Food and Agriculture
Organization of the
United Nations

8
FOOD
SAFETY
AND
QUALITY
SERIES

ISSN 2415-1173

CLIMATE CHANGE:
UNPACKING THE BURDEN ON FOOD SAFETY

CLIMATE CHANGE: UNPACKING THE BURDEN ON FOOD SAFETY

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS
ROME, 2020

Required citation:
FAO. 2020. *Climate change: Unpacking the burden on food safety*. Food safety and quality series No. 8. Rome. https://doi.org/10.4060/ca8185en

The designations employed and the presentation of material in this information product do not imply the expression of any opinion whatsoever on the part of the Food and Agriculture Organization of the United Nations (FAO) concerning the legal or development status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. Dashed lines on maps represent approximate border lines for which there may not yet be full agreement. The mention of specific companies or products of manufacturers, whether or not these have been patented, does not imply that these have been endorsed or recommended by FAO in preference to others of a similar nature that are not mentioned.

The views expressed in this information product are those of the author(s) and do not necessarily reflect the views or policies of FAO.

ISSN: 2664-5246 (Online)
ISSN 2415-1173 (Print)

ISBN 978-92-5-132293-2
© FAO, 2020

Some rights reserved. This work is made available under the Creative Commons Attribution-NonCommercial-Share Alike 3.0 IGO licence (CC BY-NC-SA 3.0 IGO; https://creativecommons.org/licenses/by-nc-sa/3.0/igo/legalcode).

Under the terms of this licence, this work may be copied, redistributed and adapted for non-commercial purposes, provided that the work is appropriately cited. In any use of this work, there should be no suggestion that FAO endorses any specific organization, products or services. The use of the FAO logo is not permitted. If the work is adapted, then it must be licensed under the same or equivalent Creative Commons licence. If a translation of this work is created, it must include the following disclaimer along with the required citation: "This translation was not created by the Food and Agriculture Organization of the United Nations (FAO). FAO is not responsible for the content or accuracy of this translation. The original [Language] edition shall be the authoritative edition."

Disputes arising under the licence that cannot be settled amicably will be resolved by mediation and arbitration as described in Article 8 of the licence except as otherwise provided herein. The applicable mediation rules will be the mediation rules of the World Intellectual Property Organization http://www.wipo.int/amc/en/mediation/rules and any arbitration will be conducted in accordance with the Arbitration Rules of the United Nations Commission on International Trade Law (UNCITRAL).

Third-party materials. Users wishing to reuse material from this work that is attributed to a third party, such as tables, figures or images, are responsible for determining whether permission is needed for that reuse and for obtaining permission from the copyright holder. The risk of claims resulting from infringement of any third-party-owned component in the work rests solely with the user.

Sales, rights and licensing. FAO information products are available on the FAO website (www.fao.org/publications) and can be purchased through publications-sales@fao.org. Requests for commercial use should be submitted via: www.fao.org/contact-us/licence-request. Queries regarding rights and licensing should be submitted to: copyright@fao.org.

Cover photos (from left to right):
Flooded marketplace in Cambodia, ©mrmichaelangelo/ Shutterstock.com; algal blooms (red tide) off the coast of Greece, © Gr-Siamidis/ Shutterstock.com; corn damaged by fungal infection, © Budimir Jevtic/ Shutterstock.com

Design and layout: studio Bartoleschi

CONTENTS

CHAPTER 2.E

CHAPTER 2.F

CHAPTER 3

CHAPTER 4

FIGURES

BOXES

© David Doubilet/National Geographic Creative

Diver under a massive mass of Sargassum (seaweed) near Mexico.

© FAO/Petterik Wiggers

© ChameleonsEye/Shutterstock.com

Top: staff from the Ethiopian Ministry of Agriculture spraying insecticides against locusts; bottom: health warning about fishing from water containing toxic algal species (*Alexandrium* sp.) in Australia.

PREFACE

While the impacts of climate change on global food production and food security are well known, the effects of climate change on food safety are much less so. Since, the relationship between climate change and food safety hazards is not always easy to see, this publication, *Climate change: Unpacking the burden on food safety*, attempts to provide some clarity. Changes in global food systems and the increased globalization of the food supply means that populations worldwide are at risk of exposure to various food safety hazards. This can affect public health, food security, national economies and international trade. In this already complicated scenario, the challenges posed by climate change have additional implications that need to be understood and addressed. This publication is aimed at a broad audience and it is hoped that everyone who reads this comes away with a realization of the complexity of the issues at stake and an appreciation of the work that lay in front of us.

ACKNOWLEDGEMENTS

The research and drafting of the publication was carried out by Keya Mukherjee (Food Safety and Quality Unit, FAO), under the technical leadership and guidance of Vittorio Fattori (Food Safety and Quality Officer, FAO).

The support and guidance of Markus Lipp, Head of the Food Safety and Quality unit, FAO, are gratefully recognized.

Various FAO staff provided technical inputs and insights during the entire process of the publication's development, in particular: Alice Green (Food Safety and Quality Unit), Eva Kohlschmid (Plant Production and Protection Division) and Elizabeth Laval (Climate and Environment Division).

