that use of veterinary medicines is likely to increase in the coming decades (Boxall *et al.*, 2009; Tirado *et al.*, 2010; Lake *et al.*, 2012) due to increased disease challenges. However, this subject is speculative by nature, data are limited, and other reviewers suggest the evidence base is fragmented and precise prediction of changes to disease load is difficult given the complexity of livestock systems and the myriad interacting factors (Fears & Meulen, 2012; Vermeulen, Campbell, & Ingram, 2012; Thornton, van de Steeg, Notenbaert, & Herrero, 2009).

Pig and poultry production on IoI are almost exclusively indoor, intensive systems and are expected to be insulated from the effects of climate change which might impact veterinary drug use. There is a very small number of extensive, free-range outdoor rearing systems, however these are often organic systems which are less likely to respond to climate-related disease challenges by increasing drug use. Cattle and sheep production on IoI generally follow extensive, outdoor systems and will therefore be more responsive to changes in climate.

One of the few animal diseases which can be clearly linked to changes in climate and is of particular relevance to IoI is infection by helminth parasites (roundworms and flukes). Murphy *et al.* (2006) claim it is the norm for cattle in Ireland to be simultaneously parasitised with a variety of helminths. Consequently, farms on IoI routinely administer significant quantities of anti-helminth drugs (anthelmintics). According to Bennema *et al.* (2010) 59% of dairy herds in Ireland use preventative anthelmintics compared with 17% in the UK and 6% in Germany. This high usage is reflected in a study showing that of seven European countries Ireland had the highest incidence of anthelmintic residues in locally purchased beef, albeit within permitted limits (Cooper *et al.*, 2012). Application of anthelmintics, usually once or twice per year, is ingrained in the farming culture of IoI and they are one of the most commonly administered veterinary livestock drugs in this region. Given that the aetiology of the parasite infections which require treatment with anthelmintics can be more closely correlated with climate factors than other classes of veterinary drug, a review of this topic forms the core of this chapter.

4.2 Local climate change predictions

Temperature changes on IoI over the 21st century can now be predicted with a relatively high degree of confidence (Sweeney *et al.*, 2009). Average temperatures will rise by 1.4 to 1.8°C by 2050 and in excess of 2°C by the end of the century relative to the 1961-1990 baseline. Summer and autumn are projected to warm faster than winter and spring, with the midlands and east of IoI warming more than coastal areas. Rainfall predictions are less certain but represent the most important aspect of climate change which will affect livestock production on IoI. Average rainfall is projected to increase by 10% in winter and reduce by 12-17% in summer by 2050. By the 2080s winter rain will have increased by 11-17% and summer rain reduced by 14-25%. The midlands will be susceptible to the largest winter rainfall increases. The southern and eastern coasts will experience the driest summers, rainfall being reduced by 30-40% by the 2080s. Changes in the frequency of extreme weather events will also be seen. Lengthier heat waves, a substantial reduction in the number of frost days, lengthier rainfall events in winter and more intense downpours in summer are projected. At the same time summer droughts are more likely, especially for eastern and southern regions (Sweeney *et al.*, 2009).

The consequences of climate change are complex with many inter-related variables impacting our multi-faceted agricultural production systems. However, grass production underpins many of these systems. It is the most important agricultural crop on IoI and is the main feed source for the sheep, dairy and beef livestock industries. It has been predicted that climate change will not have a catastrophic impact on grassland production in Ireland (Holden & Brereton, 2002). However, regional changes in yields are likely and irrigation may become necessary in the drier east and southeast. Theoretical turnout date of housed animals may come earlier in the season due to higher temperatures but this may be prevented by higher rainfall. Such changes may impact disease dynamics, particularly those affected by stocking density, housing conditions and pasture-dwelling vectors. Changes to something as fundamental as grass growth may therefore lead to changes in administration of veterinary medicines and thus to prevalence of their potentially harmful residues in our food.

4.3 Political context

Agricultural production on IoI has the capacity to enter a new growth phase following reform of the EU Common Agricultural Policy and phasing out of milk quotas by 2015. Both governments on IoI have a vision for the sustainable expansion of livestock production and increasing export trade, as expressed through the Department of Agriculture, Food and the Marine's Food Harvest 2020 report in the Republic of Ireland (ROI), and the Agri-Food Strategy Board's Going for Growth Action Plan 2013-2020 and the Department of Agriculture and Rural Development's (DARD) Strategic Plan 2012-2020 in NI. For example, Food Harvest 2020 envisages a 50% increase in milk production and 20% increase in value of beef products in ROI. Going for Growth aims for a 60% increase in NI agri-food industry turnover by 2020. Such expansion of agricultural production, as it seeks to emulate the burgeoning local food production sector, will see rising numbers of livestock animals and will have to take into account longer term changes in the environment arising from climate change. Assuring the safety of local food production must continue to be of primary concern.

Monitoring food of animal origin for chemical residues arising from veterinary medicines on IoI is carried out under EU regulations primarily by the Agri-Food and Biosciences Institute (AFBI) in NI and Teagasc in RoI under their National Surveillance Schemes and other testing programmes. Discussions are ongoing within the European Commission to recast Council Directive 96/23/EEC which defines the structure of these schemes. It is not yet clear what changes this will bring but it is generally believed the new legislation will encourage a more risk- based approach to testing edible tissues for residues. Member States may soon be given more freedom to decide how to target their National Surveillance Schemes.

4.4 Potential impacts of climate change on use of veterinary medicines on the island of Ireland

A. Anthelmintics – Helminth parasitism

Since parasites of animals are among the main limitations to livestock production and therefore food security (Wall & Morgan, 2009), understanding the effects of climate change on their epidemiology, and consequently their control, is a priority in the face of increasing global food demand.

The main economically important helminth parasites in sheep and cattle in both NI and ROI are the nematodes, Nematodirus spp., Teladorsagia/Ostertagia circumcincta and Haemonchus contortus, as well as the trematodes Fasciola hepatica (the liver fluke) and rumen fluke species (Paramphistomum spp. and Calicophoron spp.). Other nematodes, such as Cooperia spp., Chabertia spp. and Oesophagostomum spp., can be important in some circumstances, but usually as part of a mixed burden (Morgan & van Dijk, 2012).

These debilitating internal parasite infections can cause symptoms such as ill thrift, scouring, anaemia and parasitic bronchitis. Liver fluke disease or fasciolosis limits production in sheep, goats and cattle, with economic losses due to reduced growth and fertility, death and condemnation of livers at slaughter (Gordon *et al*., 2013). As well as their effects on meat, milk and wool production, parasites cost the livestock industry many millions of pounds each year due to the costs associated with their control. Fasciolosis alone costs the livestock industry in ROI €90 million and that in NI £50 million per year. Recent estimates place the annual global spend on anthelmintic drugs at more than US $3 billion (Dalton *et al*., 2013).

Historically, a seasonality has been evident in parasitic nematode infection. Fig. 1 shows the accepted high risk periods for parasitic disease in young stock, although factors such as changes in climate, management and treatment strategies can affect the occurrence of disease. Teladorsagia/Ostertagia circumcincta and Trichostrongylus spp. may overwinter on pasture and the numbers of larvae decline in spring. During the early spring months, hypobiotic larvae overwintering in ewes mature and start to produce eggs; an increase in pasture contamination levels occurs over several worm generations, with both adults and young stock contributing to this. The published epidemiology of Nematodirus spp.

suggests this parasite overwinters as infective larvae in the egg (van Dijk, Sargison, Kenyon, & Skuce, 2010) then, in spring, a mass hatch of eggs is followed by a rapid decline of the larval population. Typically at this time, the pasture is grazed by parasite-naïve animals. The entire H. contortus population overwinters in the adult host. Worms mature during the lambing season; female adult worms are highly fecund and pasture contamination builds up rapidly. The relatively high temperature threshold for development of H. contortus and the inhibition of developing larvae in hosts in autumn result in a rapid fall in the number of larvae at pasture in the autumn.

The hatching of liver fluke eggs and the multiplication of snails (the intermediate host) depend on adequate moisture and temperatures greater than 10ºC. Such conditions usually occur from May–October in the UK, although patterns have been changing in recent years. The incidence of fasciolosis is highest in years when rainfall is above average during May–July. In wet summers, snail populations multiply rapidly and snails are invaded by hatched miracidia from May–July. If wet weather continues, the snails shed massive numbers of cercariae onto pasture during July–October. Conversely, if the climate in May–July is dry or cold, fewer snails appear, fewer fluke eggs hatch and levels of contamination in the autumn are much lower. Fasciolosis occurs in three main clinical forms – acute, subacute and chronic fasciolosis. Which form occurs depends on the numbers of infective metacercariae ingested and the period of time over which they are ingested (Abbott, Taylor, & Stubbings, 2012a). Acute disease occurs from July to December, sub-acute from October to January and chronic disease from January to April.

Paramphistomum cervi was thought to be the predominant species of rumen fluke infecting ruminants in ROI, but it now appears that Calicophoron daubneyi is the prevailing species in NI (personal communication). The life cycle of rumen flukes is similar to that of F. hepatica, in that it requires two hosts: a mammalian definitive host and a snail intermediate host. C. daubneyi and F. hepatica are often found as co-infections, share similar life cycles and perhaps even share the same mud snail intermediate host (Skuce & Zadoks, 2013). In the UK, it has been suggested that dispersal of snails by flooding events and changes in farm management practices may be responsible for the apparent emergence of the parasite (Foster *et al.*, 2008).

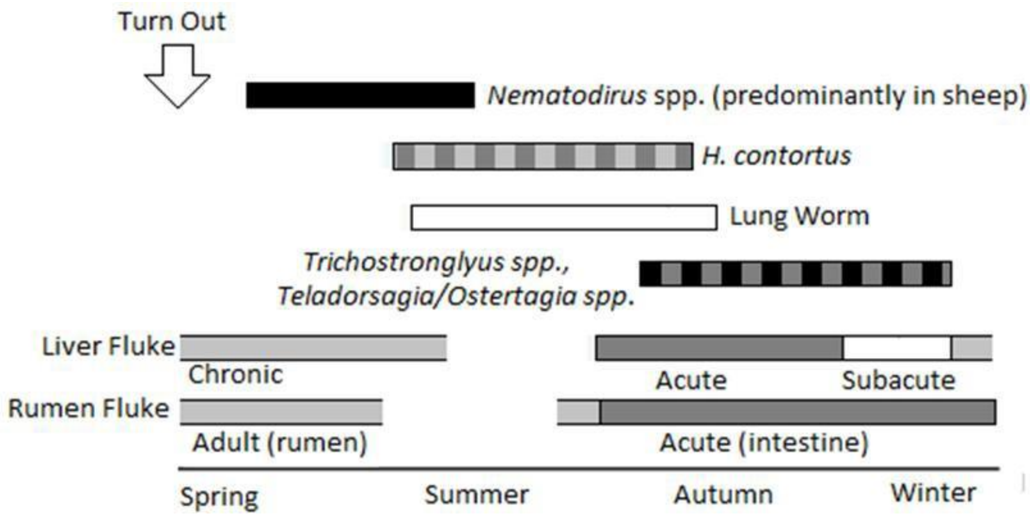


Figure 4.1: Classic pattern of the high risk periods for parasitic disease during the calendar year (adapted from Peebles, 2005; van Dijk, Sargison, Kenyon & Skuce, 2010).

Parasite control: Anthelmintic drugs

Choosing the right anthelmintic product and getting the most from it are key factors, not only in the fight against anthelmintic drug resistance, but also in ensuring optimal performance at least cost. However, this can be complicated by the wide variety of brand names, the number of anthelmintic groups, their respective withdrawal periods, their spectra of activity and the development of anthelmintic resistance (Abbott, Taylor, & Stubbings, 2012b).

Anthelmintic products can be considered as having either a broad or narrow spectrum of anti- parasitic activity. Included within the broad spectrum category are:

- the benzimidazoles (BZ), including triclabendazole, albendazole, fenbendazole, mebendazole, oxfendazole and ricobendazole
- levamisole (Lev)
- the avermectins (AVMs), including abamectin, doramectin, eprinomectin and ivermectin
- moxidectin (Mox)
- the Amino-Acetonitrile Derivatives (AAD), including monepantel

Products of a narrow spectrum of activity include: clorsulon, closantel, nitroxynil, oxyclozanide and triclabendazole (NOAH, 2013).

Generally speaking, broad spectrum anthelmintics are used to treat lungworm and gastrointestinal nematode infections, while the narrow spectrum products are predominantly used to treat liver and rumen fluke infections. Exceptions to this generalisation exist and include the use of closantel to treat haemonchosis, as well as fasciolosis, and the use of albendazole to treat fasciolosis, as well as various nematode infections. Combinations of anthelmintics with similar spectra of activity and different mechanisms of action and resistance are available for control of sheep nematodes (Bartram, 2013). Additionally, combinations of broad and narrow spectrum anthelmintics are available. These are formulated to provide broad spectrum control of parasites from different phyla (nematodes and liver fluke), rather than a mixture of two or more distinct classes of anthelmintics with a similar spectrum of activity to control only one phylum.

One of the main requirements for sustainability of anthelmintics, particularly the macrocyclic lactones (MLs: AVMs and Mox), was the need for guidelines and training for veterinarians and advisors involved in investigating reported treatment failures and suspect anthelmintic resistance. A working group of UK researchers and practitioners devised a set of guidelines in 2003 (Sustainable Control of Parasites in Sheep, or "SCOPS") aimed at maintaining anthelmintic efficacy on farms. Over the years that followed, these guidelines have been promoted through meetings, promotional literature and the agricultural press. The recommendations are currently in their fourth iteration. Similarly, a technical manual for veterinary surgeons and advisors has been produced with the acronym "COWS" (Control Of Worms Sustainably: Taylor, 2012a), with the intention of shaping effective helminth control programmes for cattle herd owners.

Climate change and helminth parasitism

Climate change (specifically increased temperature and rainfall) will affect the distribution, reproduction, maturation and survival rate of parasites, their vectors and their intermediate hosts (Mas-Coma, Valero, & Bargues, 2009). An increase in the number of generations and expansion of the periods during which conditions are favourable for survival and transmission would be expected to increase potential abundance of endemic parasites. Similarly, warming in temperate areas might enable the spread of more pathogenic species from the tropics. Therefore, it can be assumed that, as a result of climate change, animals will tend to suffer increasingly high levels of infection.

As well as effects on overall parasite abundance, changes in temporal transmission windows could affect disease risk in a non-linear way: by increasing exposure of parasite-naïve animals to infection (Faccini, Santos, & Bechara, 2004), or by increased nutritional stress as a result of lower digestible protein in grass grown at higher temperatures (Wall, Rose, Ellse, & Morgan, 2011).

While the influence of temperature and moisture on the free-living stages of gastrointestinal nematodes has been described in detail, and evidence for global climate change is mounting, there have been only a few attempts to relate altered incidence or seasonal patterns of disease to climate change. A study of this type has been completed for NI, but not for ROI. The results of the NI study revealed that Trichostrongylosis/Teladorsagiosis predominantly shows a generalised all-year-round distribution, most likely due to high rates of larval survival within the temperature range of NI (McMahon *et al.*, 2012). Considering the seasonal distribution pattern, there was increased incidence of infection in August, as well as higher numbers of cases diagnosed through the autumn to winter months (September to February), indicating a temporal extension of the transmission window, shown in Fig. 2, over the previously described historic pattern (Fig. 1).

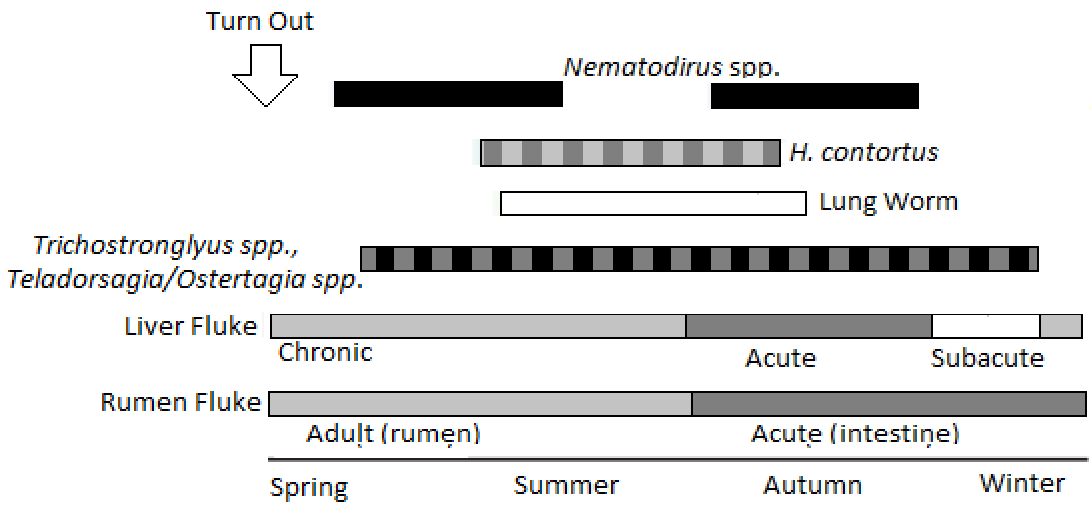


Figure 4.2: Current understanding of the high risk periods for infections of parasitic disease over the calendar year (adapted from McMahon *et al.*, 2012).

While the classic pattern of spring nematodirosis was noted in the findings of the NI study, this was in addition to more significant infection levels detected during the autumn months. This indicates that there is a rapid development of eggs in the summer, which are ready to hatch without chilling in the autumn (van Dijk, David, Baird, & Morgan, 2008), and that large-scale hatching of the eggs from spring infections occurs as the average temperatures decline in the same year (van Dijk & Morgan, 2008). It is conceivable that the late season rise in Nematodirus spp. infections has reduced the relative importance of spring nematodirosis, shifting the emphasis towards autumn infections. Any further temperature increase would be expected to exacerbate this shift in focus (McMahon *et al.*, 2012).

The observed seasonal, regional and between-year changes in rates of diagnosis may be explained by the effects of rising temperature on parasite transmission. The mean annual temperature has increased in the past 10 years in NI, although the trend is significant for some months only, with temperature increasing earlier and more significantly in February and the following spring months (March to May) than later in the year (McMahon *et al.*, 2012). Higher maximum temperatures during the summer months encourage the accumulation of infective stages from successive generations of adult parasites, increasing parasite abundance and risk of disease. Higher maximum temperatures towards the end of the year, as well as higher minimum temperatures, enhance the ability of larvae to survive on pasture and thus extend the range of larval availability beyond the previously established infection windows. Higher autumn temperatures are likely to increase the proportion of ingested larvae that develop to adults and cause disease in the following weeks, rather than triggering the larvae to enter hypobiosis (or arrested development: van Dijk, David, Baird, & Morgan, 2008).

Over the period investigated (1999-2009), significant decreases in rainfall were detected in April, May and November, while significant increases in rainfall were detected in January to March, September and December. Increased rainfall to the degree shown in NI is predicted to slow the desiccation of faecal deposits, which normally results in the death of the eggs and pre-infective larvae.

The incidence of fasciolosis has risen in recent years, a likely consequence of climate change (Kenyon, Sargison, Skuce, & Jackson, 2009; van Dijk, Sargison, Kenyon, & Skuce, 2010). This trend has been predicted to continue well into the future and the impact of long-term climate changes on the risk of disease in the UK has been estimated (Fox *et al.*, 2011; Fairweather, 2011a). It is predicted that serious outbreaks of fasciolosis will become the norm in parts of Scotland by 2020 and in Wales by 2050 (Fox *et al.*, 2011). While extreme weather conditions, such as high temperatures, drought and heavy rainfall, may be detrimental to the fluke and its snail host, the authors also point to occasions where high levels of disease followed drought years (Fox *et al.*, 2011). To a certain extent, short-term hostile climatic changes may be cushioned by the longevity of the fluke within its primary host and by infections in reservoir hosts (Kenyon, Sargison, Skuce & Jackson, 2009).

Unfortunately, climate change overlaps with a number of anthropogenic and environmental modifications which are able to give rise to outbreaks of parasitic diseases on their own. Similarly, a major confounding factor in measuring the effects of climate change on parasitism is the rise of anthelmintic-resistant parasite populations (van Dijk, Sargison, Kenyon, & Skuce, 2010). Anthelmintic resistance is currently a major issue in ruminant production in many countries worldwide (Kaplan & Vidyashankar, 2012) and, consequently, constrains sustainable agricultural systems (Fitzpatrick, 2013). Thus, establishing the causality of disease emergence by climate change is usually not an easy task without an understanding of the anthelmintic resistance status in a given area.

Anthelmintic use and anthelmintic resistance

The following sections deal with the known usage patterns of anthelmintics to control parasitic diseases in both ROI and NI. At the time of writing, no published reports of anthelmintic resistance or parasite control strategies in cattle exist; similarly, information relating to the prevalence of drug resistance in trematode species remains sparse. For information on best practice guidelines for treating parasitic infections, the reader is directed to Abbott, Taylor, & Stubbings (2012c) for sheep and Taylor (2012a) for cattle.

ROI

Patten, Good, Hanrahan, & de Waal (2011) carried out a questionnaire survey into anthelmintic usage on lowland sheep farms and identified several sub-optimal practices which are known to be selective for anthelmintic resistance. These included:

- following a set treatment plan with no indication of treatment timing through faecal egg count testing or utilisation of the national forecast systems
- high treatment frequency (i.e. four or more treatments given in a “normal” year)
- the potential for under-dosing through incorrect weight estimation
- the potential for under-dosing through improperly calibrated equipment
- the selection of product based on previous experience of good effect being the most important factor in anthelmintic choice
- the repeated exposure of helminth populations to the same anthelmintic class in successive years

With growing evidence of anthelmintic-resistant parasites in ROI (Good, Hanrahan, & Kinsella, 2003), judicious use of anthelmintics is of paramount importance for the sustainability of production systems.

In a recently completed survey, there was evidence of resistance to BZ (on >88% of farms), Lev (>39%) and suspected ivermectin resistance on a small number of farms (11%), although these figures need to be confirmed (Good *et al.*, 2012). T. circumcincta, Trichostrongylus spp. and Cooperia spp. were the main species identified.

The current status of anthelmintic resistance in liver fluke is less well known. In a comparative study on the efficacy of four anthelmintics in a hill flock in the west of Ireland, the results showed that oxyclozanide, closantel and nitroxynil were still fully effective (with faecal egg count being reduced by 100% by day 14 post-treatment), while triclabendazole efficacy was reduced (with faecal egg count reductions of between 49% and 66%, based on arithmetic means, over the period 7–56 days post-treatment: Mooney *et al.*, 2009).

NI

Recently, resistance to the (then) available anthelmintic classes was recorded as being prevalent in 81% of flocks in NI tested for BZ resistance; 14% of flocks tested for Lev resistance; and in 50% and 62% of flocks tested for AVM and Mox resistance, respectively. AAD resistance was absent in all flocks tested (McMahon *et al.*, 2013a).

BZ efficacy was highest against Trichostrongylus spp. (51%) and lowest against Teladorsagia spp. Lev was 100% effective in treating Cooperia spp., but ineffective (0%) in treating Trichostrongylus spp. AVM efficacy was highest when treating H. contortus (100%) and T. circumcincta (73%), with a marginally lower efficacy against Trichostrongylus spp. (71%). Mox efficacy was 33% against Trichostrongylus spp., 68% against T. circumcincta, 97% against Cooperia spp. and 100% against H. contortus infections (McMahon *et al.*, 2013a).

Between 2005 and 2011, a number of changes in management practices were identified (McMahon *et al.*, 2013c). Those changes which would be expected to slow the spread of anthelmintic resistance included increased duration of quarantine separation and increased contribution to the in refugia population by ewes. The *in refugia* population is a population of parasites unexposed to drug treatment and is most commonly found in untreated hosts. However, a number of practices which are selective for anthelmintic resistance are still commonly used in NI. They include using unchecked dosing equipment, co-grazing sheep and cattle, always using the same anthelmintic product, and a decreasing contribution to the in refugia population by lambs (McMahon *et al.*, 2013b).

Between 2008 and 2011, annual rotation between flukicide groups was practiced by 30% of flock owners, with 24% rotating with each successive treatment and the remaining 46% opting to use the same product in successive years, allowing repeated exposure of the parasite population to the anthelmintic compounds.

Between 2000 and 2005, annual rotation between available drug groups was practiced by 10% of flock owners, with 8% of the survey population rotating with each successive treatment, while 83% had never changed their product choice over the survey period.

Changes in the proportions of drug use, grouped by anthelmintic class, have been observed over the time periods of the reported surveys (2000-2005 and 2008-2011: McMahon *et al.*, 2013b; Figure 4.3).

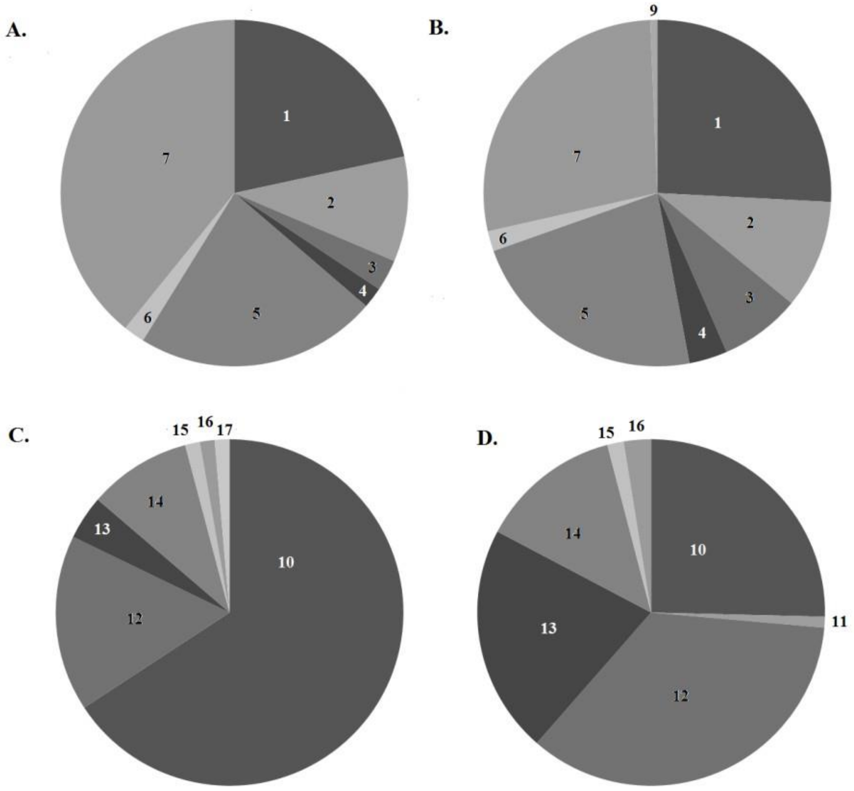


Figure 4.3: Average proportions of anthelmintic products used to treat nematode infection over the periods 2000-2005 (A) and 2008-2011 (B) and trematode infections over the same periods (C and D, respectively). Products containing: 1 = Benzimidazoles; 2 = Benzimidazoles*; 3 = Levamisole; 4 = Levamisole*; 5 = Avermectin; 6 = Avermectin*; 7 = Moxidectin; 8 = Moxidectin*; 9 = Amino-acetonitrile derivative (N.B. only available since 2008); 10 = Triclabendazole; 11 = Triclabendazole*; 12 = Closantel; 13 = Closantel*; 14 = Nitroxynil; 15 = Oxyclozanide*; 16 = Albendazole; and 17 = Clorsulon (* denotes product delivered in combination formulation).

Relatively little is known about the levels of triclabendazole resistance; this reflects both the lack of large-scale surveys and the lack of universally accepted criteria for the declaration of flukicide resistance (Fairweather, 2011b). Preliminary observations suggest a prevalence of 38% resistance in NI (unpublished data). Currently, it is advised that faecal egg count reduction testing is employed in tandem with other diagnostic measures such as drench and slaughter, histological examination of fluke material recovered at necropsy post-treatment, coproantigen reduction testing or the egg hatch assay currently in development. With that being said, the perception in the farming community is that triclabendazole resistance is widespread and this is reflected in the reduction of triclabendazole use between surveyed periods, from 67% use by 2005 to 26% by 2011. This gap has largely been filled by closantel, either as a single active or in combination with ivermectin: its use increasing from 22% by 2005 to 56% by 2011. Closantel's popularity is demonstrated by it being the most common anthelmintic residue detected in a survey of beef purchased in ROI in 2009-2010 (Cooper *et al.*, 2012).

The rise of Lev use between 2000-2005 and 2008-2011 may reflect the suggestion that is it used in the treatment of quarantined animals, or that is remains a functional alternative to the MLs in the face of increasing ML resistance. The greater use of Lev in combination products is likely due to the increased awareness of rumen fluke; for example, at the time of writing, the only products licensed in the UK for the treatment of rumen fluke are those which combine the salicylanilide oxyclozanide with Lev.

Product selection is influenced heavily by price, method of application and a history of effective use (Patten, Good, Hanrahan, & de Waal, 2011; McMahon *et al.*, 2013c). Increasing levels of anthelmintic resistance (confirmed or anecdotal accounts), therefore, will have an effect on product selection which, in turn, will have an effect on when the meat or milk produced will be suitable for human consumption, given that different anthelmintic products are subject to different withdrawal periods.

<u>The anthelmintic challenge to be faced</u>

Recent years have seen the release of new anthelmintics, namely, the AADs (Zolvix©) and the release of the first multiple-active formulation (in the UK). However, there are no more new anthelmintics on the horizon and evidence suggests that resistance emerges within a relatively short time period (<10 years) following the commercial release of a new anthelmintic compound (Kaplan, 2004). Reports of resistance to MLs are increasing in frequency in NI and Great Britain (Bartley *et al.*, 2012; Jones, Pearson, & Jeckel, 2012; Stubbings, 2012; McMahon *et al.*, 2013a). It is clear that effective parasite control in the future requires action in the present to increase awareness of best practice procedures to minimise the spread of resistance and the occurrence of drug residues in livestock produce.

To a large extent, farmers on IoI do not seem to be following the published SCOPS/COWS guidelines (Patten, Good, Hanrahan, & de Waal, 2011; McMahon *et al.*, 2013c). Already there have been large- scale shifts in product use (Fig. 3) and changes in treatment timing (McMahon *et al.*, 2013b; unpublished observations). These changes in timing are linked to the withdrawal periods of products, the perception of resistance, the spectra of activity of the products and the altered seasonal appearance of parasites (Figs. 1 and 2). These alterations have not arisen through the emergence of anthelmintic resistance alone, but as a result of a combination of factors. Such factors include more favourable climatic conditions for the completion of the parasites' life cycles, large- scale movements of livestock and their parasites following the Foot and Mouth Disease outbreak in the UK and farmers being encouraged to retain or introduce wetlands into farming systems as part of environmental programmes (Skuce & Zadoks, 2013).parasite control

<u>The future of helminth parasite control</u>

Renewed appreciation of the influence of climate on the epidemiology of helminth parasites is essential. With a sufficient level of knowledge, it will be possible to:

- predict the main times of infection and intervene accordingly
- track the fate of eggs produced by drug-resistant nematodes and ensure adequate dilution *in refugia*
- model the effects of climate change and build rational strategic and farm level responses accordingly (Morgan & van Dijk, 2012)

Any response to increased parasite challenge that relies on increasing anthelmintic drug use is likely to be self-defeating through the further development of drug resistance. This applies to targeted treatments as well as generally increased treatment frequency in summer.

Future sustainable control strategies for helminth resistance to anthelmintics require an integrated approach, including environmental management, taking into account the climate and species of parasites in different areas, as well as chemoprophylaxis to minimise the pressure for parasite adaptation (Papadopoulos, 2008). Meteorological data to predict the prevalence of parasitic disease is compiled and released annually by organisations such as NADIS (National Animal Disease Information Service) and AFBI, for both Nematodirus spp. infection and fasciolosis. These forecasts provide an indication of the best times to treat for the respective helminthoses. Together with the guidelines to slow the development of resistance, such measures will be vital in shaping the future of livestock production, which has to face the challenges of continuing climate change, minimising anthelmintic drug residues and ensuring food safety.

B. Other endoparasiticides

Babesiosis is a parasitic infection caused by protozoa of the genus Babesia leading to lysis of the red blood cells. It is spread via ticks and is a significant disease of cattle, although its incidence in IoI has declined markedly in recent years (19 cases noted in 2011; AFBI, 2012). The "castor bean tick", Ixodes ricinus, is the only tick which affects Irish livestock. It has been suggested that climate change may increase the geographical range of ticks in Western Europe (they favour mild, moist conditions) with a consequent increased incidence of babesiosis (Hasle *et al.*, 2010). Increased use of babesiosis chemotherapies such as imidocarb is therefore possible and residue monitoring programmes should be alert to changing patterns of use.

C. Ectoparasiticides

Livestock are also susceptible to infestation by ectoparasites. Sheep are particularly vulnerable to external parasitic conditions such as blowfly strike, sheep scab (Psoroptic mange, a form of allergic dermatitis caused by the mite Psoroptes ovis), and ticks, lice, mites and keds. Treatments generally involve pour-on products or, to a lesser degree, dipping in synthetic pyrethroid or organophosphorus compounds, although concerns over toxicity to the farmer and the environment persist. Ectoparasite infestations are also treated with injectable macrocyclic lactones.

Treatment with pour-on and dipping products can be considered food safety issues since pyrethroid residues can be detected in edible tissues, and meat is monitored routinely to ensure compliance with maximum residue limits, as is also the case with macrocyclic lactones.

Climate warming is predicted to have profound effects on the incidence of blowfly strike in Great Britain (Rose & Wall, 2011) through faster blowfly development, increased numbers of generations and prolonged periods of favourable conditions for fly survival. A warmer climate may also affect strike incidence indirectly through changes to the seasonal pattern of sheep susceptibility and the timing of seasonal farm management practices (Wall, Rose, Ellse, & Morgan, 2011). Conversely, lice infestations tend to be worse in cooler seasons, so climate change is unlikely to make veterinary treatment more common. By contrast, climate change is thought to have already affected the epidemiology and geographical distribution of tick infestations making them more prevalent (Taylor, 2012b). However, precise prediction of climate effects on the incidence of ectoparasite infestations is uncertain due to subtle and conflicting interactions of humidity and temperature, free-living and host-bound life stages, and indirect effects on the host species and husbandry practices (Wall, Rose, Ellse, & Morgan, 2011, Morgan & Wall, 2009). Indeed, one recent Europe-wide model predicts less favourable conditions for tick survival on IoI by 2050, but improving conditions by 2080 (Porretta *et al.*, 2013). Nevertheless, climate change raises the possibility of changing patterns of veterinary drug administration to combat ectoparasites with consequent potential for impacts on residues in edible tissues.

D. Antibiotics

A variety of veterinary antibiotics are used therapeutically to treat a wide range of bacterial diseases and secondary infections in livestock. They are also used to control established outbreaks of disease and to prophylactically protect animals considered to be at risk of infection. Since 2006 the use of antibiotics as growth promoters in EU livestock has been banned. Climate change may, via various routes, have adverse impacts on bacterial livestock diseases which can be treated with antibiotics.

a) Changes to ground conditions: Increased flooding and waterlogged ground (likely consequences of local climate change) have the potential to increase endemic bacterial animal diseases spread via the faecal-oral route (viz. reservoirs of infective bacteria in the soil and faeces), although survival of pathogens in the environment is typically less in warmer conditions (Gale *et al.*, 2009). Salmonellosis, calf diphtheria, listeriosis, leptospirosis, tetanus, enzootic abortions, stiff lamb disease and others could become more common, requiring enhanced antibiotic treatments. Cases of botulism and anthrax may even increase (Gale *et al.*, 2009); however, with slaughter being the primary control policy rather than chemotherapy for such serious diseases (as also for bovine tuberculosis and brucellosis), these latter do not per se represent an enhanced chemical food safety risk. Populations of rodents carrying bacterial diseases may be displaced by flooding, changing the risk of transmission to livestock. Poorer ground conditions may also lead to more livestock hoof problems and lameness requiring antibiotic treatment for foot rot and digital dermatitis.

b) Vector-borne bacterial infections: Tick infestations may increase as their favourable seasonal periods of mild, moist conditions lengthen. Tick-borne bacterial diseases such as tick-borne fever (a common but largely unrecognised and untreated infection), tick pyaemia, Q fever, anaplasmosis and Lyme disease may become more common and antibiotic treatments may rise. Lyme disease, caused by Borrelia burgdorferi, is strongly associated with deer populations (which are growing on IoI) and is rarely diagnosed and symptoms may be minor in livestock. However, its impact may grow if climate change alters tick prevalence and brings deer and livestock populations into closer proximity.

c) Weather conditions: The epidemiologies of many bacterial diseases are influenced by the interplay of temperature and humidity. The predicted warmer, wetter weather on IoI may be conducive to increased cases of mastitis in cattle and dermatophilosis (lump wool) in sheep. In regions where warmer and drier conditions are forecast, cases of keratoconjunctivitis (pink eye) may increase where dust and flies are predisposing factors in the summer months. Wetter conditions in the colder months could potentially lead to more cases of pneumonia in calves and pasteurellosis (enzootic pneumonia) in sheep, particularly if routine handling practices are disrupted. Furthermore, if climate change encourages the intensification of production, for example housing animals more frequently to avoid bad weather, more cases of atypical pneumonia in sheep and other diseases of intensification may be seen. In addition to bacterial diseases, toxoplasmosis in sheep (caused by the protozoan Toxoplasma gondii) also responds to sulphonamide antibiotic treatment, although vaccination is the preferred approach. As described below for coccidial infections, predicted warm, wet weather may assist the survival of the infective oocysts in faeces and grass and may lead to an increase in toxoplasmosis-related abortions. More frequent administration of antibiotics or preventative coccidiostat drugs may follow.

The degree to which such theoretical changes to disease dynamics will actually occur on IoI is difficult to predict, since there will be other drivers in the coming decades (e.g. changing husbandry practices) which may mitigate their effects. Furthermore, increased drug administration may not automatically follow increased disease prevalence – this will always depend on the economic viability of using extra veterinary medicines. However, the above list serves to illustrate the possible wide ranging effects of climate change on antibiotic drug use and the need to ensure our residues testing schemes are maintained and remain adaptable to changing practices on-farm.

E. Antiviral drugs

Livestock are susceptible to a range of viral diseases with major welfare and economic impacts. Research into treatment of viral livestock diseases has largely focused on development of vaccination programmes, with variable success. Thanks to vaccination and control programmes initiated in the 1980s, several European countries are now officially free of Aujeszky's disease, a contagious and lethal viral disease of pigs. However, vaccines are available only against limited serotypes of the Bluetongue virus, highlighting the difficulty of ongoing protection via vaccination as viruses mutate and different strains become prevalent in subsequent years. As was the case with the Foot and Mouth Disease outbreak in the UK in 2001, whilst effective vaccines were available, widespread isolation and culling of infected animals is often required in the event of viral disease outbreaks, as vaccination can be prohibitively expensive or may provide incomplete protection. Sales in ROI of veterinary preventative vaccines for farm animal species grew by over 80% between 2007 and 2011 indicating a growing acceptance within the farming community of preventative approaches to livestock health (AFBI, 2012).

Whilst vaccination, husbandry control measures and culling have been the traditional approaches to dealing with viral diseases in livestock, research also focuses on the development of innate resistance through breeding programmes. Beyond these varied approaches, the use of antiviral drugs to treat infected animals is controversial. Antiviral drug treatments have generally been limited to companion animals, but have potential for wider application to livestock.

The highly pathogenic and zoonotic H5N1 strain of the avian influenza virus became widespread during 2003-2004, spreading from Asia to Europe resulting in millions of poultry infections and several hundred human cases. In the wake of these outbreaks and reports of prophylactic use of antiviral drugs in poultry flocks in Asia, the FAO, OIE and WHO jointly urged Member States in 2005 "not to use antiviral drugs in animals in order to preserve the efficacy of these drugs for the treatment of influenza infections in humans. They strongly request Member States to ban the use of antiviral drugs in animals" (WHO, 2005). Analytical methods have been developed to test for residues of some antiviral drugs in poultry meat (Berendsen *et al.*, 2012), but widespread adoption of antiviral drugs by livestock industries has thus far been averted. Residues of antiviral drugs do not currently form a part of routine residues testing plans in Europe.

Yet the use of antiviral drugs in combination with other control strategies has been proposed as the most efficacious and cost-effective means of eradicating some viral disease outbreaks such as classical swine fever in countries with high density livestock (Wageningen UR, 2012). If greater therapeutic use is made of existing antiviral drugs or new drugs are developed specifically for livestock diseases, further toxicological assessment of the risk posed by residues entering the human food chain would be necessary.

Climate change will undoubtedly have a significant influence on emerging vector-borne viral diseases in Western Europe (Gale *et al.*, 2009). This has already been demonstrated by the northward expansion of the Bluetongue virus from Africa to Southern Europe (causing a non-contagious disease of ruminants with variable symptoms), although whether climate change is responsible for its subsequent appearance in Western Europe in 2006 is debatable (Paul-Pierre, 2009). Bluetongue is transmitted by biting Culicoides midges and IoI is currently free of the disease following its initial and isolated appearance in north Antrim in 2008 via importation of cattle from Europe. Similarly, the Schmallenberg virus, also transmitted via midges, causing abortions or premature births with congenital deformity in sheep and cattle, appeared in Western Europe in 2011. The spread of midges and other virus vectors such as ticks (vector for Louping ill in sheep, for example) may be significantly affected by the changes in climate predicted for North-western Europe. If significant animal viruses become endemic on IoI, there may be pressure to use antiviral drugs on a routine basis for both economic and animal welfare reasons or to increase usage of acaricide drugs to kill ticks and other virus vectors. The possibility of harmful residues in food would then be an issue, possibly requiring new toxicological assessments, setting of legislative limits and implementation of testing plans to ensure food safety. Such developments would be subject to the continuing tensions between clinical human and veterinary concerns. It is to be hoped that the painful lessons currently being learned from the long-term use of antibiotic compounds in livestock production (the development of drug resistant bacteria capable of infecting the human population) will be heeded should the potential arise for widespread use of livestock antiviral drugs.