FAO is grateful to the following experts, Angelo Maggiore (European Food Safety Authority), David Miller (Carleton University, Canada) and Marie-Yasmine Dechraoui Bottein (Intergovernmental Oceanographic Commission of UNESCO) for generously taking the time to provide insightful comments and recommendations.

Gratitude also goes to the publications unit at FAO, Dirk Schulz (Food Safety and Quality Unit) who facilitated the publication process as well as Jane Shaw (editor) and Bartoleschi studio (graphics designer) whose dedicated contributions made the final publication possible. We would also like to thank Mia Rowan (Food Safety and Quality Unit) for her help in refining the document.

Finally, special thanks goes out to Renata Clarke (erstwhile Head of the Food Safety and Quality unit, FAO) who was instrumental in drawing attention to this topic and published a pioneering FAO document to highlight the issues, 'Climate Change: Implications for Food Safety' (2008). She also, initiated the development of this publication.

ABBREVIATIONS AND ACRONYMS

AMR	antimicrobial resistance
AMU	antimicrobial use
As	arsenic
AU	African Union
Cd	cadmium
CDC	Centers for Disease Control and Prevention
CP	ciguatera poisoning
Co	cobalt
CO_2	carbon dioxide
COP	Conference of the Parties
CPR	Continuous Plankton Recorder
Cr	chromium
Cu	copper
DALY	disability-adjusted life year
EFSA	European Food Safety Authority
ENSO	El Niño Southern Oscillation
EU	European Union
Fe	iron
FERG	Foodborne Disease Burden Epidemiology Reference Group (WHO-based)
Gg	gigagram
GHG	greenhouse gas
HAB	harmful algal bloom
HACCP	hazard analysis and critical control points
Hg	mercury
INFOSAN	International Food Safety Authorities Network
IPCC	Intergovernmental Panel on Climate Change
IPM	integrated pest management
JECFA	Joint FAO/WHO Expert Committee on Food Additives
KJWA	Koronivia Joint Work on Agriculture
L	litre

LMIC	low- and middle-income countries
MeHg	methylmercury
Mg	magnesium
Mn	manganese
NCD	non-communicable disease
NDCs	nationally determined contributions
Ni	nickel
$nTiO_2$	nanoparticles of titanium dioxide
OECD	Organisation for Economic Co-operation and Development
Pb	lead
PSP	paralytic shellfish poisoning
RASFF	Rapid Alert System for Food and Feed
SDG	Sustainable Development Goal
Se	selenium
TDI	tolerable daily intake
UN	United Nations
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
WHO	World Health Organization
WTO	World Trade Organization
Zn	zinc

EXECUTIVE SUMMARY

"Right now, we are facing a man-made disaster of global scale. Our greatest threat in thousands of years. Climate change."

Sir David Attenborough
at the UN Climate Change Conference COP24,
Katowice Poland.

Indeed, climate change is a complex challenge that poses a major threat to our planet and life, as we know it. Over time, many scientific uncertainties about climate change - its causes and global implications -have been addressed and the evidence continues to mount. Today, we know that increasing temperatures, ocean warming and acidification, severe droughts and wildfires, untimely heavy precipitation and acid rain, melting glaciers and rising sea levels and amplification of extreme weather events are causing unprecedented damage to our food systems. Even a single environmental driver like rising temperatures can have varying degrees of effect across multiple food safety hazards, simultaneously, around the world, with subsequent impacts on public health and international trade. While the global impact is difficult to quantify, an attempt to capture some of the effects of climate change on select food safety hazards is made in this publication. The food safety hazards considered are foodborne pathogens and parasites, harmful algal blooms, pesticides, mycotoxins and heavy metals with emphasis on methylmercury.

A general introduction to the implications of climate change on the planetary ecosystem and by extension on the global food systems and food safety is provided in the first chapter. The second chapter is divided into sub-chapters with each one dedicated to a distinct food safety hazard and provides a unique perspective of how climate change affects it. When taken together, the sub-chapters provide a broad spectrum of the multitude of food safety issues that are impacted by climate change globally. Moreover, it is also important to acknowledge that the different food safety hazards that occupy the same 'physical space' also interact with each other. These relationships themselves are affected by climactic factors. An appreciation of the complicated interlinkages within the food safety sphere is important in order to fully understand the scope of the impact that climate change has on food systems and ultimately on us through our diet. However, this goes beyond the scope of the current publication, which examines the complex relationships that different environmental factors associated with climate change have on various food safety hazards.

Changes in temperature, precipitation and other environmental factors are expected to affect the geographic distribution and persistence of foodborne pathogens and parasites. For instance, there is evidence to link increasing temperatures to higher incidences of infections by several foodborne pathogens like *Salmonella* spp. and *Campylobacter* spp. in different parts of the world. Climate change is increasing the frequency and severity of extreme weather events like hurricanes, which result in flooding leading to increased likelihood of outbreaks of waterborne diseases like cholera. Prolonged droughts, on the other hand, can put stress on the availability and usage of water in a given area, affecting businesses like food processing plants where food safety may be compromised to compensate for the lack of sufficient water. Additionally, various food- and waterborne pathogens are becoming resistant to antimicrobials and recent evidence points to a potential association of rising temperatures with increased rates of antimicrobial resistance.

Climate change is also affecting the quality of water globally by exacerbating conditions that lead to algal blooms, which are worsening along coastlines and in lakes. An overabundance of fertilizer application combined with more frequent and intense precipitation are among the factors leading to increased eutrophication in waterbodies and algal blooms. The frequency and duration of certain endemic harmful algal blooms have increased globally. Moreover, there is evidence to show that climate change is enabling various species that form harmful algal blooms to expand to new areas, most of which are not prepared to meet the challenges associated with their detection and surveillance, thereby putting public health at risk. Algal blooms lead to 'dead' zones or hypoxic areas that cannot support marine life, resulting in severe ramifications to the ecosystem in the area and massive economic losses to coastal communities. Increasing incidences of algal blooms in combination with climate change are expected to drive further expansion of these 'dead' zones in the oceans.

On land, rising soil temperatures are expected to facilitate the uptake of heavy metals by plants for instance, arsenic in rice, a staple crop known to accumulate heavy metals in the plant as well as the grain. Heavy precipitation events, especially in mining areas, can release various heavy metals in to the surrounding areas, compromising food and water quality. A combination of acid rain and fertilizer-induced soil acidification are affecting the bioavailability and mobilization of heavy metals. Accelerated permafrost thawing may release large, historically trapped inventories of heavy metals like mercury into our fresh-water systems. This mercury gets methylated in aquatic systems and the process is affected by a number of different environmental factors that are influenced by climate change. Bioaccumulation of methylmercury in the aquatic food chain is a major concern under climate change conditions.

Climate change is altering the geographic distribution and life cycles of pests, which in turn are expected to change pesticide application trends. This could complicate issues related to pesticide usage like soil degradation, water quality deterioration and biodiversity reduction. Elevated temperatures lead to volatilization of pesticides reducing their efficacy. This phenomenon, combined with the increased growth of pests, is likely to prompt greater pesticide use to maintain agricultural productivity. The volatilization of persistent pesticides has led to the deposition of these chemicals in remote areas like the Arctic where thawing permafrost is releasing them back into the environment and, ultimately into our food chain.

Mycotoxin contamination in staple crops is a major health concern and barrier to international trade. Some of the important factors that influence mycotoxin production – temperature, relative humidity and crop damage by pests - are affected by climate change. As warmer temperatures make cooler temperate zones conducive to agriculture, they could open up new habitats for pests and fungal species. There are already reports of the emergence of mycotoxins in areas with no history of prior contamination. A number of these regions lack the capacity for outbreak management making it difficult to curtail damage to the local economies and public health. Inadequate storage and transportation facilities under climate change conditions are also bound to affect mycotoxin production and dissemination.

After delving into ways climate change is affecting our food systems, the third chapter describes some aspects of the future of food and the related food safety concerns. As our world and food systems adapt to climate change, food safety authorities everywhere must be cognizant of the issues on the horizon to prepare for upcoming challenges. Intelligence gathering and foresight are useful tools that can be used to adopt a preventive perspective to food safety as opposed to a reactionary and responsive approach. Alongside surveillance techniques, these tools will help countries to avert hazards and keep food safe. The fourth and concluding chapter emphasizes the importance of investing in capacity development in the food safety arena, especially in the developing countries that are grappling with the burden of climate change. With climate change shifting the food safety landscape, the need for stronger and transparent collaborations among all the relevant actors in the food chain is stressed and some potential benefits in adopting forward-looking approaches in the food safety sphere are explored.

Top: fire retardant dropped to control largescale wildfires; bottom: macroalgal blooms off the coast of China.

CHAPTER 1

INTRODUCTION

Climate change is the defining issue of our time. Not only is it an environmental and ecological concern affecting all natural systems, but it also has important implications for the global development agenda. Elevated temperatures, land and water scarcity, precipitation variability and extreme weather conditions have adverse impacts on agricultural production and destroy food systems. Population groups who are already vulnerable to food insecurity and malnutrition risk sinking lower into food and nutrition crisis under climate change. The aim of the United Nations Conference on Environment and Development (the Earth Summit) held in 1992 in Rio de Janeiro, Brazil was to address these issues and facilitate coordinated international efforts to deliver solutions for mitigating the effects of climate change. The Earth Summit saw countries commit to pursuing economic development while bearing in mind the risks of using finite environmental resources. One of the main documents signed at the summit was the significant multilateral treaty of the United Nations Framework Convention on Climate Change (UNFCCC), which urges nations to reduce their greenhouse gas (GHG) emissions. The UNFCCC, which came into force in 1994, has near-universal membership worldwide with member nations coming together annually for the Conference of the Parties (COP). Some key achievements of the UNFCCC and its various activities are presented in the 2018 document, *UN Climate Change Annual Report* (UNFCCC, 2018). The historic Paris Agreement (COP21) of 2016 sets out the global framework for strengthening international response to climate change. A core element of the implementation of the Paris Agreement is the establishment of national climate action plans or nationally determined contributions (NDCs), which are required of all parties. At the 2019 United Nations (UN) Climate Action Summit, a number of countries pledged more concrete and far-reaching actions in tune with their commitments to the Paris Agreement, a boost to momentum spurred by recognition of the urgency of climate change. Other results of the 2019 summit were a renewal of financial commitments (through the Green Climate Fund, **Box 1**) and the initiation of additional commitments in sectors such as clean energy (through the Climate Investment Platform). The Koronivia Joint Work on Agriculture (KJWA) taken at COP23 in 2017 is a landmark decision that includes agriculture and food systems in UNFCCC processes. FAO plays an important role in supporting member nations in their implementation of the KJWA.