F. Anti-inflammatory drugs

Whilst steroid hormones have been banned in the EU for livestock growth promotion, some corticosteroids (for example, dexamethasone) are licensed for veterinary use, primarily for anti-inflammatory purposes and treatment of ketosis in ruminants. Non-Steroidal Anti-Inflammatory Drugs (NSAIDs) are a large group of chemically heterogeneous drugs which are used in livestock to control pain and suppress inflammation in a manner similar to steroids but with fewer side effects. They are used primarily in cattle, horses and pigs to treat a wide range of infectious conditions including coliform (environmental) mastitis, respiratory disease, lameness and joint infections. Veterinary surgeons may also use NSAIDs before surgical procedures or after calving a cow. They are also effective in reducing acute pain associated with castration and disbudding/dehorning but are not often administered because of cost and lack of perceived need for pain relief. NSAIDs are rarely used to treat sheep for similar reasons and lack of licensed products (NADIS, 2013).

It is conceivable that climate change may indirectly lead to increased incidences of lameness and joint infections in livestock due to changes in ground conditions and stock movements resulting from the predicted increases in isolated flooding and waterlogged land on IoI. Furthermore, the predicted warmer and wetter climate may well be conducive to increased bovine coliform mastitis (Hogan, 2003) and respiratory infections (Tirado *et al.*, 2010), treatment of which often include anti- inflammatory drug administration alongside appropriate antibiotics. It is therefore possible that administration of anti-inflammatory drugs will increase in coming years and residues monitoring plans will need to be effective in forestalling any increased food safety risk.

G. Coccidiostats

Veterinary drugs which combat coccidiosis in livestock (a protozoal disease caused by parasites of the genus Eimeria) are used most heavily in intensive indoor rearing systems (Kools *et al.*, 2008), particularly the poultry and pig industries. Indoor rearing systems are expected to be largely insulated from the effects of climate change due to their biosecurity measures (Gale *et al.*, 2009) and should see little appreciable change in veterinary drug use as a result of this driver. Other drivers (economics, drug resistance issues, welfare concerns etc.) will have larger impacts on the use of anticoccidial drugs in intensive agricultural systems.

Cattle and sheep production on IoI generally follow extensive, outdoor systems. Anticoccidial drugs may also be used for therapeutic treatment of scouring (severe diarrhoea) in calves and lambs, sometimes in tandem with preventative drugs (primarily halofuginone) against cryptosporidia, one of the most common causes of scouring. Broad spectrum antibiotics may also be administered to young animals exhibiting severe symptoms of scouring to prevent bacteraemia or septicaemia. However, whilst drug treatments may be employed, the primary responses to scouring in extensive rearing systems are reactive (separate and rehydrate the calf) and preventative animal management practices (addressing bedding, cleaning and stocking density issues) rather than drug administration (AHI, 2011).

Climate change has the potential to increase the incidence and distribution of parasitic diseases, including coccidiosis, in animals reared outdoors (Taylor, 2013). Warm and moist conditions provide the optimal environment for development (sporulation) of the infectious protozoa oocysts in contaminated faeces, grass or feed, which may then be ingested by young, vulnerable animals. Predicted climatic changes in IoI, that is, higher temperatures and more frequent rainfall, are likely to increase the disease challenge to livestock in the peak seasonal period of coccidiosis in spring. Coccidiosis in lambs at pasture is already a problem in the UK with increased stocking density and reduced availability of pasture for sheep (Taylor, 2012b). A young animal's resistance to coccidial infection can also be reduced by various stress factors which can include extreme temperature and weather conditions (Taylor, 2012b). Whilst extreme weather fluctuations are an accepted consequence of global climate change, it remains to be seen if IoI will experience sufficient dramatic oscillations in temperature and rainfall to cause significant increased stress to young livestock in the field.

Climate change therefore has the potential to increase the need for administration of various licensed veterinary medications to treat coccidiosis and cryptosporidiosis in livestock reared outdoors or in open sheds. However, given that such infections, often leading to scouring, are primarily treated in young animals, increased drug use may not necessarily represent an increased food safety risk in the form of harmful drug residues, since sufficient withdrawal periods will have been observed prior to slaughter some months later.

H. Drug residues in the environment

The occurrence, fate and persistence of veterinary drug residues and their subsequent effects in the environment is a growing area of research which may still be considered to be in its infancy (Kemper, 2008). It is estimated that, depending on the product, 30-90% of the antimicrobial compounds administered to livestock are excreted unaltered or as active biotransformation products. These residues can enter the environment, contaminating land and waterways either directly through faeces and urine from grazing animals, or indirectly through routine application of manure and slurry to agricultural land as fertilisers. Pharmaceuticals used in human medicine may also find their way onto agricultural land via the recycling of waste water in irrigation systems and application of biosolids (sewage sludge) as agricultural fertiliser (Monteiro & Boxall, 2009). Such use of biosolids in agriculture is encouraged by official Codes of Practice on IoI as "the most sustainable option of sludge management" and providing "both the macro and micro nutrients required for healthy plant and animal growth" (DECLG, 2008). However, biosolids fertilisation is not widespread on IoI as only a small percentage of agricultural land is required to dispose of the currently available material from human waste treatment plants.

Research into the subsequent effects of veterinary and human pharmaceutical residues in the environment has focused largely on the evolution of antimicrobial resistant organisms and the deleterious effects on ecosystems, with aquatic systems receiving more attention that terrestrial systems (Du & Liu, 2012; Arnold *et al.*, 2013). Antibiotics and parasiticides (including anthelmintics) have been ranked as the European veterinary medicines most likely to pose risks to the environment (although anticoccidial drugs pose a high risk within intensive rearing systems) and worthy of further risk assessment (Kools *et al.*, 2008). Concentrations of residues in the environment are not regulated despite estimates that the shedding of antibiotics via manure may be up to kilograms per hectare (Kemper, 2008). It has been suggested that environmental risk assessments of human pharmaceuticals and veterinary medicines should be approached very differently due to the differing nature of their release into the environment: human pharmaceuticals can be considered to be pseudo-persistent contaminants due to their continuous release from wastewater treatment plants, whilst release of veterinary medicines is likely to be more sporadic (Brooks, Huggett, & Boxall, 2009).

The recycling of environmental pharmaceutical residues back into the human food chain and the consequent food safety issue this implies has received very little attention from researchers. Drug residues are known to accumulate in soils but their degradation routes are complex and data are limited (Monteiro & Boxall, 2009). Residues are also detectable in agricultural run-off water (MacKie *et al.*, 2006) and urban wastewaters due to the incomplete removal of pharmaceuticals in wastewater treatment plants. Research continues into methods of removal of veterinary drug residues from the environment, such as the planting of reed beds (Carvalho, Basto, & Almeida, 2012). The uptake of veterinary drugs from contaminated soils or water by plants has been demonstrated (Chitescu, Nicolau, & Stolker, 2013; Boxall *et al.*, 2006; Brooks, Huggett, & Boxall, 2009). For example, nitrofuran antibiotic residues were detected in grass from a free range paddock occupied by chickens which had inadvertently received the drug in their water (McCracken &Kennedy, 2013). The residues were bound to the grass matrix, showing this was not simple surface contamination via litter.

The accumulation of pharmaceuticals in food crops raises food safety issues for human consumers of those plants (Du & Liu, 2012) but the question remains whether such residues in plants are detectable in tissues or produce of livestock which have eaten the crops. It has been suggested there is a need for risk assessments of the exposure of humans to pharmaceuticals in food which arise from environmental uptake rather than direct application to crops or livestock. Such assessments ought to consider longer term exposure and effects on sensitive human sub-populations (Brooks, Huggett, & Boxall, 2009).

It has been shown that low levels of a banned nitrofuran antibiotic were detectable in muscle and liver of unmedicated poultry housed for only one day in a pen previously occupied by birds fed only 1% of a therapeutic nitrofuran dose (McCracken, van Rhijn, & Kennedy, 2005), demonstrating that low level contamination of animal litter can give rise to residues in edible tissues. Another banned antibiotic, chloramphenicol, has been detected in plant material due, it is suggested, to natural production by soil bacteria. This has been proposed as an explanation for several non-compliant findings of the drug in edible poultry and sheep products which posed food safety risks and impacted international trade (Berendsen *et al.*, 2010). It is reasonable to assume that climate changes on IoI could influence the uptake of environmental drug residues into plants and their subsequent release into animal tissues, but the extent of the health risk to consumers is unclear. It is thought that whilst this contamination route is viable, the risks to human health will be low (Kennedy, Cannavan, & McCracken, 2000; Boxall *et al.*, 2006; McCracken & Kennedy, 2013), particularly if mediated via large animal species, and of much lesser concern than the ongoing direct application of veterinary medicines to livestock (Balbus *et al.*, 2013). Nevertheless, reduction in emissions of antibiotics into the environment is desirable (Kemper, 2008) and composting and digestion are well-established methods for reducing antibiotics in manures (Du & Liu, 2012). Further study of the mechanisms of uptake into plants and soils is warranted (Boxall *et al.*, 2006) in addition to risk assessment of pharmaceuticals and their metabolites in soil-crop systems (Du & Liu, 2012). Exposure assessments will be affected by water availability (Arnold *et al.*, 2013) and therefore by climate driven changes in rainfall on IoI.

4.5 Conclusion

Many factors influence the emergence of animal diseases and subsequent treatments which may lead to harmful drug residues in food. As reviewed by Gale *et al.* (2009) in the Great Britain context, there is strong evidence to suggest climate change will continue to have a major impact on animal disease occurrence and prevalence. However, precise forecasting of disease emergence is problematic. Its status as an island may partially protect IoI from climate-driven changes to animal diseases, but this may simply be delaying the inevitable as global warming is likely to continue. Animal transportation (importation of diseased stock) will continue to be a major route for emerging infections.

Climate change on IoI is likely to increase the disease burden on some agricultural livestock. With the exception of parasitic helminth infections, there is little published data on the subject, but it is likely the changes will not be extreme. Nevertheless, administration of veterinary medicines to food animals is likely to increase, although distinguishing climate change effects from other drivers is difficult. For example, encroaching drug resistance may lead to administration of greater quantities of medications or alternative drugs being used inappropriately. Overall, there is the potential for more and different residues of veterinary medicines to appear in locally produced foods over an extended period. Existing food safety control measures on IoI will need to be sufficiently flexible to identify changes in the profile of veterinary residues and preclude their entry into the marketplace.

Global efforts to mitigate anthropogenic climate changes have focussed largely on reducing emissions of greenhouse gases in an effort to reduce the rate of global warming. Livestock production systems are estimated to account for around 8% of emissions in the UK, and 18% globally (Gill, Smith, & Wilkinson, 2010). Whilst livestock producers on IoI must do their part in mitigating adverse climate change effects by reducing greenhouse gas emissions during food production, such efforts in one small region will not in themselves prevent the predicted climate changes on this island.

However, the following mitigation and adaptation strategies can be implemented locally and are suggested to ensure that predicted climate change on IoI does not adversely affect food safety via increasing veterinary drug residues.

A. Mitigation: reducing veterinary drug use

Reducing the use of veterinary drugs is the most effective way of guarding against climate change-driven increases in harmful residues in food.

a) Resourcing fundamental R&D: Developing alternatives to existing drug treatments will pay long-term dividends. Primary examples include production of vaccines against helminth infections and bacteriophage therapy as an alternative to livestock antibiotics.
b) Educating farmers and producers: Livestock management practices which reduce drug usage should be promoted to primary producers. Examples include in refugia (Charlier *et al.*, 2012) and grazing strategies (Colvin, Walkden-Brown, Knox, & Scott, 2008) to control helminth infections. The message of appropriate use of effective veterinary medicines must continue to be driven home to avoid unnecessary administration of drugs which can lead to animal welfare issues, greater residues in food and increasing drug resistance. Ingrained treatment practices on-farm can inhibit adoption of more effective treatment strategies.

B. Adaptation: enhancing residues monitoring

We are fortunate to have chemical residues testing laboratories with international reputations on IoI which regularly perform to the highest standards in EU proficiency tests for veterinary drug residues and are in the forefront of research and development in this field. Multi-analyte residue detection methods are constantly being implemented in the residues laboratories in both jurisdictions using state-of-the-art mass spectrometric equipment in addition to a range of rapid screening procedures. As required by EU legislation, extensive residue monitoring programmes are in place and additional testing schemes are ongoing to protect IoI produce and consumer safety.

To ensure that climate change does not adversely affect our food safety, sufficient resources must be in place to expand the scope of this testing. For example, as veterinary drugs succumb to increasingly resistant microbe and parasite strains, less common drugs may gain in popularity with producers. Testing schemes must encompass relevant new and emerging veterinary drugs and take account of the possibility of increased usage of existing drugs as disease loads on livestock increase.

With changes imminent to EU legislation governing residues testing, it is likely that National Surveillance Schemes will be adapted to a more targeted, risk-based sampling approach. Should risk assessment become integral to our food safety testing regimes, the risks associated with climate change as described in this chapter must be taken into account and resources made available to gather the necessary data.

C. Adaptation: filling the knowledge gaps

a) Veterinary drug use: There is a need for reliable, quantitative, local data defining the types and amounts of veterinary medicines used in food production on IoI. Currently only limited sales or questionnaire figures are available.
b) Veterinary drug residues in the environment: There is a need for comprehensive research to measure residues in the environment and the extent to which they are recycled back into the food chain.
c) Environmental residues and resistance: fundamental research is needed on the relationship between veterinary residues in the IoI environment and the occurrence of drug resistant target species (Kemper, 2008) to determine (a) if there is a link, (b) if there are critical threshold concentrations, and (c) if the link can be circumvented (Call, Matthews, Subbiah, & Liu, 2013).

5 Effect of climatic changes on prevalence of harmful algal blooms and the implications to aquaculture food safety

5.1 Introduction

Over the last three decades, anthropogenic influences have increased atmospheric greenhouse gas concentrations (CO_2, CH_4, N_2O and fluorinated gases) which are believed to be linked with recent climate changes and if continued are predicted by the Intergovernmental Panel on Climate Change (IPCC) to greatly affect future climates on a global scale. The essential climate variables for the three domains, atmospheric, oceanic and terrestrial, for a global climate observing system are summarised in Table 5.1.

Table 5.1: The Global Climate Observing System (GCOS) Essential Climate Variables (ECVs)

Domain		Essential Climate Variables
Atmospheric	Surface	Air temperature, Precipitation, Air pressure, Surface radiation budget, Water vapour, Wind speed and direction.
	Upper air	Earth radiation budget (including solar irradiance), Upper-air temperature, Wind speed and direction, Water vapour, Cloud properties.
	Composition	Carbon dioxide, Methane, Ozone, Other long-lived greenhouse gases, Aerosol properties
Oceanic	Surface	Temperature, Salinity, Ocean acidity, Carbon dioxide partial pressure, Sea state, Sea level, Sea ice, Current, Ocean colour, Phytoplankton.
	Sub-surface	Temperature, Salinity, Current, Nutrients, Carbon dioxide partial pressure, Ocean acidity, Ocean tracers, Oxygen.
Terrestrial	Land surface	Land cover (including vegetation type), Albedo, Fraction of absorbed photosynthetically active radiation (FAPAR), Leaf area index (LAI), Above-ground biomass, Soil carbon, Soil moisture, Fire disturbance, Permafrost.
	Hydrology	River discharge, Lakes, Snow cover, Glaciers and ice caps, Ice sheets, Groundwater, Water use (irrigation).

The measurement, recording and interlinking of these climate observations are essential for understanding trends and patterns to develop enhanced models for future climate predictions.

Such models can be utilised to manage and plan for the future in a wide range of socio-economic sectors whereby then mitigation strategies can be implemented. Currently, climate change is projected to impact broadly across ecosystems, societies and economies, increasing pressure on all livelihoods and food supplies, including those in the fisheries and aquaculture sector. For marine and freshwater systems, increasing concentrations of greenhouse gases are expected to increase surface temperatures, lower pH through acidification, and cause changes to vertical mixing and upwelling remobilising pollutants in sediments thereby modifying precipitation and evaporation patterns (Moore *et al.*, 2008). The global mean surface temperature has increased by 0.74 ± 0.18 C over the past 100 years, while the global average sea level has risen by 1.8 mm per year since 1961 with the Arctic sea ice shrinking by 2.7 ± 0.6% per decade (Carere *et al.*, 2011). To add, the global surface ocean acidity has increased by over 30% since the Industrial Revolution. These climatic changes and changing interlinking climatic factors of each of the three domains are postulated to have impending direct and indirect effects between the aquatic environments and human health through aspects of water quality and food safety. Some authors have suggested that harmful algal blooms (HABs) are increasing globally due to these anthropogenic influences (Smayda, 1990; Hallegraeff, 1993), while others have stressed that climate variability (apart from increased monitoring and awareness) are equally important (Sellner *et al.*, 2003; Anderson *et al.*, 2012). Nevertheless, meteorological factors, such as ambient temperature and humidity, can influence the occurrence of outbreaks of waterborne diseases, pathogens and toxin producing harmful algal blooms (HABs) which can bioaccumulate in aquaculture products such as shellfish and finfish eg salmon, trout. These diseases, pathogens and toxins can pass along the food chain causing illness or death if consumed by humans or other organisms. Those most at risk of experiencing serious effects from water- and food-borne diseases are the very young, elderly, infirm, and people with compromised immune systems.

5.2 Climatic factors for the Island of Ireland

The IoI is an island on the western fringe of Europe between latitude 51.5 and 55.5 degrees north, and longitude 5.5 to 10.5 degrees west. Its greatest length, from Malin Head in the north to Mizen Head in the south, is 486 km and its greatest width from east to west is approximately 275 km. The outstanding feature of the Irish climatic conditions is its changeable weather patterns, a characteristic which it shares with all the countries that lie in the path of the temperate depressions. It is recognised internationally as an ideal site for conducting baseline atmospheric and oceanic measurements. For the atmospheric greenhouse gases, the current carbon dioxide (CO_2) concentrations of more than 390 ppm as measured at Mace Head, Co. Galway are in line with observations from around the globe and are higher than at any time over the last 400 years. The concentrations of other greenhouse gases including methane (CH4) and nitrous oxide (N2O) are approximately 140% and 20% respectively above pre-industrial values and concentrations continue to increase. In keeping with global trends the mean annual surface air temperature has increased by approximately 0.8 C over the last 110 years. The number of annual frost days has decreased whilst the number of warm days has increased. Theaverage annual national rainfall has increased by approximately 60 mm or 5% in the period 1981 to 2010, compared to the 30-year period 1961 to 1990. However, clear changes in rainfall spatial patterns across the country cannot be determined with a high level of confidence. Rainfall is believed to be heaviest on the westward side of the island where it may exceed 3,000 mm in Kerry, Mayo and Donegal. The east is much drier and Dublin records on average only 785 mm annually.

To date no long-term wind speed patterns or changes can be concluded with confidence. Due to the islands positioning it is additionally in an exceptional location to monitor oceanic climatic conditions for the temperate regions of Europe. Oceanographic data has been collected at Main Head for over 60 years. Although divided in governing authorities the island has sovereign rights and jurisdiction over a seabed area greater than 900,000 km2, including deep-sea areas of over 3,000 m depth but it should be noted that the area managed under NI jurisdiction is relatively small. The mean annual sea surface temperature, as measured at Malin Head, Co. Donegal, is now more than 1.0 C higher than the long-term average calculated for the period 1961–1990. The temperature of the oceans is influenced by a number of factors, including the amount of heat from the sun transferred to the water, surface and sub-surface circulation and current patterns. Global ocean surface temperatures have increased by approximately

0.7°C since the 1850s, with rapid warming since the 1960s. Temperature also determines both the plant and animal species present, thereby impacting biodiversity and fishing; it also influences the weather patterns and climate experienced on land. Monitoring of ocean temperature is important as thermal expansion due to warming, leading to sea-level rise. Sea surface temperature can also be inferred from satellite observations with an accuracy of greater than ±0.3°C. Although temperatures are generally increasing, inter-annual variability is high. During the period 2002 to 2012 the average annual coastal sea surface temperatures have been shown to vary significantly with no identifiable trend.

Salinity is defined as the total amount of dissolved salts in water. These constitute approximately 3.5% of the ocean's mass, the remaining percentage being pure water. Although decadal changes have been observed, no longterm trend in salinity levels of the northeast Atlantic has been detected. Monitoring of ocean salinity changes is an indirect method of detecting changes in precipitation, evaporation, river runoff and ice melt and therefore helps in understanding changes in the Earth's hydrological cycle.

Atmospheric carbon dioxide (CO_2) caused by human activities is absorbed by seawater and leads to ocean acidification. It is estimated that levels of ocean acidity have increased by 30% over the last 200 years and projections by the IPCC are that it could increase by a further 120% by 2100, if emissions of CO_2 continue unabated. Although the ecological implications of ocean acidification are still unclear, there is mounting concern as to the potential effects of such rapid acidification on many marine species and in particular on calcifying species such as corals, shellfish and crustaceans. This has the potential for large knock-on effects on the whole ocean ecosystem and related socio-economic activities, including fishing and aquaculture. Since the start of industrialisation some 200 years ago human activities have released a staggering 500 million metric tons of carbon dioxide (CO_2) into the atmosphere. Between a quarter and third of these emissions have been absorbed by the oceans, reducing the effect on the global climate but resulting in a change to surface ocean chemistry known as ocean acidification. OA could harm commercially important shellfish species by affecting the formation of shells in adults, juveniles and larvae, changing reproductive success and recruitment, or by affecting the organisms on which shellfish feed. The problem is down to simple chemistry. When CO_2 dissolves in seawater, it forms carbonic acid (H_2CO_3) which separates into its 2-component ions: bicarbonate (HCO_3-), carbonate (CO_3) and hydrogen (H+). A liquid's pH is determined by the amount of H+ it contains and as more CO_2 is added to the system, more free H+ ions are produced resulting in an increase in acidity. Seawater is naturally alkaline, with a pH of around 8.2. The uptake of excess CO2 drives the pH down, and although the surface ocean will never become truly "acidic", it is certainly becoming less alkaline. It is projected that at current CO_2 emission rates, the mean surface ocean pH may fall by 0.4 pH units by 2100, equivalent to a 150% increase in the concentration of H+. A change this large and rapid has not happened for at least 65 million years. These changes also affect the delicate balance of carbonate ions in seawater. As CO_2 and H^+ concentrations increase, they react with free carbonate ions (CO_2) to produce HCO_3. So the availability of carbonate decreases and calcifying organisms, such as shellfish, may struggle to produce and maintain their calcium carbonate shells and skeletons.

Observations of wave height, direction, length and frequency are relevant for monitoring changes in the marine environment, such as winds, storms and extreme events. Knowledge of sea state and how it is changing is also vital for the offshore oil industry, ocean energy development, shipping, coastal erosion and flooding among others. Increasing wave heights have been observed over the last 50 years in the northeast Atlantic, along with a northward displacement of storm tracks.

All major cities in Ireland are in coastal locations subject to tides and any significant rise in sea levels could have major economic, social and environmental impacts. Estimates for the twentieth century show that the global average sea level rose at a rate of about 1.7 mm per year whilst estimates derived from satellite measurements for the period 1993 to 2012 indicate a rise of 3.18 mm per year. Sea levels are rising primarily because increasing global temperatures cause thermal expansion of the oceans as well as increasing freshwater input due to melting ice sources (e.g. glaciers and ice sheets, permafrost). An additional contributor to sea-level change, called 'isostatic glacial adjustment', has caused the north of

Ireland to rise differentially as the land recovers from the loss of the huge mass of ice which covered it during the last Ice Age.

Ocean currents transport heat, freshwater and carbon from one part of the ocean to another and play a key role in determining climate conditions. The North Atlantic Current (NAC), an extension of the Gulf Stream draws relatively warm and saline subtropical waters northeastward across the Atlantic Ocean, helping to maintain the temperate climate conditions in northwestern Europe. Although multi-annual and decadal changes in the strength of the NAC have been recorded, there is no coherent evidence for a long-term trend

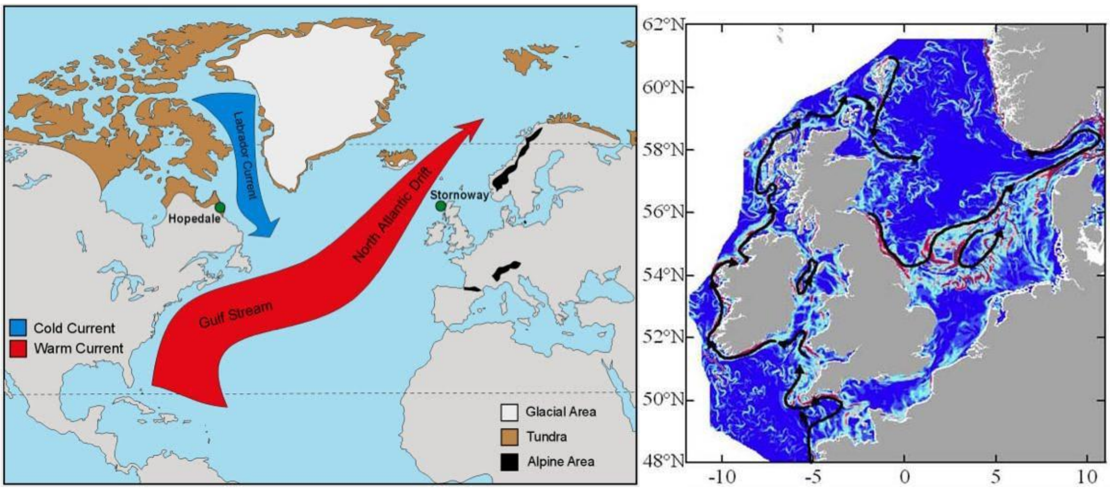


Figure 5.1: Overview of the oceanic currents and shallow thermohaline circulation pathways around Ireland Adapted from Hill *et al* 2008

The Gulf Streamis the most important ocean-current system in the northern hemisphere, which stretches from Florida to north-western Europe. The North Atlantic Drift is an eastern extension of this stream. This thermohaline ocean circulation system carries warm water from the equator to the west coast of Ireland, making the country's climate warmer than it otherwise would be to those of similar latitude (Figure 5.1). Therefore Ireland's mild and temperate climate is a reflection of the fact that its shores are bathed by the relatively warm ocean waters of the North Atlantic Drift. For this reason extremely high or low ocean temperatures are virtually unknown. The 2013 UN Intergovernmental Panel on Climate Change (IPCC) report predicted that global warming and melting of Arctic Ice will affect currents in the Atlantic Ocean though through the 20-44% weakening of the circulation of warm and cold water in the Atlantic, which includes the Gulf Stream, by the end of the century. It is believed that such a slow-down in the Gulf Stream will have a big impact on Ireland, causing cooling of about 1 C and disrupting weather patterns. Scientists warn that the resulting cooling would mask the impacts of global warming on the country, but play havoc with the weather. Similar to global observations the sub-surface and deep offshore waters around Ireland between 1991 and 2010 show substantial increases in acidity. Historically, the sea level has not been measured with the necessary accuracy to determine sea-level changes around Ireland. Nonetheless, measurements from Newlyn, in southwest England, show a sea-level rise of 17 mm per decade since 1916. These observations are believed to resemble the conditions to the south of Ireland. Since 2000, the occurrence of some potentially harmful ocean phytoplankton species during the winter months has increased. Though there has been a significant growth and consolidation of ocean-observing systems since 2000, which is proving invaluable in improving understanding of ocean climate. This increase in HABs may in fact be noted due to improved quality of monitoring over this same time span. In addition, the analysis of long-term river flows from over 40 measurement sites around the country shows a tendency for increasing annual mean flows. Moreover, seasonal analysis indicates that summer mean flows are dominated by increasing trends while there is a tendency also for increases in winter mean flows.

Ocean colour refers to the sunlight reflected from the surface of the ocean. The particular characteristics of this reflected light are determined by the water constituents, primarily phytoplankton, suspended particles and dissolved organic compounds. Monitoring of ocean colour provides information on water quality and early warning of phytoplankton blooms and pollution events. Changes in colour patterns and characteristics can be related to and are indicative of climate changes. Changes in climate such as altered rainfall patterns are also likely to influence nutrient inputs to the marine environment and therefore may also affect estuarine and coastal ecosystems. There is an optimum range for dissolved oxygen concentration in oceanic water to avoid stress and potential death to ocean life. Projections indicate that concentrations could decrease by up to 20%, in part because of ocean warming and increased stratification in calm waters, leading to dead zones where no marine life is maintained. Other human-induced depletion is caused by excessive nutrient discharge into river and coastal systems. Observations are vital to give early warning of oxygen- depleted areas and to track the impact of climate change.

No single authority is charged with making the full range of observations of ECVs for Ireland. The monitoring networks and measurement systems that do exist are managed by a range of different bodies, including state agencies, regional authorities and third-level institutions. In many instances the observations made are not strictly for climate monitoring purposes but for operational requirements or research. Nonetheless for certain meteorological parameters monitoring has been performed for a significant number of years. Since 2000, the remote collection of climatic factors from different buoy sites around Ireland, positioned as illustrated in Figure 5.2, has been underway. The data that has been collected is atmospheric pressure, wind direction, speed and gust, wave height, period and direction, air and sea temperature, dew points and relative humidity.

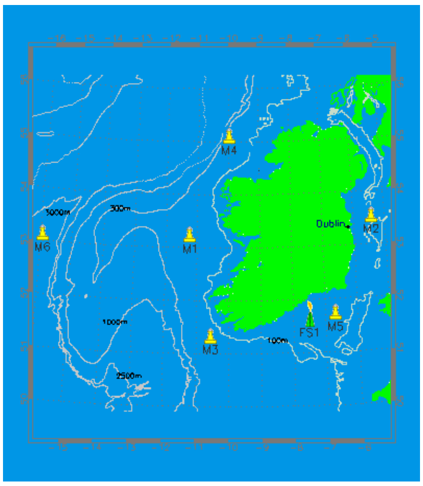


Figure 5.2: Positioning of climatic buoys in Irish coastal waters

The climatic data recorded from these buoys can be mapped to see if there is any variability between sites and regions of Ireland which may be more favorable to invasive species or the proliferation of algal blooms. The average parameter for each month was plotted for each buoy relative to the lifespan of the buoy from the data available. This was perfored to determine climatic variables more due to location (Figure 5.3). Between the regions in this time period the key variations are in wave height and period, air and sea temperature, dew points and relative humidity. However, there are breaks in the data collected over these years but trends in location and months can be observed. As the buoys are at identified longitude and latitudes these parameters may be used to determine if there are direct relationships between the incidences of phytoplankton and toxin occurrence relative to the current climate.

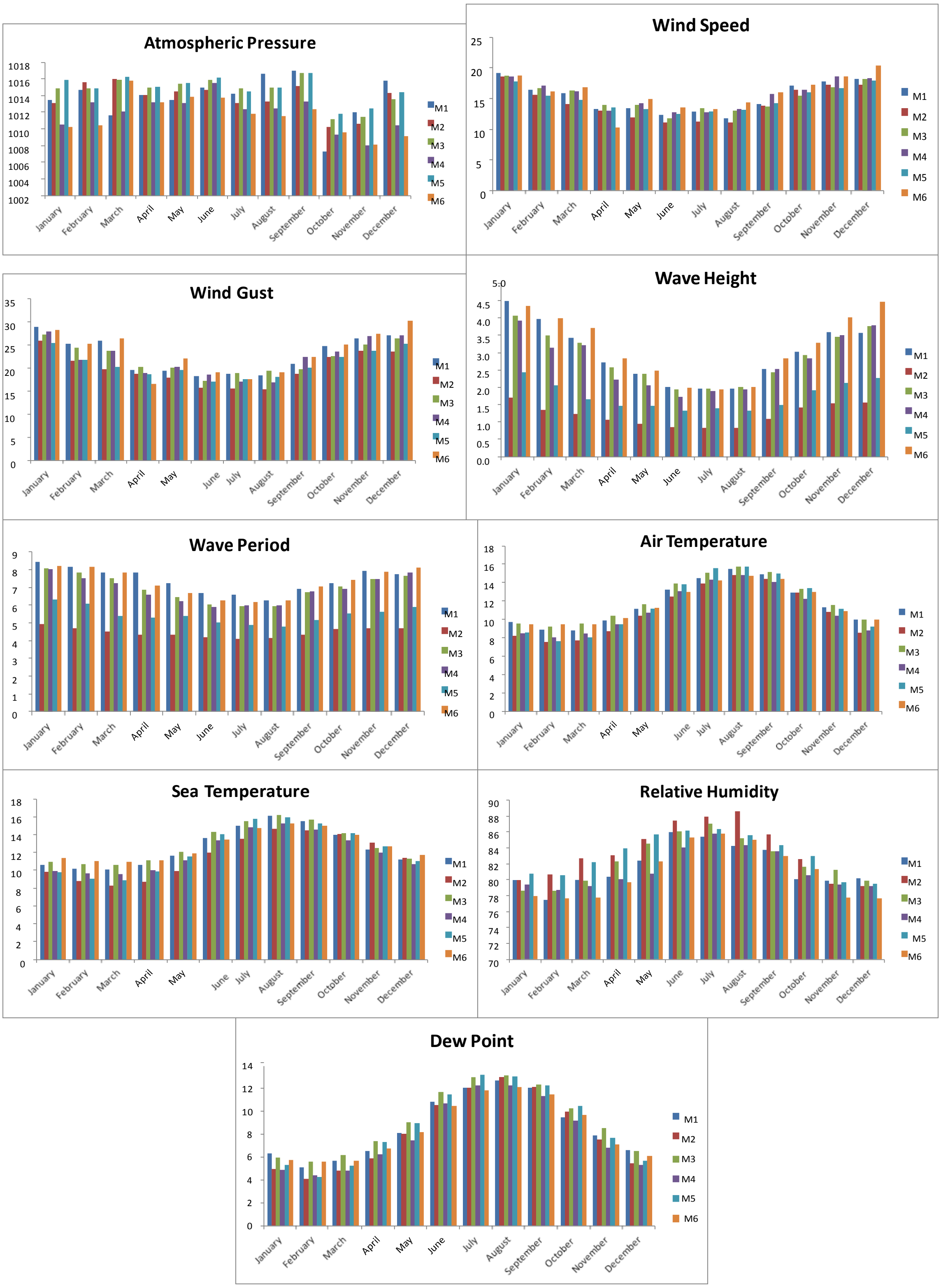


Figure 5.3: Climate graphs (Average over the time span M1: 2001 to 2007; M2: 2001 to 2012; M3: 2002 to 2012; M4: 2003 to 2012; M5: 2004 to 2012; M5: 2006 to 2012)

5.3 Aquaculture on the island of Ireland

Aquaculture is the cultivation of aquatic organisms usually for the purposes of human consumption. Globally it is acknowledged that aquaculture is supplying 50% of the world's fish production but production is not distributed evenly around the globe. China is currently is the largest producer of aquaculture. According to the Food and Agricultural Organisation (FAO), aquaculture "is understood to mean the farming of aquatic organisms including fish, molluscs, crustaceans and aquatic plants. Farming implies some form of intervention in the rearing process to enhance production and survival, such as regular stocking, feeding and protection from predators. Farming also implies individual or corporate ownership of the stock being cultivated." In Ireland Aquaculture is defined as the sea or land based cultivation of marine, brackish or freshwater aquatic organisms including zooplankton, shellfish (molluscs) such as mussels and oysters, crustaceans such as brine shrimps, echinoderms such as sea urchins, finfish such as salmon and trout, and aquatic plants including seaweed and other algae. The growth of aquaculture in Ireland from the 1950's is illustrated in Figure 5.4.

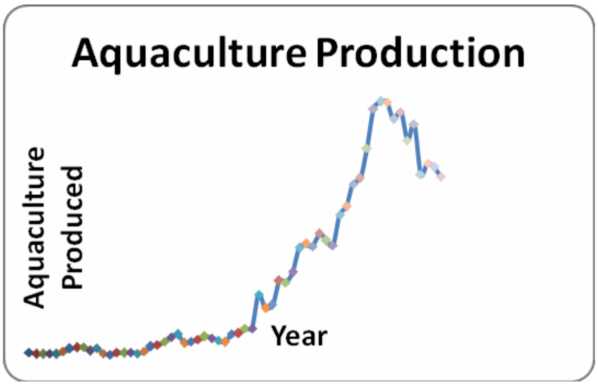


Figure 5.4: Aquaculture production in Ireland from 1950-2012

On the IoI, mussels (Mytilus edulis) and Atlantic salmon (Salmo salar) are the most commonly farmed marine species.Irish aquaculture produces more shellfish than marine finfish (Figure 5.5). Mussels accounted for almost 80% of Irish shellfish production, followed by Pacific oysters, native oysters, clams and scallops. Finfish produced were primarily Atlantic salmon in addition to small volumes of sea and freshwater reared trout. Although Ireland produces more shellfish than finfish, the finfish sector has a higher economic value. Irish finfish was valued at €75.0 million compared with €44 million for shellfish (BIM, 2012).

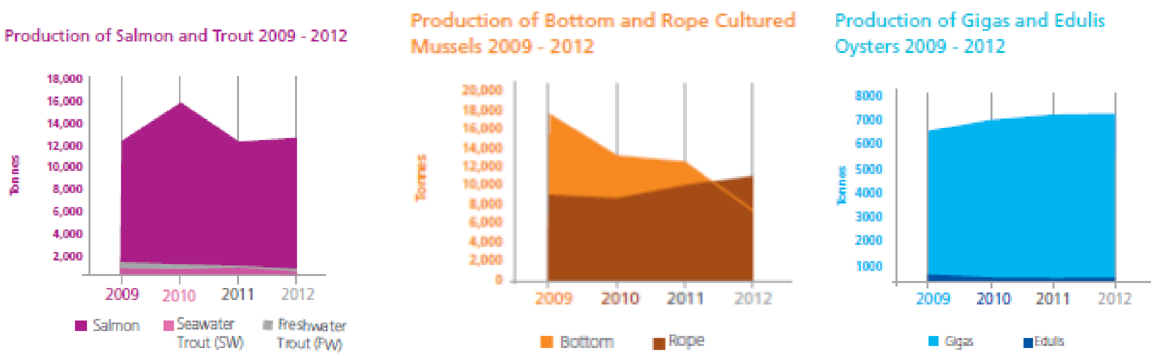


Figure 5.5: Aquaculture production in Ireland from finfish and shellfish from 2009-2012

NI produces very little marine finfish and therefore marine aquaculture is dominated with shellfish production. Blue mussels currently represent the greatest proportion of production. In 2011, 7060 tonnes of mussels, 50 tonnes of pacific oysters and 1 tonne of king scallops were produced in NI at a value of £5.5 million.

Callaway and co-workers (2012) discussed the widely acknowledged close relationships between prevailing environmental conditions, the complex ecology of the aquatic environment and the success of aquaculture production. It has been noted that the health of both finfish and shellfish is heavily dependent on environmental conditions, such as temperature, salinity, oxygen solubility and dissolved waste products (Mydlarz *et al.*, 2006). Aquaculture facilities are often located in areas which are front line locations to experience climate change impacts: coasts and estuaries are susceptible to changes in water temperature, storm intensity or frequency and sea level. Additionally, the routine physical processes of waves, tides, rivers, and associated erosion or deposition may alter the suitability of the abiotic environment. Comparably additional concerns for rivers and estuaries are sediments, nutrients, pathogens and contaminants associated with run-off due to changes to flood frequency and magnitude. The distribution of a specific species may be limited by its ability to survive depending on its environmental optima and the conditions following climatic effects. If the environment changes substantially a species may become immuno- compromised and more susceptible to disease or predation. On a more complex level, shifts in the aquatic ecosystem will impact upon not only the abundance of parasites, pathogens, prey and predators but also affect their inter-relationships and dominance (Karvonen *et al.*, 2010). As a consequence changes in the normal climatic conditions may promote the proliferation and extension of non-native species depending on their ability to over-winter. Algal blooms, the rapid growth of phytoplankton, are one example. Some algal blooms are appropriately termed ecosystem disruptive algal blooms as are non-toxic but interfere with the energy transfer through the ecosystem or cause fish kills through oxygen depletion. Toxin producing harmful algal blooms have been identified as a potential area of concern specifically relating to food safety on the IoI but also to food security through ensuring sustainability in growth of the aquaculture industry. Since the initial developments in the early 1970s, the Irish aquaculture industry has grown to become an important contributor to the economy of the region with a significant proportion built up in exports of seafood (€415 million in 2011). There has been a steady, and in some cases exponential increase, in both output and value, in job creation, and in the diversity of sites used and species farmed. If this was to be compromised due to increased algal blooms caused by climate change without advanced safety and mitigation procedures the growth in industry would suffer. In Ireland the aquaculture products at greatest risk from these blooms are Mussels, Pacific oysters (Crassostrea gigas), native oysters (Ostrea edulis), clams and scallops as the main shellfish species being produced. Though other products such as salmon, accounting for >95% of finfish produced, rainbow trout, cod, abalone, Arctic charr and perch could also be affected locally. Traditional products such as seaweeds and sea vegetables may also be at risk of toxin accumulation. The global market in import and export however allows the distribution of products worldwide and methods of detection and regulations should not be restricted to local climates and produce.