BOX 1

CLIMATE CHANGE – FINANCIAL REPERCUSSIONS AND COMMITMENTS

Climate change is increasing global economic inequality between high- and low or middle-income countries. This is because developing countries not only experience more climate change-related incidents but also lack the resources needed to cope with the aftermath of crises (Diffenbaugh and Burke, 2019). The UN system has been at the forefront of helping climate-vulnerable nations with numerous climate change adaptation and mitigation projects. According to the UNFCCC, USD 681 billion was spent on various climate change adaptation and resilience building activities in 2016. The flagship UN Green Climate Fund was established in 2010 following the 2009 United Nations Climate Change Conference held in Copenhagen (the Copenhagen Summit) and has provided financial assistance to countries facing grave consequences of climate change. A record USD 9.8 billion has recently been pledged by developed nations to replenish the fund. Not only will timely climate adaptation promote resilience in the natural resources base but it also has economic benefits. In 2019, research by the Global Commission on Adaptation (to climate change) found that global investments of USD 1.8 trillion over the decade of 2020–2030 in the five core areas of early warning systems, climate-resilient infrastructure, global mangrove protection, more resilient water resources and improved dryland agricultural crop production will lead to an estimated USD 7 trillion in net benefits resulting from timely climate adaptation. When prioritizing climate-related projects, investors of climate finance must adopt a holistic approach to funding and keep in mind the carbon-value of every dollar spent. The prioritization of investments in climate-related projects must be aligned with the needs of climate-vulnerable countries and low-income nations. It has been estimated that the agriculture sector bears a fourth of the total economic impact of extreme events related to climate change (FAO, 2015). Far greater investments in the agriculture, forestry and land-management sectors are needed (Yeo, 2019).

In addition, although it is widely accepted that developing countries with very low carbon footprints bear the brunt of climate change, Ricke and co-authors (2018) found that the international distribution of the country-level social cost of carbon was uneven. The countries that are the largest carbon emitters also stand to accrue high domestic economic damage associated with the effects. This shows that both high and low carbon emitters can gain from reductions in carbon emissions, albeit in different ways. Climate change is a global issue that requires global responsibility and stronger commitment to climate policies and projects is needed from all countries.

FAO is committed to achieving food security for all by making agriculture, forestry and fisheries more productive, sustainable and resilient in the face of climate change. While climate change has an impact on agriculture and food security, agriculture sectors also contribute to climate change with almost a quarter of total GHG emissions (IPCC, 2019). Cognizant of this unprecedented dual challenge, FAO has been taking steps to work towards climate change adaptation and mitigation (**Box 2**). Climate change also jeopardizes FAO's vision of ending hunger and eradicating poverty, which lies at the heart of the 2030 Agenda for Sustainable Development and its goals. Some of these challenges are highlighted in *The State of Food Security and Nutrition in the World 2018: Building climate resilience for food security and nutrition* and *The State of Food and Agriculture 2016: Climate change, agriculture and food security* (FAO, 2018; 2016). However, achieving food security is not possible without paying due attention to food safety (Section III), which is a complex issue that stretches from pre-production through to the consumption of food. As the world faces a dynamic shift towards sustainable agricultural production practices and changing food systems in the face of climate change, consideration to food safety is imperative in ensuring that sufficient nutritious and safe food is available throughout the food chain. FAO was one of the first UN agencies to recognize that climate change will have significant impacts on the food safety landscape and will pose substantial challenges to sustainability and development. In 2008, FAO published a pioneering document on this topic entitled *Climate change: Implications for food safety*, which provided a broad overview of the associations between climate change-induced environmental factors and specific food safety issues that include algal blooms, methylmercury, mycotoxins and foodborne pathogens. The document also emphasized the need for policy-makers and other relevant actors in the global food system to prepare for emerging food safety risks caused by climate change, and the importance of close collaboration and development of timely innovative adaptive strategies.