5.4 Harmful algal blooms and food safety

Phytoplankton, derived from Greek with phyton meaning "plant", and planktos meaning "wanderer" or "drifter ". There are over 5000 known species. The two main classes are dinoflagellates and diatoms. Dinoflagellates use a whip-like tail, or flagella, to move through the water and their bodies are covered with complex shells. Diatoms also have shells, but they are made of a different substance and their structure is rigid and made of interlocking parts. Diatoms instead rely on ocean currents to travel through the water. All classes are photosynthesizing microscopic organisms that contain chlorophyll and require sunlight in order to live and grow. They are agents for "primary production," through their absorption of significant amounts of carbon dioxide (CO_2) from the atmosphere, although much of this is released when the plankton die. Nonetheless this process is the base and sustenance for the aquatic food web and may be greatly affected by climatic conditions. Most phytoplankton are buoyant and float in the upper part of the ocean, where sunlight penetrates the water. Phytoplankton also require inorganic nutrients such as nitrates, phosphates, silicates, iron and sulfur which they convert into proteins, fats, and carbohydrates. Nutrient concentrations in Irish coastal waters are determined by concentrations in shelf seas and biogeochemical processes that may release or remove nutrients from the water column. Other important sources in coastal waters are associated with riverine inputs from both natural sources and human activities – for example agricultural application of fertiliser and municipal waste discharges. In a balanced ecosystem, phytoplankton provide food for a wide range of sea creatures including whales, fish, shrimp, snails, shellfish and jellyfish. When too many nutrients are available, phytoplankton may grow out of control and form harmful algal blooms (HABs). These blooms can produce extremely toxic compounds that have harmful effects on fish, shellfish, birds and mammal. In the marine environment, the most important harmful algae and their poisoning syndromes are diatoms from the genus Pseudo-nitzschia (amnesic shellfish poisoning), and species of dinoflagellates from the genera Alexandrium, Pyrodinium, and Gymnodinium (paralytic shellfish poisoning), Dinophysis and Prorocentrum (diarrhetic shellfish poisoning), Azadinium spinosum (Azaspiracid poisoning), Karenia (neurotoxic shellfish poisoning), Ostreopsis (palytoxin poisoning) and Gambierdiscus (ciguatera fish poisoning) (Campas *et al.*, 2007; Campbell *et al.*, 2011). A number of human illnesses are caused by ingesting seafood. The food vectors and short term and known long term health implications for the different poisoning syndromes are indicated in Table 5.2. These toxins may cause respiratory and digestive problems, memory loss, seizures, lesions and skin irritation, or even fatalities in fish, birds, and mammals (including humans) (Anderson *et al.* 2002, Sellner *et al.* 2003). Some of these toxins can be acutely lethal and are some of the most powerful natural substances known; additionally, no antidote exists to any HAB toxin (Glibert *et al.* 2005). The Food and Drug Administration in the US recently claimed that 15-20% of seafood poisoning incidences are due to marine toxins. However, there are currently no means of verifying the toxin presence in clinical investigations and generally as the symptoms present similar to bacterial or viral food poisoning toxic incidences go unreported. As these toxins are tasteless, odourless, and heat and acid stable, normal food preparation procedures will not prevent intoxication if the fish or shellfish is contaminated (Baden *et al.* 1995, Fleming *et al.* 2006). In addition to human health effects, HABs also have detrimental economic impacts due to closure of commercial fisheries, public health costs and other related environmental and socio-cultural impacts (Trainer & Suddleson 2005; NOAA - CSCOR 2008). In the freshwater environment the most important HABs are caused by certain species of cyanobacteria (blue green algae) such as from the genera Anabaena, Microcystis (Kite-Powell *et al.*, 2008). These HABs also produce potent toxins with short term and potential long term health effects as outlined in Table 5.3. Rivers, lakes and underground water are not only vital for drinking water but also supply agriculture and the industry for food production and processing, recreational opportunities and ecosystem maintenance. Excellent water quality is important to ensure both animal and human health safety. It is important to ensure that systems are in place to prevent toxins from HABS entering the food chain from environment to farm to processing to fork.

Table 5.2: Toxin producing marine harmful algae, their consequential effects and prevalence in Ireland

Poisoning syndrome	Toxin	Phytoplankton species (Action Limit cells/L)	Vector (Action Limit)	Occurrence on the IoI	Short term Health Consequences	Long term Health consequences
Amnesic Shellfish Poisoning	Domoic acid	Pseudo-nitzscia sp (150,000)	Shellfish (20mg/kg)	Yes Regulated Monitored	Vomiting, diarrhea, liver inflammation, abdominal pain, confusion disorientation, memory loss	Anterograde memory deficit, seizures leading to coma and death
Diarrhetic Shellfish Poisoning	Okadaic acid and dinophysistoxin s	Dinophysis sp Prorocenturum lima (100)	Shellfish (160 g/kg)	Yes Regulated Monitored	Nausea, vomiting, diarrhea, abdominal pain accompanied by chills, headache, fever	Gastrointestinal tumour promoter in laboratory animals
	Azaspiracids	Azadinium sp	Shellfish (160 g/kg)	Yes Regulated Monitored	Causes diarrhea and neurotoxic effects	Unknown
	Yessotoxin	Protoceratium reticulatum Lingulodinium polyedrum	Shellfish (1mg/kg)	Yes Regulated Monitored	Unknown	Unknown
	Pectenotoxin	Dinophysis fortii	Shellfish (160 g/kg	Yes Regulated Monitored		
Paralytic shellfish poisoning	Saxitoxins	Alexandrium sp (Present)	Shellfish Crustacean s (800 g/kg)	Yes Regulated Monitored	Tingling, burning, numbness, drowsiness, incoherent speech, respiratory paralysis leading to death	Unknown
	Tetrodotoxin	Shewanella alga sp Pseudomonas sp	Gastropods, fish	Not detected Not monitored		
Neurotoxic	Brevetoxin	Karenia sp	Shellfish	Not detected	Numbness of lips, tongue and	Unknown

shellfish poisoning				Not monitored	throat, muscular aches, fever chills, muscle pains, abdominal cramping, nausea, diarrhea, vomiting, reduced heart rate, pupil dilation	
	Palytoxin ostreocin Maitotoxin	Palythea Ostreopsis sp	Fish Crustacean Shellfish	Not detected Not monitored	Causes vomiting, diarrhea, respiratory distress and death	Unknown
	Gymnodimine Spirolides Pinnatoxins	Gymnodinium sp Karenia sp Alexandrium ostenfeldii	Shellfish	Detected Not monitored	Unknown. Causes similar effects in mice to DSP toxins	Unknown
Ciguatera Fish Poisoning	Ciguatoxin	Gambierdiscus sp Amphidinium sp	Reef Fish	Not detected Not monitored	Abdominal pain, nausea, vomiting, diarrhea, paresthesias, temperature dysthesia, pain, weakness, bradycardia, hypotension	Recurrent symptoms from months to years of chronic depression

Table 5.3: Toxin producing freswater harmful algae, their consequential effects and prevalence in Ireland

Toxin	Genera	Vector	Occurrence in freshwater on the IoI	Short term Health Consequences	Long term Health consequences
Microcystins	Anabaena, Aphanocapsa, Hapalosphon, Microcystis, Nostoc, Oscillatoria, Planktothrix	Drinking water Irrigation water	Yes Not monitored	Gastrointestinal, liver inflammation, and hemorrhage and liver failure leading to death, pneumonia, dermatitis	Tumor promoter, liver failure leading to death
Nodularins	Nodularia spumigena	Drinking water Irrigation water	Not monitored	Similar to Microcystins	Similar to Microcystins
Saxitoxins	Anabaena, Aphanizomenon, Cylindrospermopsis, Lyngbya	Drinking water Irrigation water	Not monitored	Tingling, burning, numbness, drowsiness, incoherent speech, respiratory paralysis leading to death	Unknown
Anatoxins	Anabaena, Aphanizomenon, Oscillatoria, Planktothrix	Drinking water Irrigation water	Yes Not monitored	Tingling, burning, numbness, drowsiness, incoherent speech, respiratory paralysis leading to death	Cardiac arrhythmia leading to death
Cylindrospermopsin	Aphanizomenon, Cylindrospermopsis, Umezakia	Drinking water Irrigation water	Not monitored	Gastrointestinal, liver inflammation and hemorrhage, pneumonia, dermatitis	Malaise, anorexia, liver failure leading to death
Lipopolysaccharide	Aphanizomenon, Oscillatoria	Drinking water Irrigation water	Not monitored	Gastrointestinal, dermatitis	Unknown
Lyngbyatoxins	Lyngbya	Drinking water Irrigation water	Not monitored	Dermatitis	Skin tumors (Fujiki *et al.* 1990), unknown
BMAA	Anabaena, Cylindrospermopsin, Microcystis, Nostoc, Planktothrix	Drinking water Irrigation water	Not monitored		Potential link to neurodegenerative diseases

The European Water Framework Directive (WFD; Directive, 2000) establishes an integrated and coordinated framework for the sustainable management of aquatic environments by European member states. Its purposes include preventing deterioration of water bodies, promoting sustainable water use, and ensuring ‘enhanced protection and improvement of the aquatic environment’. Though monitoring of water quality under this framework can vary in member states. In Europe the legislative controls of marine biotoxins in shellfish are prescribed by European food hygiene and safety legislation EC/854/2004. This legislation requires all EU member states to have in place an "official control" monitoring system that ensures there are checks for the presence of marine biotoxins in shellfish production and re-laying areas and in products placed on the market. There is also a requirement for the monitoring of toxin-producing phytoplankton in production and re-laying areas. As such phytoplankton monitoring programs are in place throughout Europe but these can vary between member states depending on the perceived risk.

Under EU legislation a competent authority has the statutory responsibility for ensuring the delivery of an effective official control programme. A competent authority is required to take action to close production or relaying areas, and to prevent harvesting or the sale of products found to contain levels of biotoxins above the prescribed set European limits. One of the greatest risks to food safety from harmful algal blooms is the legislation governing their monitoring. To date not all marine biotoxins are named in legislation or have legislative action limits. Though they are loosely covered where no regulatory limits are setspecifically it is not obligatory to monitor for these toxins therefore this legislation does notprovide sufficient protection to human health. Regulation (EC) no 854/2004 [21]stipulates that: “Fishery products derived from poisonous fish of the followingfamilies must not be placed on the market: Tetraodontidae, Molidae, Diodontidae andCanthigasteridae. Fishery products containing biotoxins such as ciguatoxin or muscleparalysing toxins must not be placed on the market. However fishery products such asgastropods complying with Regulation 853/2004 may be placed on the market”. To comply with EC/853/2004 bivalve molluscs must not contain marine biotoxins in total quantities (measured in the whole body or any part edible separately) that exceed the following limits:

a) for paralytic shellfish poison (PSP), 800 micrograms per kilogram;
b) for amnesic shellfish poison (ASP), 20 milligrams of domoic acid per kilogram;
c) for okadaic acid, dinophysistoxins and pectenotoxins together, 160 micrograms of okadaic acid equivalents per kilogram;
d) for yessotoxins, 1 milligram of yessotoxin equivalent per kilogram;
e) for azaspiracids, 160 micrograms of azaspiracid equivalents per kilogram.

For the legislation there are no regulatory action limits for spirolides, tetrodotoxin, brevetoxin, ciguatoxin or palytoxin or for any freshwater toxins and therefore generally there is no routine monitoring conducted for what are described as unregulated toxins. For this reason seafood containing these toxins may be consumed as similarly there is currently no other means of verifying human exposure other than through biotoxin monitoring in seafood (Hinder *et al.*, 2011). For known potential phytoplankton or cyanobacterial species and their emerging toxins that have the potential to relocate due to varied mechanisms into different regions and survive due to climatic variations the legislation has to protect the consumer and cover these risks. In addition, there has to be suitable means and resources for monitoring and detecting these known emerging toxins. In the global economy and food supply chain these risks are not only topical from the point of view of climate change but on the import or export or products from different regions of the world.

5.5 Climate effects on Harmful Algal Blooms

If HABs, particularly of toxic nature, were to increase in frequency, duration or toxicity this would also lead to an increase in risk in toxin exposure on seafood consumption. Changes in climate may be creating aquatic environments particularly suited to both marine and freshwater HAB-forming species of algae. To date, several studies have suggested possible relationships between climate and the magnitude, frequency, duration and effect of harmful algal blooms (HABs) (Dale and Edwards 2006; Edwards 2006; Hallegraeff, 1993; Hayes *et al*., 2001; Trainer *et al*., 2003) but limited correlative data utilising knowledge and expertise in climatology, oceanography, hydrology, biology and epidemiology is currently available. It is extremely difficult to separate the influence of climate change (natural and anthropogenic) from other anthropogenic impacts that are known to contribute to HABs using the limited datasets that are currently available. Even the relationship between phytoplankton or cyanobacterial biomass and HAB species toxicity is complicated. Toxic HABs can have harmful effects even if the species is not dominant and toxin production may be related to hydroclimatic conditions and can vary among strains within a species, even during the course of one bloom event (Barin *et al*. 2005). Some species, such as Alexandrium fundyense, can cause significant toxicity in shellfish even when present at very low abundances (Barin *et al*. 2005) while others are only toxic at high concentration (Anderson *et al*. 2002). Even some species of the same genus possess varying levels of toxicity (Trainer & Suddleson 2005). Furthermore, if bacteria growth increases with climate change and increasing temperature, the toxicity of some HAB species may also increase; however further work is needed to define the relationship between other species such as bacteria and parasites and algal toxin production (Richardson 1997). For infectious disease it is reported that climate limits the range and weather determines the duration and intensity of outbreaks (Epstein, 2001) which could also be applicable to HABs. In the overall phytoplankton community harmful algae are only a small representative though their individual responses to climate variability and change can differ. Their growth is strongly determined by temperature, light, and the availability of nutrients. Therefore climate-water interactions result in changes to the phytoplankton community, and can influence HAB frequencies.

Warmer temperatures may result in expanded ranges and frequency of warm water harmful algae species such as the tropical marine dinoflagellates proceeding on a poleward expansion and therefore more geographically widespread. Certain species such as Alexandrium catenella thrive above temperatures of 15 C therefore if the temperature is higher than seasonally normal the HAB may proliferate for longer periods of time with the greater the increase in temperature propagating the greater predicted duration of the bloom (Trainer *et al*., 2003). Increasingly extreme weather events may also increase the geographical habitat of these harmful algae species. Edwards *et al*. (2006) showed that HABs are indeed increasing in some areas of the Northeast Atlantic, although the increase is not spatially homogenous and is restricted to specific habitat types. It is evident that increase in the ratio of dinoflagellates versus diatoms has been observed in the southern North Sea (Hickel, 1998).Dinoflagellate abundances have increased to the detriment of diatom populations in some marine ecosystems, such as the North-East Atlantic (Edwards *et al*. 2006), the Grand Banks area of the North-West Atlantic (Johns *et al*. 2003) and Baltic Sea (Wasmund & Uhlig 2003). This shift in community composition has been linked to increased sea surface temperature; in the North-East Atlantic, increased sea surface temperature during winter months has resulted in an earlier growth and succession of flagellates such as Prorocentrum spp. and Dinophysis spp. (Edwards & Richardson 2004, Edwards *et al*. 2006). Additionally, dinoflagellates are well-suited to stratified water (Margalef 1978) and therefore may not only respond physiologically to temperature, but may also respond indirectly if climate warming enhances stratified conditions or if stratification occurs earlier in the season (Edwards & Richardson 2004). Experimental results suggest warming sea surface temperature and increased water stratification may lead to an increase in growth rates of some HAB taxa including Prorocentrum spp. and Dinophysis spp. (Peperzak 2003). Increasing sea surface temperature has also been found to lead to decreased surface nutrient concentrations which favour the smaller dinoflagellates and are detrimental to the larger diatoms (Bopp *et al.* 2005). Thus, it appears that in some areas regional climatic changes favour dinoflagellates over diatoms, therefore increasing the likelihood of occurrence of HAB-forming species. However, the extent to which regional climate change will influence HAB dynamics is uncertain as separating the effects of climate change from natural variability remains a key scientific challenge. Additionally, some HAB-forming dinoflagellates form resting cysts during their lifecycles. These cysts sink to the sea floor and when environmental conditions are favourable to growth they break open to propagate the area with the species. Some cysts can remain viable for decades, but if growth conditions occur more recurrently, cysts may reseed more often, causing frequent HAB blooms (Dale 2001).

As yet there is no evidence linking any aspect of HABs to ocean acidification. However research is underway by the International Atomic Energy association to use experimental radiotracer and radioassay methods to evaluate the impact of ocean acidification on both saxitoxin content in dinoflagellates responsible for Paralytic Shellfish Poisoning and harmful algae physiology and biomass production following the hypotheses illustrated in Figure 5.6. The ecological effect of ocean acidification is in its infancy and the extent of current knowledge is limited. For example, it has been demonstrated that increasing acidification will reduce calcification of marine organisms causing calcium carbonate shell dissolution in mussels facilitating disease. It is possible that ocean acidification may cause changes in HAB dynamics through changes in phytoplankton community composition; however, there are insufficient data to draw any conclusions about the impacts that increasing CO_2 might have on the growth and composition of HAB-causing marine phytoplankton (The Royal Society 2005). Some studies have illustrated that with increasing CO_2 levels and stressing the organism in depleted nutrient conditions such as low levels of silicon for diatoms that toxin production was higher. The ocean is normally alkaline in pH but marine biotoxins such as saxitoxins are preferably stable in lower pH solutions degrading over time in alkaline conditions therefore if the ocean was more acidic does this mean that some toxins would prolong naturally in the environment for longer

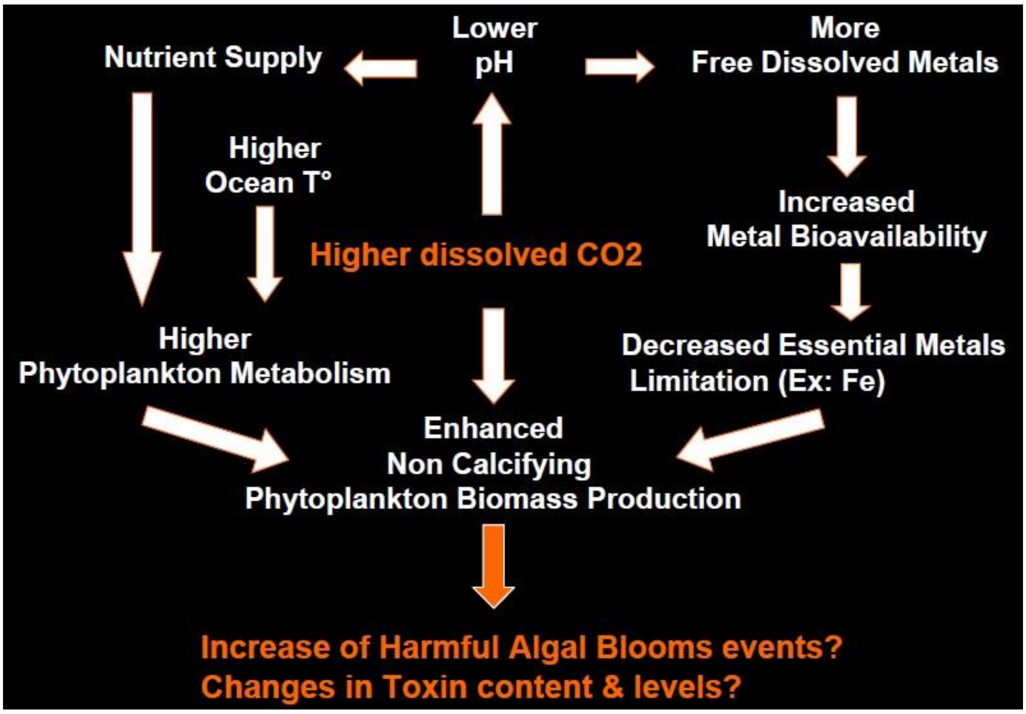


Figure 5.6: Hypothetical schematic for examining the effects of ocean acidification

In addition to changes in climate, increased anthropogenic nutrients are thought to be a key cause of HABs (Sellner *et al.* 2003). Sea level rise, increased precipitation and flash floods are most likely to affect harmful algal communities through increased nutrient release to coastal and marine waters. In combination with the stratification effects at ocean and freshwater interfaces during summer months (Figure 5.7) this may allow proliferating blooms to travel on jet currents (Figure 5.2) around the island. These currents however do not appear to expand into the region of NI or the East coast and is possibly one reason as to why toxic episodes do not occur at as high a frequency in those regions.