BOX 2

FAO AND CLIMATE CHANGE

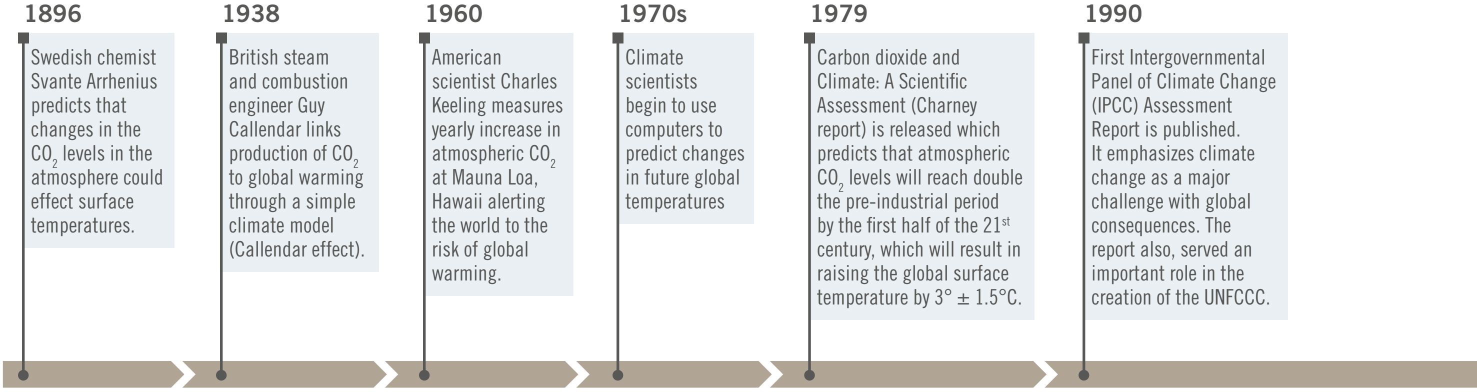
Climate change was adopted as a cross-cutting theme throughout the FAO Strategic Framework in 2015. This means that each strategic programme (at the regional or country level) includes climate change implications and adaptations. The first corporate FAO Strategy on Climate Change (FAO, 2017) aims to support Member Nations in achieving their commitments to addressing climate change under the Paris Agreement by translating FAO's core mandate into strategic choices and priorities for the global, regional, national and local levels. Through participation in numerous global programmes, FAO plays a major role in enabling the agriculture, forestry and fishery sectors to adopt progressive steps towards more climate-friendly practices. Above all, FAO continues to serve as a knowledge provider and strives to contribute evidence-based information on climate change adaptation and mitigation in food and agriculture systems tailored to country contexts. The flagship publication of 2016, *The State of Food and Agriculture 2016: Climate change, agriculture and food security* (FAO, 2016), identified strategies, information and financing opportunities that countries need in order to transform their food and agriculture sectors to make them more prepared for the impacts of climate change.

SECTION I: OBJECTIVES AND SCOPE OF THE DOCUMENT

Scientific evidence supporting the causes (**Figure 1**) and impacts of climate change is growing. While the effects of climate change on food security are well documented, numerous gaps remain in the global understanding of how climate change can affect various food safety hazards. The objective of this document is to address these gaps by elucidating selected food safety hazards and attempting to quantify some of the current and anticipated food safety issues that are associated with various climate change drivers. The publication also aims to bolster attention to some of the food safety risks described in *Climate change: Implications for food safety* (2008) as scientific research has generated better understanding of the challenges over the years since its publication. While science supporting the impacts of climate change on food safety continues to evolve, the present document captures and presents information that is deemed to provide the best available evidence of the main impacts on food safety issues. This publication does not cover all of the possible food safety implications resulting from climate change, but attempts to describe and quantify some of the major ones.

The intended audience is broad and includes all the relevant actors in the food safety arena, from policy-makers to the general public. It is hoped that the document will disseminate tangible information that ultimately – in the wake of climate change – can

FIGURE 1. **SOME MAJOR MILESTONES IN CLIMATE CHANGE SCIENCE – WITH EMPHASIS ON THE DISCOVERY OF THE CONTRIBUTION OF CO_2 TO GLOBAL WARMING. SOME KEY UN AGREEMENTS ARE ALSO SHOWN.**



1896 Swedish chemist Svante Arrhenius predicts that changes in the CO_2 levels in the atmosphere could effect surface temperatures.

1938 British steam and combustion engineer Guy Callendar links production of CO_2 to global warming through a simple climate model (Callendar effect).

1960 American scientist Charles Keeling measures yearly increase in atmospheric CO_2 at Mauna Loa, Hawaii alerting the world to the risk of global warming.

1970s Climate scientists begin to use computers to predict changes in future global temperatures

1979 Carbon dioxide and Climate: A Scientific Assessment (Charney report) is released which predicts that atmospheric CO_2 levels will reach double the pre-industrial period by the first half of the 21st century, which will result in raising the global surface temperature by 3° ± 1.5°C.

1990 First Intergovernmental Panel of Climate Change (IPCC) Assessment Report is published. It emphasizes climate change as a major challenge with global consequences. The report also, served an important role in the creation of the UNFCCC.

assist in the formulation and advancement of food system policies in multiple sectors by fostering closer collaboration among policy-makers, risk assessors, risk managers and researchers. The document also aims to highlight knowledge gaps in the current understanding of how climate change affects the various facets of food safety and it is hoped that this will encourage researchers to come forward and help build a complete picture of this mammoth issue. Additionally, it is hoped that the document will serve to educate the general public of their enormous responsibility as consumers and of how climate change can fundamentally affect the quality of their lives and their future.

The publication is based on a thorough literature review compiled by searching for information on both the expected and the existing impacts of climate change on food safety. Data were collected from scientific articles, book chapters, media reports and publications from various UN organizations, particularly FAO, the World Health Organization (WHO) and the United Nations Environment Programme (UNEP). The search for relevant scientific articles covered the electronic database sources Google Scholar, Web of Science and PubMed and included only pertinent articles written in English and published between January 2010 and February 2020. Articles with earlier publication dates are used mainly to provide a historical perspective on a specific issue. Experts from different disciplines were consulted during the drafting process.