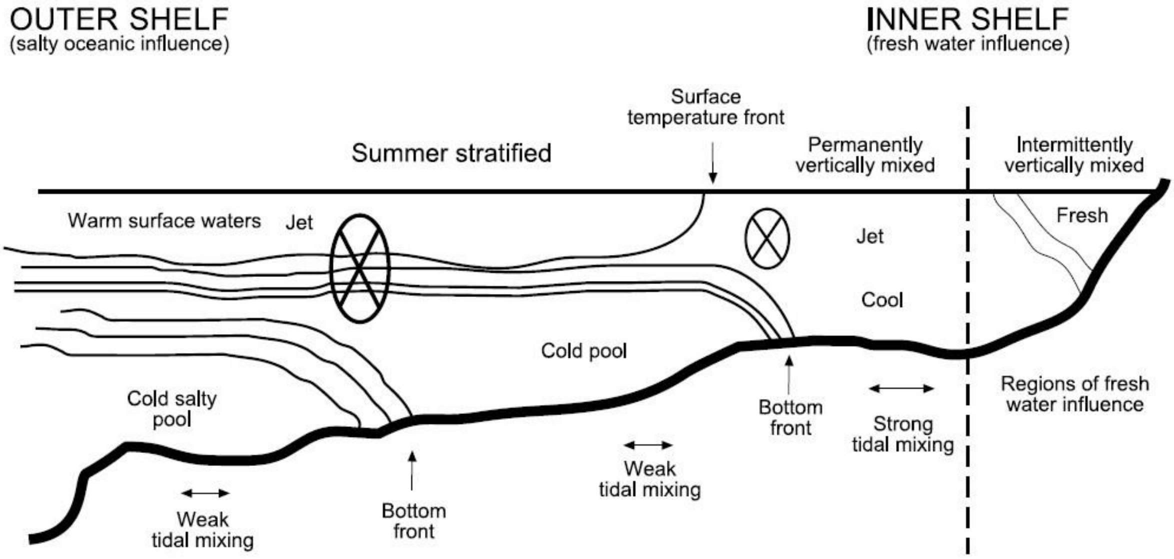


Figure 5.7: Diagram illustrating the stratification at freshwater and ocean interfaces

Flash flooding and an increase in storm events as predicted in some areas of climate change may release frequent 'pulses' of nutrients into coastal waters (Carter *et al.* 2007). High nutrient pulses have been found to alter the phytoplankton functional group composition of receiving waters (Paerl *et al.* 2007). Two key nutrients required for phytoplankton growth, nitrogen and phosphorus, are found in fertilizers and animal and human waste; however silicon, which is only required for diatom growth, is not added to the environment through human activity. Therefore run-off from land, including floodwaters and increased river flow due to heavy precipitation, is likely to be richer in nitrogen and phosphorus than in silicon, leading to an imbalance of these nutrients in coastal regions. Increased concentrations of nitrogen and phosphorus without a corresponding increase in silicon may cause changes in phytoplankton community composition, favouring dinoflagellates, which have no biological requirement for silicon, at the expense of diatoms (Officer & Ryther 1980, Smayda 1990). In the Easter Mediterranean, for example, a sudden pulse of high nutrient water lead to an increase in phytoplankton biomass and the dominance of Pseudo-nitzschia calliantha, a toxic HAB species (Spatharis *et al.* 2007). Such a shift in the phytoplankton community towards dinoflagellate dominance may result in increased numbers of HAB species in regions prone to increased anthropogenic nutrients. The link to nutrient-status (water and phytoplankton), temperature and ocean acidification do need to be clarified, there is also a need for information on their competitors and consumers, both planktonic and benthic. Recent work has shown a profound shift in the relative abundance of diatoms and dinoflagellates in UK waters (Hinder *et al.*, 2012). Dinoflagellates (both HAB and non-HAB taxa) have declined markedly in abundance, while diatoms (both HAB and non-HAB taxa) have increased. These patterns have been linked to the combined effects of rising water temperatures and increasingly windy conditions (Hinder *et al.*, 2012).

Climate change is predicted to cause a rise in sea level of at least 0.6 m by 2100 (Nicholls *et al.* 2007). As the sea reclaims low-lying land, areas that are currently intensively farmed or urbanised may be drowned, causing the addition of nutrients, particularly nitrogen and phosphorus, to coastal systems. Additionally, as sea levels rise, wetland habitats are lost. Wetlands act as natural filters for anthropogenic nutrients and are therefore important in regulating nutrient loads to coastal waters.

Wetlands and mangrove habitats also provide a natural form of protection from storm surges and flooding (Nicholls *et al.* 2007). Without these habitats, coastal waters may be more prone to increased levels of nutrients and nutrient imbalance. Measures taken in order to prevent or lessen the severity of impact of sea level rise and flash flooding may also alter nutrient loads to coastal waters. For example, the Iron Gates dam built on the Danube River was found to more efficiently retain silicon than nitrogen or phosphorus. This, along with increased nitrogen and phosphorus loads, resulted in an increase in non-diatom blooms and bloom intensity (including some HAB species) in the Black Sea (Humborg *et al.* 1997, Moncheva *et al.* 2001).

Rivers and lakes are impacted by changes in climate, most notably changes in rainfall patterns but also in temperature and levels. Conversely, rivers play an important role in regional and local climate. Groundwater is located beneath the ground surface in pore spaces and fractures of geologic formations and is not only influenced by rainfall and dry periods but also by human use as the main supply of drinking water. Risks to groundwater quality and quantity that may be exacerbated under a changing climate include depletion, pollution and salinisation. Changes in the climate can cause alterations in the volume of water rivers carry, leading to droughts and floods which can have several social, economic and environmental impacts. Increased precipitation and flash flooding may affect both marine and freshwater HAB communities through changes in salinity as well as changes in nutrients. Several HAB-forming species appear to be responding particularly well in regions which are both warming and becoming increasingly fresh (Edwards *et al.* 2006). For example, Norwegian coastal waters of the North Sea have experienced a decrease in salinity related to increased precipitation and increased terrestrial run-off. At the same time, several HAB-forming species such as Ceratium spp., Dinophysis spp., Protoperidinium spp., and Prorocentrum spp. have increased in abundance in this area (Edwards *et al.* 2006). A rise in sea level will increase water depths, leading to increased tidal exchange and reduced salinity. If climate change does result in increased freshwater run-off to coastal waters which are also warming, these same species could serve as archetypical of what may occur in other coastal regions experiencing analogous changes. In addition microcystins and nodularins have also been reported in seafood from brackish waters so the risk of freshwater blooms contaminating seafood in these circumstances may also be increased.

5.6 Occurrence of Harmful Algal Blooms and incidence of toxic contaminations in Ireland

The IoI falls under two member states for the monitoring and detection of both phytoplankton and marine biotoxins. In NI the competent authority is the Food Standards Agency and the testing is performed by contractual agreement with AFBI. In Ireland the competent authority is the Food Standards Authority of Ireland and the testing is performed by the Marine Institute.

In NI phytoplankton and shellfish monitoring have been performed since 1997 though to date no correlation has been performed with any climatic data collected. Water samples are taken fortnightly throughout the year from beds which are in production. As well as the four main target phytoplankton groups (Alexandrium spp., Dinophysis spp., Prorocentrum lima and Pseudo- nitzschia spp.) samples collected during 2012 also contained the target species Prorocentrum minimum, Karenia mikimotoi, Noctiluca scintillans and the genus Phaeocystis spp. The genus Alexandrium spp. contains a number of species which have the potential to produce Paralytic Shellfish Toxins (PSTs). In 2012, Alexandrium spp. were present in 2.2% of samples analysed (2.4% of samples in 2011) but recorded only from Belfast and Carlingford Loughs. Both its occurrence and abundance were low in 2012.The maximum cell abundance recorded was 180 cells/L in a sample taken from the Flynn site (Carlingford Lough) on the 31st July. Historically levels of Alexandrium spp. recorded in Northern Irish waters have been low with the exception being summer 1996 when both high cell counts in water samples and toxicity in shellfish were recorded in samples taken from Belfast Lough. Killough remains the only site where Alexandrium spp. have not been detected in official control water samples.

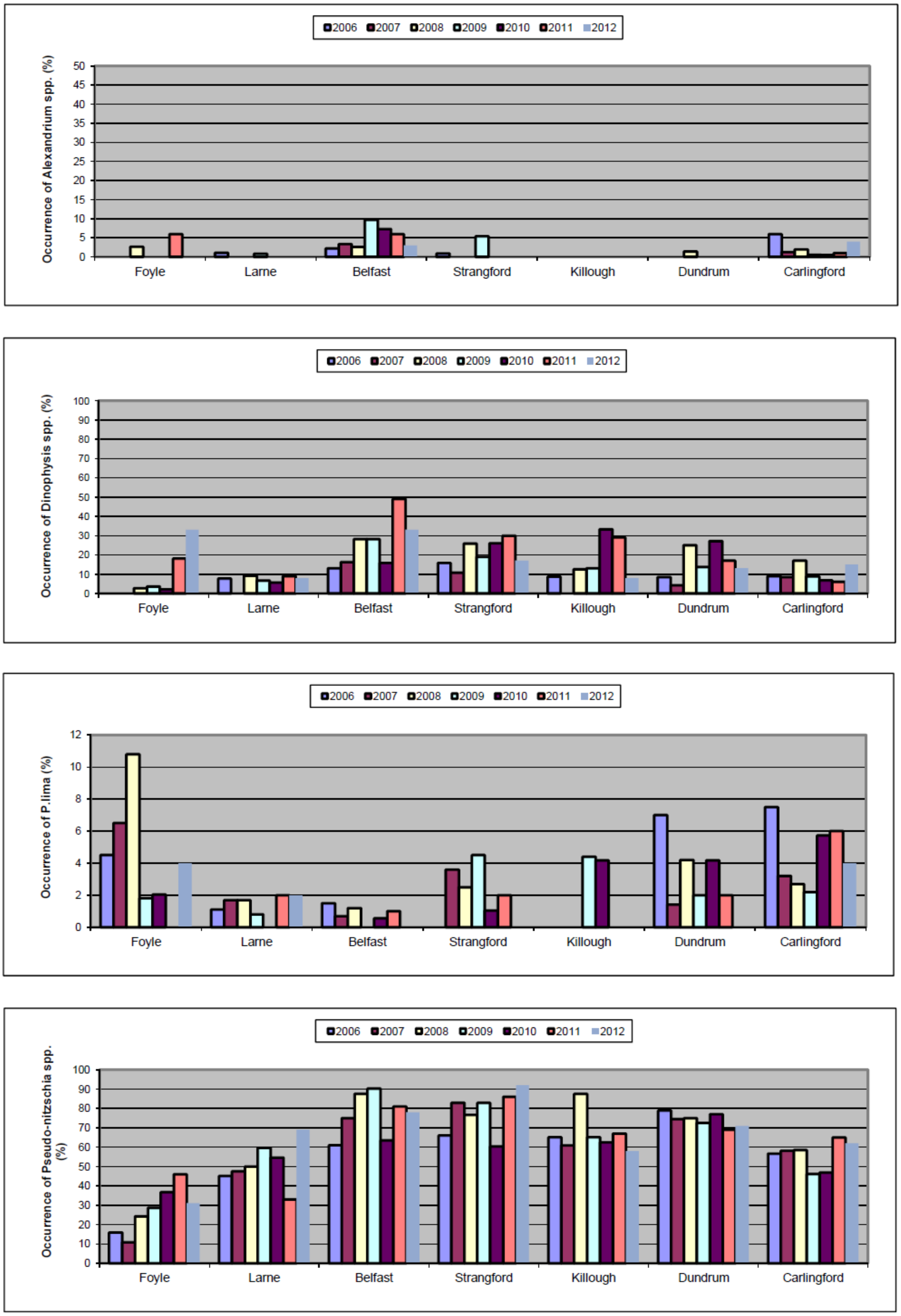


Figure 5.8: Occurrence of the four major target organisms 2006-2012

The genera Dinophysis consists of more than 200 species a small number of which have been implicated in toxin production. Cells of Dinophysis spp. were routinely identified to species level, where possible, in N. Ireland water samples. An average of 21.4% of water samples contained cells belonging to this genera, Dinophysis acuminata being the dominant species. This is in agreement with the results from previous years when this species has been the dominant member of the genus in NI waters. Spatial variation ranged from the presence in 8% of Killough samples to 33% of Belfast Lough samples. A bloom of Dinophysis spp. was recorded in Belfast Lough in July. A maximum abundance of 2,200 cells/L was recorded during this period in a sample from Middle Bank on 16th July. Okadaic acid (measured using LC-MS/MS) was recorded in mussels from the lough at this time but levels were below the European Union (EU) regulatory limit of 160 µg/kg.The DST producer, Prorocentrum lima, was recorded in three of the seven coastal areas and in 1.8% of all water samples analysed. Cell abundance was generally low except for a sample taken from Production Area 4 in Lough Foyle on 24th January which recorded a value of 22,620 cells/L. P. lima is an epiphytic species preferring to grow on a substrate. During this time 'keep boxes' were deployed at this site and it was hypothesised that the keep box may have been providing the hard substrate for P. limato grow on. However, scrape samples taken directly from the keep box on the 7th February showed no trace of the epiphyte P. Lima growing on this structure.

The occurrence of the four main species from 2006 to 2012 is illustrated in Figure 5.8 but there does not appear to be any trends in these species and year to year variation is inevitable. However, it would be beneficial to explore the parameters (anthropogenic or climatic) that caused the year to year variation.

Shellfish samples are taken from each bed monthly with sampling rotated to ensure the entire water body is samples twice a month. NI production areas have experienced closures due to biotoxin levels above the regulatory limit in most years however the frequency is low but increasing in range from 2% of samples in 2008 to 4% in 2011. These closures were due to the detection of diarrhetic toxins mainly from Dinophysis sp in mussels and oysters and the detection of domoic acid in scallops. In mid June 2012 Pseudo-nitzschia sp began to rise in Belfast Lough with counts above 150, 000 cells one month later. Pseudo-nitzschia sp which produce domoic acid toxin is more commonly found in scallops though the first report of domoic acid in blue mussels that caused a closure in NI was reported in 2012. Contamination in blue mussels reached 28 g/kg. The majority of the shellfish production sites are on the East coast of NI and as such may be protected from invasive algal blooms originating from warmer waters of the Gulf Stream and North Atlantic drift and thermohaline jets (Figure2) which project around the west coast of Ireland and as such production areas such as Foyle and even Carlingford from these jets would be the most susceptible.

Although data has been collated on phytoplankton and toxins in shellfish from the mid 1980s in Ireland which coincides with the growth of the aquaculture sector (Figure 5.3) improved monitoring and recording of both phytoplankton and European regulated marine biotoxins in shellfish was implemented in the early 2000's by the Marine Institute. Toxin analysis in shellfish has been carried out in Ireland since 1984 using animal bioassays and after 2002, chemical analyses (LC-MS) for certain toxins was introduced to the existing biotoxin monitoring programme. This coincides with the same time period as the implementation of the remote buoys for the marine institute. However, this time span of up to twelve years is not yet significant to mapping changes in climatic conditions. The establishment as to whether HAB events are increasing relative to climate change has been hindered by uncoordinated, insufficient and incomplete record keeping of plankton composition over continuous time periods in the same sites due to resources available for this research. However, the data currently available can be utilized to look for trends in environmental conditions relative to occurrence or growth of phytoplankton species and the prevalence of toxins in shellfish at different sites. Off the coast of the IoI with the exception of Ostreopsis and Gamberdiscus, harmful algal blooms have been recorded which can not only be detrimental to human health through food safety but to the economy of the Irish aquaculture industry. Climate change may have a significant effect on the prevalence and distribution of occurring blooms. Most phytoplankton species have the ability to generate cysts which then bloom under ideal conditions but there are a number of species that are generally not toxic but yet cause significant problems to the shellfish and finfish industry regularly in Ireland. Noctiluca scintillans (orange/red bloom); Karenia mikimotoi (red bloom); Phaeocystis sp (foam): Heterosigma akashiwo (brown bloom) are phytoplankton species that can cause toxic fish kills and shellfish spat mortalities. Chaetoceros covolutus, Chaetoceros concavicornis, Chaetoceros densus, Chaetoceros eibenii and Chaetoceros danicus species are phytoplankton species found in Irish waters that are not toxic but when present in the water column can create problems to farmed finfish by clogging their gills, causing irritation and therefore mucus production by the gill tissue, which stresses the fish, sometimes causing mortalities on farmed finfish. Blooms of Karenia mikimotoi have caused mass mortalities of farmed fish and coastal benthic communities through unwanted affects of a combination of anoxia and toxicity. These blooms are known to produce toxic compounds to marine life but are believed not to be detrimental to humans though there has been limited identification of the toxins or toxicological studies performed to determine ill health effects in the short or long term. The occurrence of these blooms appears to be increasing over the last decade on the south and west coasts of Ireland.

In relation to food safety and human health similar to NI the most significant phytoplankton blooms are that of Dinophysis acuta and acuminata, Prorocenturum Lima, Alexandrium sp, Pseudo-nitzschia sp but also Azadinium sp. The genus Dinophysis is a common component of the marine flora in Irish waters in summer. Dinophysis acuta is present at highest cell concentrations between July and September. Dinophysis acuminata is present at highest cell concentrations between June and August. Shellfish that feed on these armoured dinoflagellates can build up toxins responsible for Diarrheic Shellfish Poisoning outbreaks. In Ireland, shellfish production sites are frequently closed in summer from contamination by these dinoflagellates. The mean annual closures that occurred between 1984 and 2008 were 63 and 108 days off the west and south coast respectively. In 2010, Dinophysis acuta appeared off the south west coast for a long period of time with high cell concentrations of the order of 2680 cells/L, from May to November, and was associated with the prolonged closures of the longline mussel culture industry.

Azadinium sp is a minute dinoflagellate as is extremely difficult to identify using light microscopy the traditional methodology for monitoring phytoplankton. However, molecular techniques are now being implemented for the detection of this and other algal species. This species of algae has only been identified in the last few years but it is known to produce the Irish derived toxin “Azaspiracid”. This toxin was first recognised through the DSP mouse bioassay test for diarrhetic lipophilic toxins. Shellfish closures on the west coast of Ireland are significantly high from 2002 to 2012 due to this toxin. To date unlike Dinophysis which tends to occur only in some months toxic incidences from azaspiracid tends to occur throughout the year. Alexandrium sp is known to occur in Cork Harbour and paralytic shellfish poisoning toxins above regulatory limits in shellfish have been recorded. Pseudo-nitzschia sp which produce domoic acid toxin is more commonly found in scallops though incidences of domoic acid contamination have also been recorded in blue mussels.

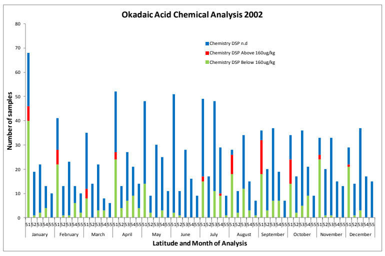
The occurrences of toxic episodes for blue mussels above the regulatory limit was examined for each of the toxins monitored in Ireland relative to longitude distribution (Figure 5.9). The most toxic occurrences appear at longitudes of 51 N which correlates most with buoy M3. At this longitude the sea temperature and dew point would be marginally higher on the west coast. However, for a more accurate assessment the temperature at the time of the sample collection should be compared.

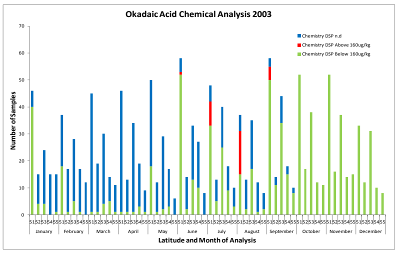
In addition there should be improved correlation between phytoplankton counts, toxin produced and toxin accumulated in shellfish to determine the lag phases between the first identification of species and relative to toxin detection in shellfish to the point where the action level is reached. Different environmental factors may not only affect HAB production but also toxin accumulation and biosynthesis in the species.

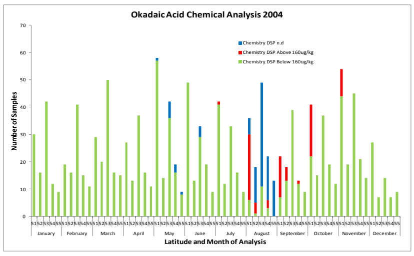
Figure 5.9: Toxic incidences recorded as above the action limit as measured by each method over the recorded time periods

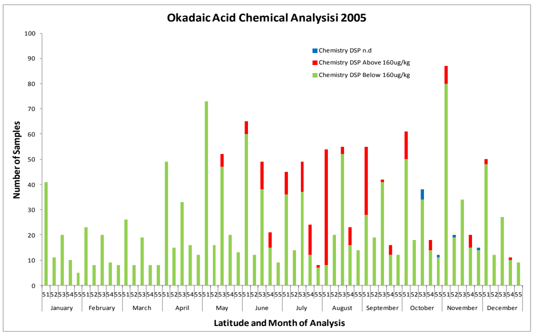
<u>(a) DSP Mouse Bioassay for Blue Mussels</u>