1994
The United Nations Framework Convention on Climate Change (UNFCCC) comes into force.

1997
Kyoto Protocol, the world's first greenhouse gas emissions reduction treaty, is adopted.

2007
IPCC publishes the Assessment Report 4 (AR4), which articulated that human beings were responsible for the observed climate change.

2008
FAO publishes Climate change: Implications for food safety

2015
Historical Paris Climate Change Agreement is adopted. 195 countries pledge action to fight climate change.

2018
IPCC publishes the Global Warming of 1.5°C which explains the consequences of not limiting temperature increase to 1.5°C above pre-industrial levels.

2018
Countries adopt the Katowice Climate Package which promotes greater international cooperation to implement the Paris Climate Change Agreement.

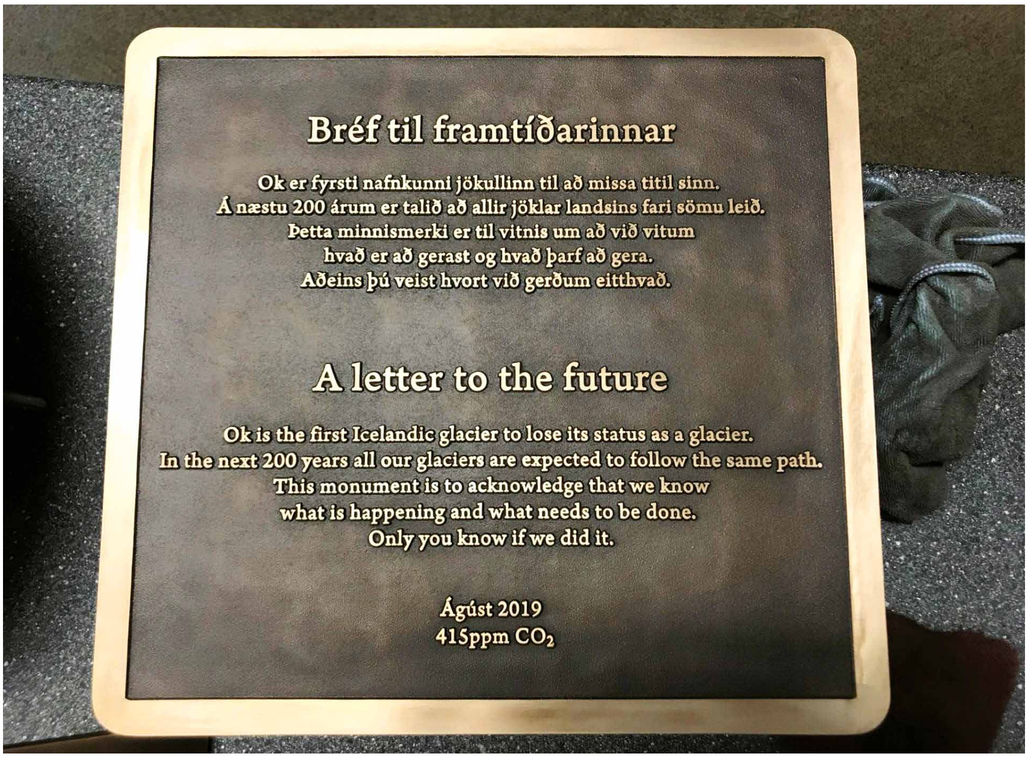
2019
UN Climate Action Summit 2019 focuses the attention of world leaders (from governments, private sectors and civil society) on the greater urgency to tackle climate change.

SECTION II: CLIMATE CHANGE – CURRENT STATUS AND FUTURE RISKS

The planet is warming at an unprecedented rate owing to human-induced activities (Neukom *et al.*, 2019a; 2019b). The consequences of failing to prevent warming of more than 1.5 °C above pre-industrial conditions have been elucidated by the Intergovernmental Panel on Climate Change (IPCC, 2018). Global atmospheric CO_2 concentration was found to be about 400 parts per million (ppm) in 2017 – a level that was last reached 3 million years ago – owing to anthropogenic causes, and it is estimated that it will exceed 900 ppm by 2100 under a "business-as-usual" scenario (Brigham-Grette *et al.*, 2013; Le Quéré *et al.*, 2016; Sosdian *et al.*, 2018). These environmental drivers of climate change are threatening the global food systems that cater for all living beings on the planet. It has been estimated that a 2 °C rise in temperatures will add 189 million more people to the 800 million already suffering from food shortages. In fact, climate change is expected to have impacts on all four pillars of food security – food availability, access to food, food utilization and stability of the food supply (Schmidhuber and Tubiello, 2007; Vermeulen, Campbell and Ingram, 2012). While global agricultural production has to increase to meet the demands of the growing population, various climate factors are predicted to cause a decrease in global crop productivity over the coming decades, thereby increasing poverty and driving food insecurity (FAO, 2016). Intensification of agriculture has heightened reliance on the use of antimicrobials (**Chapter 2.A**), fertilizers (**Chapter 2.B**) and pesticides (**Chapter 2.E**). Unless agrochemicals are used prudently, environmental degradation will intensify, especially under climate change conditions. Moreover, climate change is affecting the ability of ecosystems to recover. Research shows that certain soil microbes may be losing their capacity to adapt to climate change conditions (Bond-Lamberty *et al.*, 2016; Cavicchioli *et al.*, 2019). This and many other climate change stressors that contribute to land degradation raise questions about what food production systems will look like in the future (IPCC, 2019). In addition, the vital ecosystem services that nature provides are declining globally and this loss will be felt acutely in developing countries where populations live close to nature and have no substitutes for what it provides. For instance, millions of people do not have access to freshwater other than from water systems that are polluted, and this is likely to lead to more waterborne diseases (**Chapter 2.A**) (Chaplin-Kramer *et al.*, 2019).

Absorption of atmospheric CO_2 by the oceans is causing ocean acidification, which has major ramifications for marine ecosystems, coastal communities and the millions of people who depend on seafood for sustenance (Caldeira and Wickett, 2003; Sosdian *et al.*, 2018). Oceans that are warmer and acidic have lower capacity to absorb and store oxygen. Hypoxia is made worse by the growing algal blooms issue (**Chapter 2.B**) that have anthropogenic causes and are exacerbated by climate change conditions. It has been estimated that globally, open oceans have lost 77 billion tonnes (2 percent) of their dissolved oxygen inventory over the past 50 years, which has serious consequences for the survival of marine life (Breitburg *et al.*, 2018; Schmidtko, Stramma and Visbeck, 2017). Hypoxia and other climate factors will affect the current and future distribution of marine species as they jostle for space in reducing habitats, as can be seen, for example, in the migration of krill – a keystone prey species – towards the Antarctic (Atkinson *et al.*, 2019). Not only will such events cause an ecological catastrophe and the rearrangement of food chains but the resulting species adaptation and dispersal are also bound to affect biodiversity maintenance (Park *et al.*, 2019; Thompson and Fronhofer, 2019). These conditions will have heavy effects on commercial fisheries, which will need to adapt to climate fluctuations. A marine heat wave (the "Blob"), which occurred from 2013 to 2015, resulted in a decrease of 70 percent in Pacific cod numbers off southern Alaska, with severe effects on the local fishing industry, which is worth USD 100 million annually (Cornwall, 2019). The disappearance of other high-value fish such as the Atlantic cod from their current habitats has been predicted (McHenry *et al.*, 2019). Ocean acidification also affects the toxicity of aquatic contaminants such as methylmercury (**Chapter 2.D**), which bioaccumulates in the food chain. Rising sea temperatures are causing mass coral bleaching events and kelp forest die-offs in global oceans, creating a risk of the collapse of marine food chains (Mooney, 2016). The large-scale bleaching events that have affected vast expanses of coral reefs globally was identified as one of the nine potential "tipping points" of climate change a decade ago (Lenton *et al.*, 2019). Although the number of new coral formations is very low in areas like the Australian reef system, there are preliminary reports of recovery of certain coral species, such as *Cladocora caespitosa* in the Mediterranean Sea (Hughes *et al.*, 2019; Kersting and Linares, 2019). However, such acclimatization processes cannot be taken for granted (Comeau *et al.*, 2019). In addition, these events also have food safety implications as bleaching and destruction (for instance, through dredging) of coral reefs have been associated with increased outbreaks of ciguatera, a potent algal toxin found in seafood (Dickey and Plakas, 2010) (**Chapter 2.B**).

Rising temperatures and CO_2 levels are thawing glaciers. Data from 19 000 glaciers worldwide show that an estimated 9 000 billion tonnes of ice was lost between 1961 and 2016, and losses have accelerated over the last 30 years (Zemp *et al.*, 2019). Melting glaciers, warming oceans, increased unseasonal precipitation with lack of sufficient snowfall are leading to rise in sea levels and increased risks of flooding (Davenport *et al.*, 2019; Veng and Andersen, 2020). These are expected to have impacts on downstream agricultural fields and coastal communities, and in the future will have serious effects on infrastructure such as water treatment plants (**Chapter 2.A**) and nuclear reactors (**Chapter 2.C**), which will need to be made climate-ready (Hummel, Berry and Stacey, 2018; Robel, Seroussi and Roe, 2019). Certain small island nations, including Tuvalu and the Marshall Islands, are already sinking because of rising sea levels and coastal erosion (Nurse *et al.*, 2014). Indonesia is planning to move its sinking capital city, Jakarta, to Borneo, at a cost of USD 33 billion (Paddock and Suhartoo, 2019). Recent models predict that at least 300 million people globally will be at risk from rising sea levels by 2050 (Kulp and Strauss, 2019). According to new estimates, GHG emissions from the past will continue to contribute to rises in sea levels long after the carbon emission pledges of the Paris Climate Agreement have been met (Nauels *et al.*, 2019). Shrinking glacier cover and rising sea levels also increase the risks of more volcanic eruptions, earthquakes and more devastating tsunamis, the human cost of which cannot yet be calculated (Li *et al.*, 2018; Masih, 2018; Swindles *et al.*, 2017). In addition, the melting of permafrost and sea-ice is releasing once-buried chemicals including pesticides (**Chapter 2.E**), heavy metals such as mercury (**Chapter 2.D**), dormant ancient strains of harmful bacteria and viruses (**Chapter 2.A**), and microplastics (**Chapter 3**) into the environment. Large quantities of CO_2 and



Bréf til framtíðarinnar

Ok er fyrsti nafnkunni jökullinn til að missa titil sinn.
Á næstu 200 árum er talið að allir jöklar landsins fari sömu leið.
Þetta minnismerki er til vitnis um að við vitum
hvað er að gerast og hvað þarf að gera.
Aðeins þú veist hvort við gerðum eitthvað.