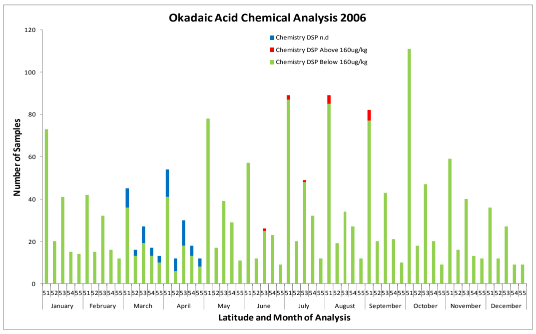
(b) DSP Chemical Analysis

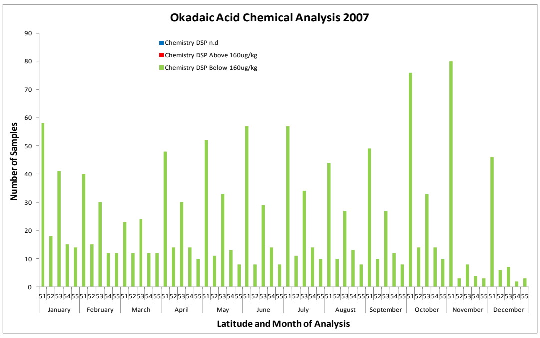


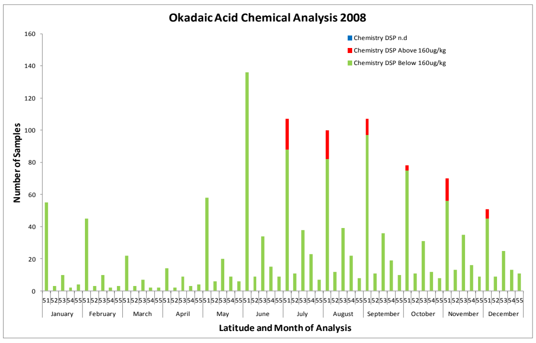


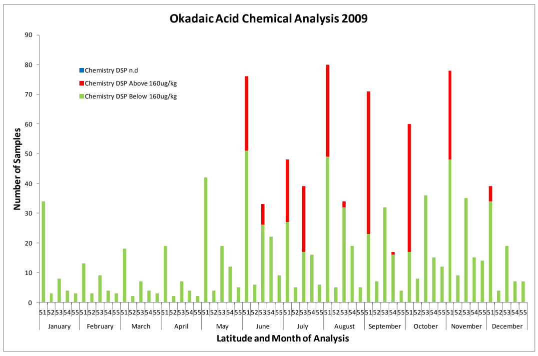


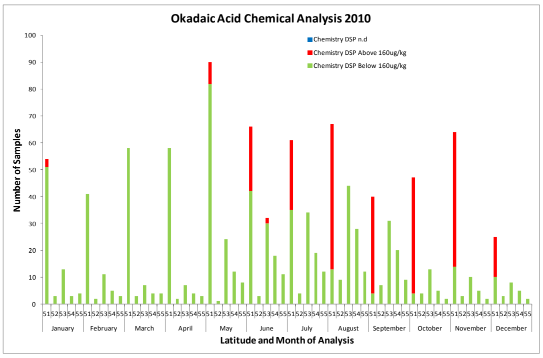


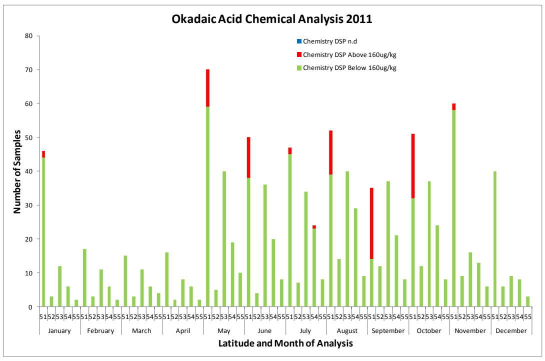


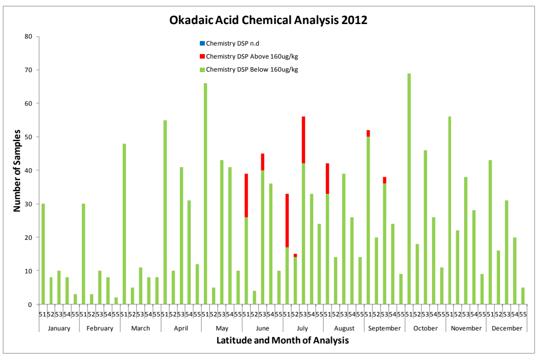




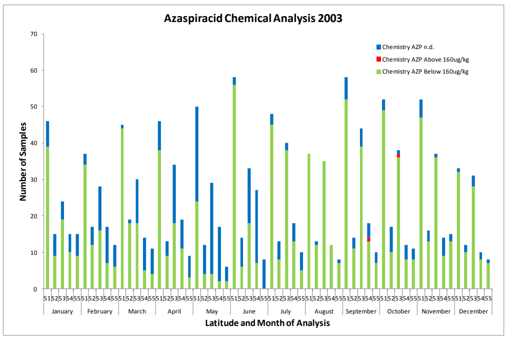


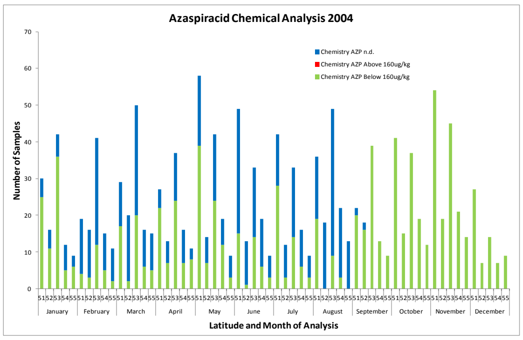


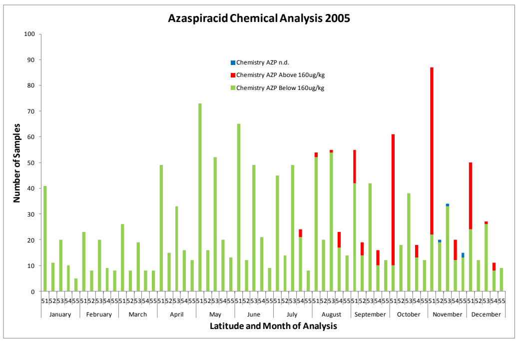


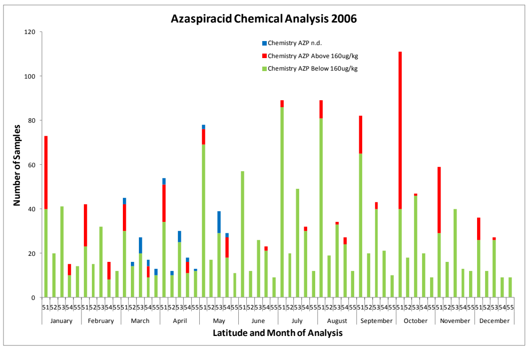


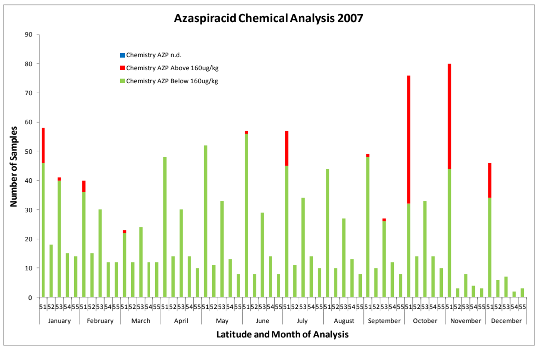
(c) Azaspiracid Chemical Analysis

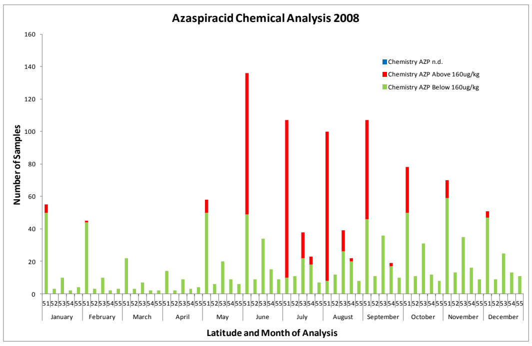


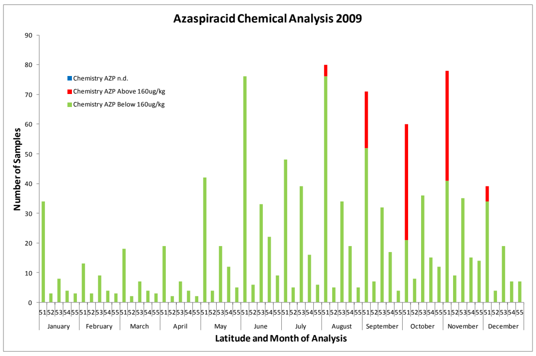


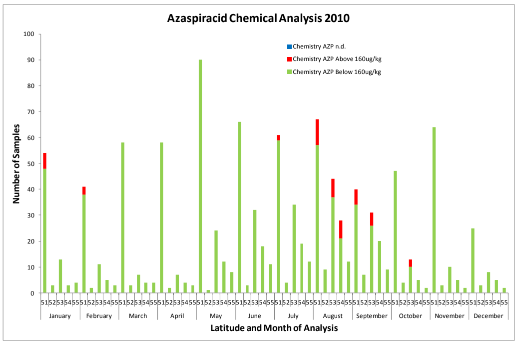


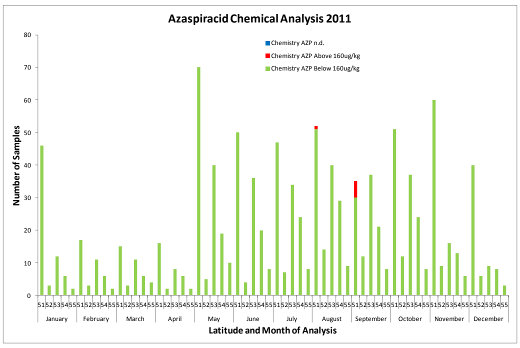


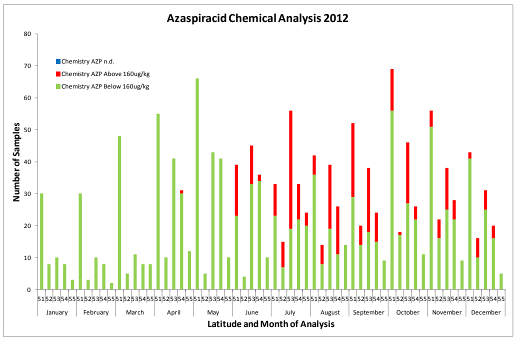




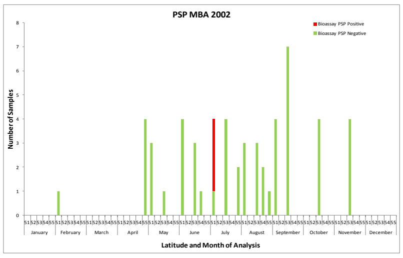


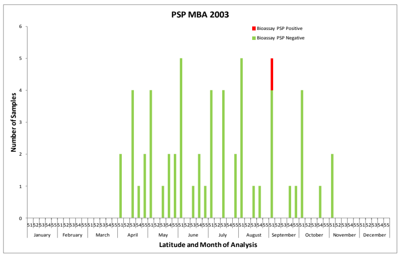


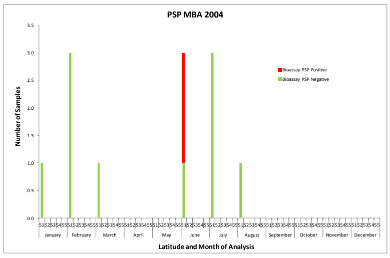


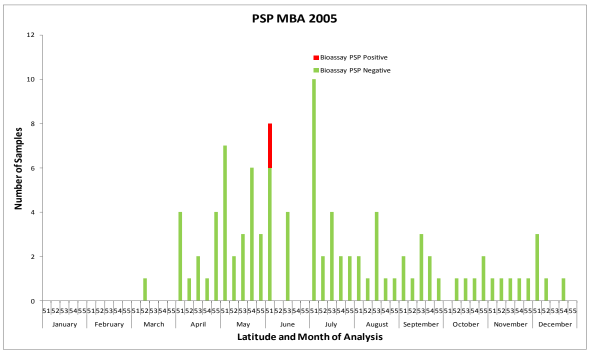


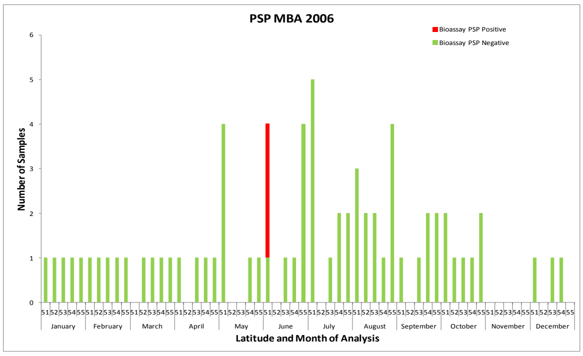
(d) PSP MBA Analysis

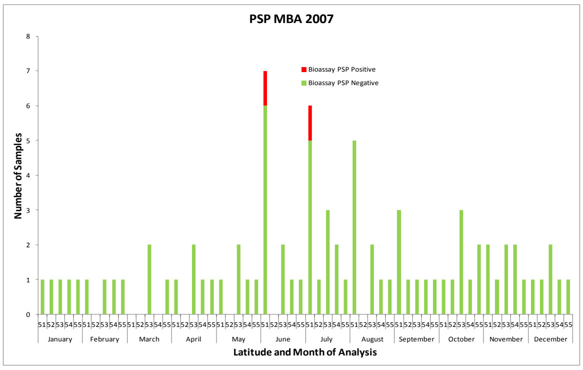


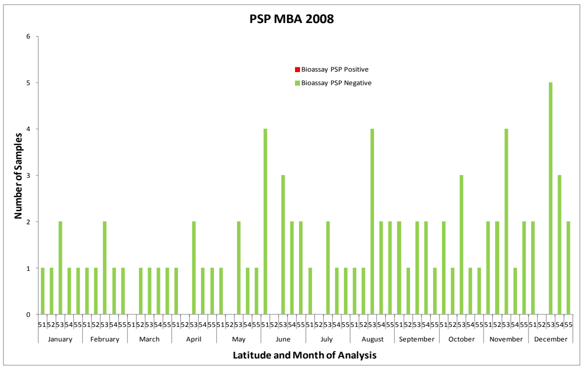


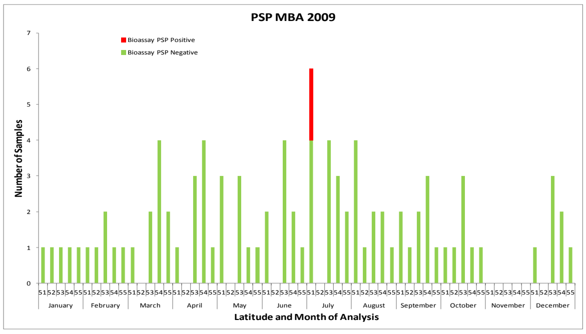


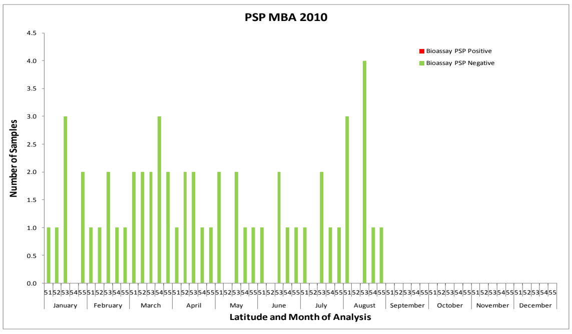


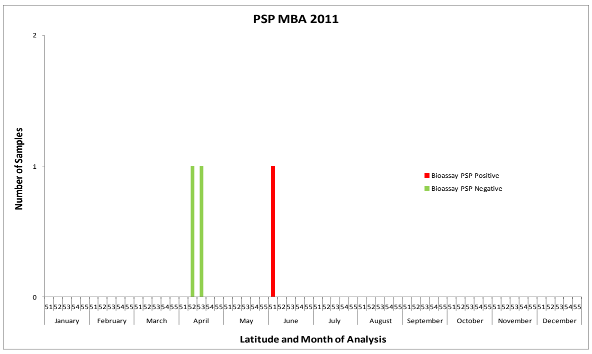


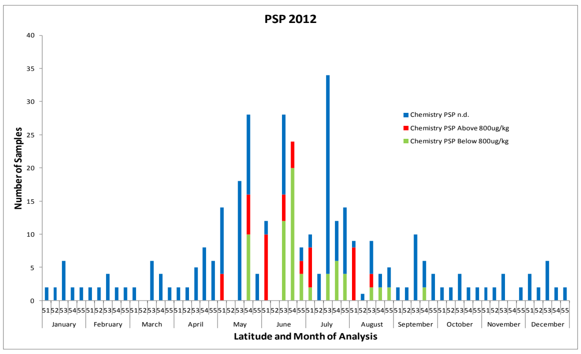




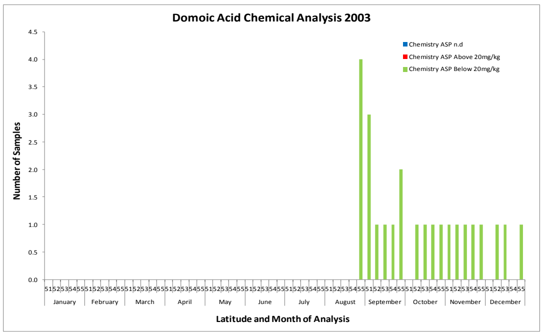


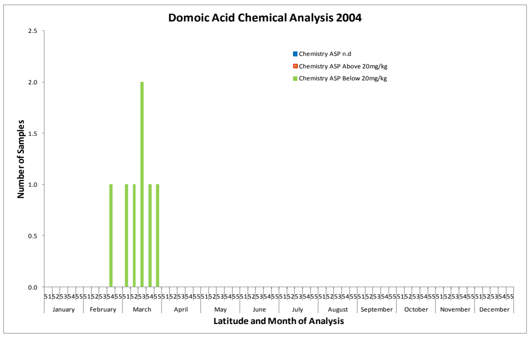


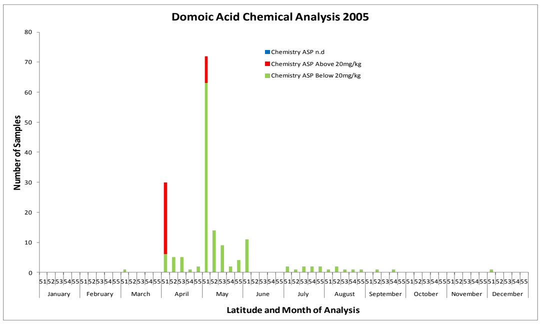


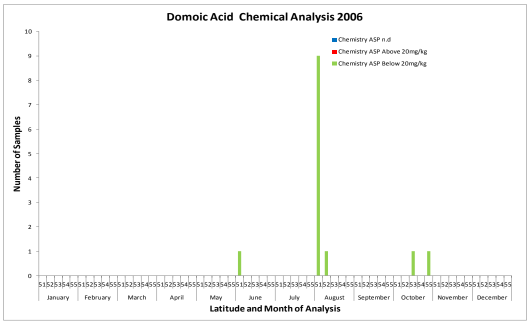


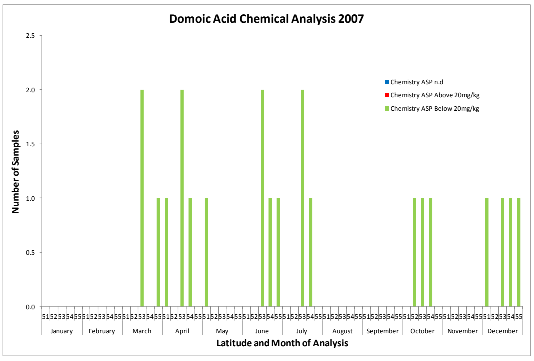
(e) Domoic Acid Chemical Analysis

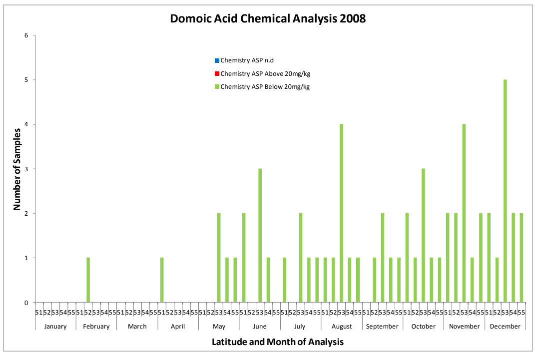


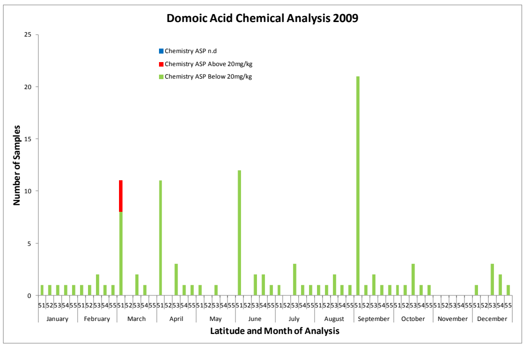


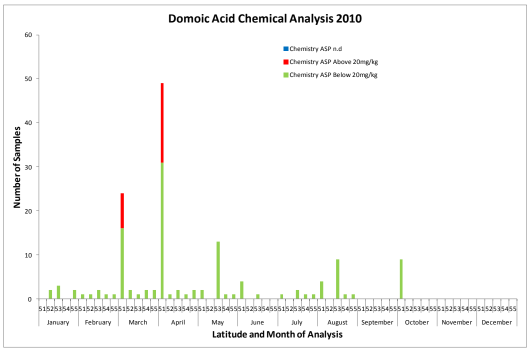


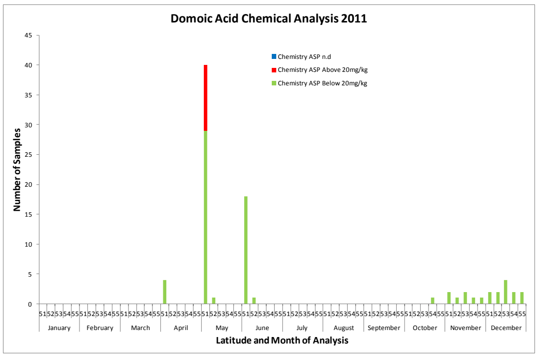


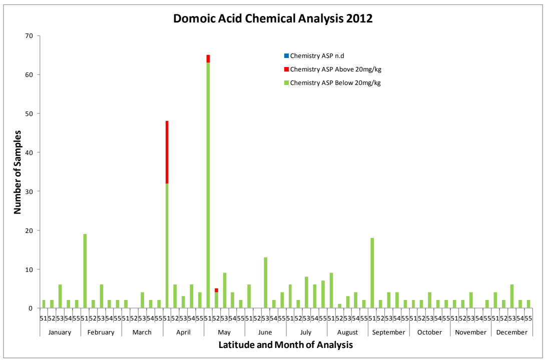












As the marine institute records all phytoplankton in the sample and not only counts of the four targeted species as performed in NI there have been interesting occurrences of species which may be of relevance to future food seafood safety. Different species Prorocentrum spp, Amphidinium sp and Coolia monotis have been recorded off the western coast and have previously been reported as ciguatoxin producers. Ciguatoxins are believed to affect globally 25, 000-500, 000 people annually and the contamination of seafood with this toxin would have severe implications. Currently there is no monitoring program for ciguatoxins and with the removal of the mouse bioassay this toxin may be missed in the lipophilic LC-MS method. A similar issue arises with the detection of Tetrodotoxin. Shellfish are highly susceptible to Vibrio species. Certain types of vibrio species are known to produce tetrodotoxin therefore a rise in water temperature which usually results in higher bacterial growth leading to more disease which may give rise to this toxin. For vibrio species a major vector is phytoplankton and zooplankton. Therefore changes in plankton distribution as a result of climate change may affect the distribution of vibrios around the coast of the IoI and Tetrodotoxin is potentially another marine toxin which could go unchecked.

In addition to the work on marine harmful algal toxins, more epidemiologic evidence is required on the effects of freshwater harmful algal toxins. The IoI has a vast venous network of freshwater rivers and lakes. NI hosts the largest freshwater lough on the island and on the island as a whole there are over 12,000 lakes, many quite small and shallow, mainly in the midlands and west. Currently on the IoI, there is no routine monitoring of freshwater for cyanobacterial toxins but there have albeit limited reports on the occurrence of microcystis blooms with microcystin and anatoxin detection in Irish lakes. Information is also required on the bioconcentration and bioaccumulation factors of these toxins in the ecosystems to determine incidence of human syndromes associated with exposure to toxins through contaminated fish products. In all likelihood these incidences will also increase if HABs occur more frequently and over greater geographic areas due to climate change. Globally, agriculture, and in particular irrigation, is the largest water-use sector, accounting for approximately 70% of all water withdrawn from rivers, lakes and the ground. Water use for agriculture on the IoI is limited to some early crop potatoes and vegetables grown under cover, mainly in the east and southeast. Monitoring of water use for agricultural purposes is important for appropriate water management and for understanding the effects of climate change on food production.There is limited research on the uptake of these freshwater toxins by plants. In fresh water aquaculture, an increased uptake of toxicants and heavy metals through accelerated metabolic rates from increased temperature by cultured, filter feeding molluscs is suggested to be plausible (Ficke *et al.*, 2007), consequently leading to food safety and certification issues.

5.7 Harmful Algal Blooms: future strategies for seafood security

Due to the complex nature of the ecological environment of harmful algal blooms the interaction of climatic variables from all the three domains may have an impact in their occurrence and prevalence. Sea temperature may be one factor that may allow the proliferation of these blooms but it is by no means the only factor playing a role. Nonetheless if sea temperature rises there may be an increase in blooms but the tidal period and currents will also play a role in addition to nutrient loading. If the North Atlantic drift slows and temperature as a whole decreases in the next century the other factors predicted in climate change will also be significant if there is increased storminess, rainfall and flooding. Much of the current environmental protection legislation requires ecosystem approach where the targets for the ecological status or health of the environment are based on the assessment of the current and desired status of the ecosystem. More specifically environmental assessment based on bioindicators that represent different aspects of ecosystem functioning and structure are requested by the European Union (EU) directives (Water Framework Directive, WFD (2000/60/EC); and Marine Strategy Framework Directive, MSFD (2008/56/EC) and also in the regional assessments carried out by the international marine conventions. As such for seafood security both for consumer and industry there should be enhanced monitoring of different factors that are involved in the HAB ecosystem.

The key areas should include:

1. Further investigations into related ecosystem communities and interactions with HABs
2. Continued monitoring of phytoplankton in the marine environment but with enhanced research for molecular detection to identify arrays of species particularly those not identifiable under the microscope whereby remote detection can occur.
3. Continued monitoring of regulated toxins in bivalve molluscs but monitoring should be expanded into other toxins and other seafood based on HAB and toxic species identified.
4. Continued monitoring of climatic conditions from regional locations with a buoy added to the Northern Irish East coast.
5. Continued monitoring of anthropogenic factors in the aquatic environment for HAB effects.
6. Monitoring of freshwater environments for both HAB species and toxins.
7. To examine bioaccumulation of freshwater toxins in plants or animals.
8. Mapping and correlation of factors to build a complex model to determine risk management strategies that can be implemented when conditions prevail.

The apparent increase in the occurrence of HABs and the recognition that changes in climate may be creating a marine environment particularly suited to HAB-forming species of algae underline the need for governments to ensure that existing risk management measures are adequate and are in line with international recommendations.

Current and adaptive strategies to combat climate change should be considered such as regular monitoring of the water quality as an early warning tool and to comply with legislation on food hygiene and safety the cultured product should also be tested for human health risks. However, the erratic and sporadic occurrence of HABs requires for monitoring systems that provide continuous and co-located time series of physical, chemical, and biotic properties with at least daily observations of phytoplankton species and concentration, nutrient and water chemistry profiles (CO_2 and O_2), temperature and salinity profiles, toxins, surface winds, and solar radiation (Wong and Lee, 2007). Nevertheless, if all this information can be connected using predictability modelling to additional data from surveillance of HAB-related contamination in products, and illness in animals and humans the generation of qualitative predictions of climatic conditions to HAB risks to food safety could be performed. Managers could then be forewarned, operate at a heightened level of caution and implement mitigation strategies to respond rapidly if HAB risks are "high to prevent food safety issues

5.8 Predictive modelling

Due to the negative effects on the industry an EU project ASIMUTH (Applied simulations and integrated modelling for the understanding of Toxic and Harmful Algal blooms) developed one such modelling system commenced to investigate the causes further and a number of oceanographic cruises were carried out in the southwest coast. Measured data from these surveys and datasets from the national monitoring programme (phytoplankton and biotoxin chemistry) data, satellite data, meteorological data and in-situ oceanographic data collected aboard research vessels were utilised to design a predictive modelling tool. This project recently won the 2013 COPERNICUS Award for the best earth-monitoring service for European citizens. The pan-European project developed an online alert system (HAB Forecast) to provide an early warning to the aquaculture industry of imminent harmful algal blooms (red tides). The new service gives producers time to adapt their culture and harvesting practices before a bloom arrives in their area, reducing potential losses which can have a devastating impact on aquaculture businesses. This is the first forecast system of its kind and was designed to combine information from monitoring stations, satellite data, biological and physical oceanic models to produce regular forecasting reports to the shellfish industry. Working with neighbouring countries allowed for inter-regional water currents to be modelled to estimate the potential impact of these blooms in advance of their arrival at aquaculture areas.Improved capacity to predict HABs is important for more effective risk management and prediction of HABs depends on modelling exercises as well as an understanding of their ecology.

There is much ongoing research to improve our understanding of the factors that influence population dynamics of harmful algae. Until recently, most research on HABs had been conducted at the local scale. The international dimension is important for understanding and addressing the global impact of climate change on HABs. Micro-algal monitoring coupled with operational oceanographic, meteorological, and remote sensing data, including modelling and other measurements are being used in the prediction of HABs. Traditional approaches, such as microscopic examination and analysis of toxins, resulting in species level of identification are unsuitable to real-time observation; however, new techniques and observational strategies for HABs are emerging and evolving (Medlin *et al*) HAB prediction is complex as it includes conceptual descriptions of ecological relationships and statistically based empirical models as well as numerical models. Predictions depend on observations which provide both input to models as well as data for model validation and error prediction (Barin *et al*. 2005). The effects of climate-related changes increase the complexity of an already complex system.

6 Pathogens across the Food Chain: Local impacts of climate change

6.1 Global climate change predictions

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. 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). As food is an essential requirement for life it is important to understand what impacts these changes in physical processes and other climate variables may have on the stability and security of the local food supply. Biological consequences will be inevitable and will include changes in entire bionetworks. 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 ecosystems. Many systems are in place, particularly in Europe, to safeguard food safety along the food 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 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; RASFF, 2012) and, in the future, as demographics shift the number of people at risk from foodborne illness will increase. In the USA the economic burden of foodborne illness has been estimated to be $14 billion/year (Batz *et al*., 2011) 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 (Sivapalasingam *et al*., 2004). 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.

6.2 Local climate change predictions

Changes to the climate on the IoI are expected to be similar with those being experienced in the global context (Sweeney *et al*., 2008). These changes include warmer, drier summers, winters with heavier rainfalls, and more extreme events such as storms and floods. Regional climate model predictions published by the Environmental Protection Agency (McGrath *et al*., 2002; Sweeney *et al*., 2005; McElwain and Sweeney 2007; 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%. The rainfall in June is expected to decrease by 10% and in December to increase by 10-25%. Regional differences are expected to occur with the greatest temperature increase predicted for the South-east and East of the IoI and an increased likelihood of flooding in the West. It is expected that the more temperate winter conditions currently experienced on the south coast of the IoI will move northwards. With the increasing average temperatures and changes in rainfall patterns an impact on phenology is expected resulting in variation in the growing season and altered agriculture opportunities with changes in yields of some crops such as potato and barley (Holden *et al.*, 2003) or the introduction of new crops such as maize and soybean (Holden and Brereton, 2003). 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. This will influence the availability and quality of water putting pressure on water supply infrastructures and the warmer sea water and effects of coastal erosion may disrupt ecosystems and influence biodiversity. Water resource management will become an issue with increased flooding interlinked with periods of drought. The impacts of gradual changes such as increasing temperature and precipitation are more predictable than the impacts of the more damaging extreme events.

6.3 Potential impacts of climate change on the microbiological quality of food

The sources of foodborne infections can be infected animals, food directly contaminated by human or animal faceal 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; Hamilton *et al.*, 2006; 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). An altered climate will result in the production of food under different environmental conditions and adaptation to and mitigation against climate change will lead to the development of new crops and livestock species specifically developed to survive in different environments and under different climatic conditions (Nichols and Lake, 2012; Lake *et al.*, 2012) resulting in food production in the future being very different. 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.*, 2006) 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 (Easterling *et al.* 2007). 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.*, 2002). In addition, as new technologies such as next generation sequencing, DNA microarray, PCR and mass spectrometry evolve, and isolation and identification techniques improve, new pathogens will be recognised.

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) therefore it is reasonable to assume that in the future patterns of food consumption will be influenced by the changes in temperature and recipitation. Agricultural adaptation to climate change may involve increased use of irrigation water and on a global basis it has been estimated that climate change will lead to a 5–8% increase in crop irrigation requirements (Döll, 2002). Although irrigation on the IoI is currently minimal it may become necessary in the future in some areas.

Using wastewater for irrigation would reduce water extraction but could increase pathogen risks for consumers (WHO, 2006) as highlighted by an outbreak in 2008 of Salmonella serotype Saintpaul which affected 1500 people in the USA, and was thought to be have been caused by irrigation of fresh food with wastewater in Mexico (Jungk *et al.* 2008).

The major energy demanding element of the food chain is refrigeration (Pelletier *et al.*, 2011) as 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 as "temperature misuse", either by cooled storage or heat processing, was considered to be a contributing factor in 32% of foodborne outbreaks in Europe (Tirado and Schmidt, 2001). With the longer, hotter summers predicted for the future the length of time associated with these higher risk behaviours will increase contributing to an overall higher occurrence of disease resulting in the summer foodborne disease outbreaks affecting more people and lasting longer. In the UK it has been predicted that if the mean air temperature rises by 1°C the burden of foodborne disease could increase by as much as 4.5% (DOH/HPA, 2008) with the result that annual food poisoning incidents in England and Wales could increase by almost 200,000 cases by the year 2050 (Bentham and Langford, 1995). When calculated on a pro rata basis using population numbers for the IoI this would equate to an approximately 20,000 increase in food poisoning incidents in the same period.

As approximately 75% of foodborne diseases are zoonotic the effect of climate change on livestock must be considered. With higher ambient temperatures livestock may become stressed (Miraglia *et al.*, 2009), more likely to become ill and therefore possibly discharge larger numbers of pathogens (Keen *et al.*, 2003). 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 which in turn could contribute to the development of antimicrobial resistance (Nicholls *et al.*, 2001; EFSA, 2006). It is expected that climate change will fuel changes in agriculture (Lobell and Gourdji, 2012) with possible crop failures as a result of either drought or extreme rainfall (Hatfield *et al.*, 2011) and dwindling harvests or total loss of production if soil fertility is altered (St.Clair and Lynch, 2010). Climate change has impacted on insect behaviour and survival (Gregory *et al.*, 2009) and the movement of insect populations (Trape *et al.*, 1996; Cannon, 1998; Purse *et al.*, 2005; Greer *et al.*, 2008; Morand *et al.*, 2013) 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.

As trade, regulation, new health threats and consumption patterns change this will lead to an increase in the scientific complexity of food and food prices will rise. Rising food costs driven by climate change may alter food consumption and force unhealthy food choices (Cummins and Macintyre 2006) which may affect the nutritional composition of foods and food safety impacting on health (Royal Society 2009; Lake *et al.*, 2012). 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, new crop and livestock species, altered use of pesticides, fertilizers, irrigation water 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).

Detection and monitoring of changes of foodborne diseases patterns and food production processes is essential to improve food quality and safety. Food safety risks along the food continuum can be managed and curtailed if food safety threats are recognised at an early stage. Integration of foodborne disease surveillance with food monitoring and food animals' statistics along the food chain would represent a source of information which could be used for risk assessment analysis and for the development of risk management strategies. Increased co-operation between animal and human health scientists would facilitate rapid detection of and response to foodborne outbreaks and disease prevention and control programmes. The mission now is to minimise food safety risks to consumers while producing 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), 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).

6.4 Impacts of climate change on foodborne pathogens

Climate can impact on each of the three sectors of the classic epidemiologic triangle, the host, the agent, and the environment, and along the food continuum, from the farm to consumer, there are links most vulnerable to climate change. Evidence of the potential impacts of climate change on foodborne and waterborne diseases include: (i) the fact that patterns of disease change with variations in temperature 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; and (iii) the fact that many foodborne and diarrhoeal diseases are seasonal (Rose *et al.*, 2001; Hall *et al.*, 2002; Koelle *et al.*, 2005(a); Emch *et al.*, 2008). Climate change will have the most impact on pathogens that have low-infective doses, can survive in the environment, and can adapt well to stress factors such as temperature and pH (FAO, 2008), including Campylobacter sp and E. coli. It has been predicted that although individual pathogens will differ in their adaptive response to climate change there will be an overall increase in infectious disease (Costello *et al.*, 2009) with estimations of a global increase of 10% in diarrhoeal disease by 2030 as a direct result of climate change (WHO, 2003).

Bacterial pathogens found in food are ubiquitous and many of them have been found to not only subsist for a long period of time in the environment but also to be able to proliferate (LeJeune *et al.*, 2001; McGee *et al.*, 2002). Pathogens must be able to survive in the environment so they can then spread (FAO, 2008) and meteorological factors such as temperature and humidity influence the growth and survival and therefore circulation of pathogens that cause foodborne diseases (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) as well as the emergence of new pathogens or the number of outbreaks of known pathogens (Harrus and Baneth, 2005). 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 of salmonellosis 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, 2001; D'Souza *et al.*, 2004; Kovats *et al.*, 2004; Fleury *et al.*, 2006). 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 upsurge 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 (Pangloli *et al.*, 2008; Naumova *et al* 2007; Koelle *et al.*, 2005a: Emch *et al.*, 2008). There is evidence for a role of climate variability in the transmission of some pathogens, for example, cholera (Koelle *et al.*, 2005b) with time series analyses indicating a link between outbreaks of cholera in Bangladesh and the El Nino Southern Oscillation (Pascual *et al.* 2000) and Vibrio vulnificus is another foodborne pathogen which is distinctly seasonal and therefore readily influenced by climate (Lipp and Rose, 1997). As higher ambient temperatures 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, 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.*, 2003).

6.5 Current and future concerns for the IoI

A. Campylobacter spp

Campylobacteriosis, caused by Campylobacter sp bacteria, is the most commonly reported foodborne disease in RoI and Europe (Westrell *et al.*, 2009) and its incidence is predicted to increase as temperatures increase as a result of climate change (Allard *et al.*, 2011). There is a vast reservoir of Campylobacter sp. in nature (Kovats and Tirado, 2006); however, the prevalent sources of infections are broiler and fresh poultry meat (EFSA, 2009, 2012) with colonisation of broiler- chicken flocks increasing as ambient temperatures rise. 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) and they are considered to be a seasonal foodborne pathogen but not as strongly linked to temperature fluctuations as other pathogens (Kovats *et al.*, 2005; Fleury *et al.*, 2006; Bi *et al.*, 2008; D'Souza *et al.*, 2004; Louis *et al.*, 2005). 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 in the summer (Hald *et al.*, 2004) and have been proposed as vectors for transmission (Nichols, 2005). In addition fly activity has been found to be closely related to environmental temperatures (Goulson *et al.*, 2005) and they emerge in spring time around the same time as campylobacteriosis cases begin to increase.Future work is needed to elucidate the pathogenesis, survival, stress adaptation and transmission mechanisms of Campylobacter sp. as understanding these biological mechanisms will enable more accurate predictions of the effects of climate change.

B. Non-cholerae vibrios

By 2050, there is expected to be between a 2-4°C increase in seawater temperature in the UK and RoI (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 pathogens, the marine vibrios, which are a genus of thermo dependent bacteria which proliferate in naturally in warm, low salinity sea water. Vibrio vulnificus and V. parahaemolyticus are contaminants that have been associated with seafood consumption (Oliver and Kaper, 2005) 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 strongly influencing the seasonal distribution of Vibrio vulnificus (Lipp and Rose, 1997). In both Europe and the USA although reported incidents of both Vibrio 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) although one of the first European non-cholerae vibrio outbreaks was as a result of consumption of UK caught crabs (Hooper *et al.*, 1974). 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 and virulence 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.

C. 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 food-borne outbreaks and food-borne 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). Contamination of irrigation water may be caused by run-off from animal pastures, the use of raw animal manures (Roever, 1998; Natvig *et al.*, 2002; Santamaria and Toranzos, 2003) and wild animal faeces (Rice *et al.*, 1995; Ackers *et al.*, 1998) from which pathogens can contaminate surface waters or leach through the ground to contaminate ground waters. This will have an important effect on water quality, consequently raising the risk of adulteration events (Curriero *et al.*, 2001; Rose *et al.*, 2001; Kistemann *et al.*, 2002). 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). After harvesting foodborne infection risks can be amplified by (i) washing of the produce in contaminated water (Wachtel and Charkowski, 2002), (ii) spreading of contaminants during processing and transport, or by (iii) operator contamination of the food just prior to consumption (Vojdani *et al.*, 2008). Strategies have been recommended to evaluate the microbiological quality of water used to wash and irrigate produce to lower the risks associated with using water from a range of water resources (Hamilton *et al.*, 2006; Tyrrel *et al.*, 2006). 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. The introduction of standardised subtyping techniques for commonly isolated pathogens with the results deposited in a 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 (Meinhardt *et al.*, 1996) and to contain a mixture of etiological agents. In rural areas private wells are used to tap into the ground water supply so limited numbers of people will be affected during a biological contamination event. As highlighted previously 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;) 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; Schuster *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) impacting on water treatment plants and their ability to handle the deluge (Wilby *et al.*, 2005; Senhorst and Zwolsman, 2005) thereby increasing the risk of waterborne disease outbreak (Thomas *et al.*, 2006). 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 and Tirado, 2006; Curriero *et al.*, 2001; Atherton *et al.*, 1995; Miettinen *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). 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. 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 tested for routinely in clinical laboratories but with the expectancy of more frequent extreme precipitation events and therefore a greater risk of water contamination this practice may also need reviewed.

6.6 Conclusion

We are already beginning to feel the adverse effects of climate change on food safety. 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. The aim is to prevent, detect and control foodborne illnesses but this is challenging because of the complex and continually evolving production and processing developments, the extensive food distribution network involved, the lack of traceability of individual food components, the influence of consumer preferences and activities, and the presence of foodborne hazards. 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 bionetwork and behaviour of foodborne pathogens. Research is required to better understand microbial interactions, pathogen survival, colonisation, attachment, stress adaptation and proliferation of foodborne pathogens in food, crops, livestock and the environment. 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 transmission of pathogens in order to decrease potential risks as heavy rainfalls flooding and overflows are expected to be more frequent. The structure and capability of local water treatment plants will need to be assessed to determine their capability to buffer the effects of climate change and the ability of the aging water infrastructure on the IoI to manage the extra capacity predicted will need evaluated.

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). Information sharing of surveillance data between industry and governmental agencies is essential. Rapid, sensitive and cost effective technologies are required to detect multiple pathogens, to enable differentiation of pathogenic from non-pathogenic organisms, and to 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 nutritional or safety issues that arise. An expanded and co-ordinated surveillance system incorporating animal health, environmental health, public health and food safety would enable a broader view of pathogens across the food chain and help with risk assessment (FAO, 2008). 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 are crucial to this global problem (Tirado *et al.*, 2010) with good agricultural and manufacturing practices, improved traceability and application of hazard analysis and critical control point programs underpinning prevention strategies.

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 food-borne 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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