A letter to the future

Ok is the first Icelandic glacier to lose its status as a glacier.
In the next 200 years all our glaciers are expected to follow the same path.
This monument is to acknowledge that we know
what is happening and what needs to be done.
Only you know if we did it.

Ágúst 2019
415ppm CO_2

Words by Andri Snær Magnason. Photo by Grétar Thorvaldsson/Málmsteypan Hella

The memorial plaque for Iceland's Okjökull glacier was made possible by the efforts of researchers from Rice University, Texas, USA

methane are also being released, which is adding to the climate change crisis (Gray, 2018; Luhn, 2019; Natali *et al.*, 2019; Obbard *et al.*, 2014; Smedley, 2019).

Climate change is expected to increase the frequency of extreme El Niño events and to amplify extreme weather events by several orders of magnitude, as evidenced by the record number of wildfires in the Arctic, the extreme heatwave in France, the unprecedented two back-to-back cyclones (Kenneth and Idai) that hit Mozambique and many others in 2019 alone (Wang *et al.*, 2019). Attribution science now makes it possible to account for the role of human-induced climate change in such extreme events and weather agencies are showing an interest in providing such information directly to the public (Schiermeier, 2018; Reed *et al.*, 2020). Extreme events alter the "carrying capacities" of ecosystems and push the coping abilities of communities to the limit. Extreme weather and conflicts are increasingly displacing populations into areas with reduced capacities to manage food safety risks. Globally, a record 7 million people were internally displaced within the first six months of 2019 as a result of extreme weather events (IDMC, 2019). Climate change-induced urban migration is altering food production systems in many countries, whether they are land-locked like Mongolia or close to the sea like Bangladesh. Harsh winters followed by lack of adequate rainfall in the summer are leading to the drying up of Mongolia's major water systems, which is severely affecting the livelihoods of herders on the steppe and driving thousands of people into the capital city of Ulaanbaatar (Denyer, 2018). On the other hand, rising sea levels and worsening seasonal floods in Bangladesh are having a serious impact on rice farmers, who are grappling with the issues of waterlogging and salt-water intrusion, which affect the productivity of the agricultural lands on which they depend for sustenance (Park, 2019). Migration of food producers into cities not only puts future food security at risk but also places pressure on resources needed to provide for a growing urban population, and increases food safety risks such as foodborne and waterborne diseases (**Chapter 2.A**). With the aim of putting future climate conditions in cities into perspective, Bastin and co-authors (2019) studied the climate patterns of 520 major cities globally and projected what these cities will be like in 2050 based on current city climate analogues. For instance, Madrid's climate in 2050 will be closer to the current climate in Marrakech, the city analogue of London is Barcelona and climates in a number of tropical and sub-tropical cities will have shifted into conditions for which there are no current climate analogues (Bastin *et al.*, 2019). This brings into sharp focus the unique challenges for which major cities must prepare to sustainably manage food, water resources, health care and infrastructure, urban planning and agriculture (**Chapter 3**), and adaptation for the future (Aragon *et al.*, 2019).

Apart from potential direct consequences (Ahima, 2020), climate change can affect human health by influencing the severity and frequency of diseases that are currently present and by creating conditions under which unanticipated health concerns arise in regions where they have not occurred before. The effects of climate change on the availability, accessibility and stability of food supplies can cause major modifications in people's diet choices, which in turn have repercussions on the health of households. According to scientific findings, climate change is expected to alter global micronutrient availability heterogeneously, thereby having repercussions on malnutrition (Nelson *et al.*, 2018). Rising CO_2 levels are expected to lower the levels of macronutrients (proteins), the micronutrients iron, zinc and vitamins B1, B2, B5 and B9 in staple foods and docosahexaenoic acid content of fish, pushing millions of people into malnutrition in the coming decades (Colombo *et al.*, 2019; Dunne, 2018; Ebi and Loladze, 2019; Smith and Myers, 2018; 2019). Future solutions to food insecurity will need to involve a shift in focus from the requirements for adequate calories from staple foods to the provision of a more diverse diet that emphasizes micronutrients (Nelson *et al.*, 2018). Food safety and nutrition are closely related. In food-insecure areas, food is often consumed with little or no regard for its safety and nutritional value. Malnutrition and reduced immunity increase susceptibility to various foodborne pathogens and toxins, leading to a worsening of the burden of foodborne diseases. While poor nutrition is associated with the increasing trend in non-communicable diseases (NCDs), ongoing scientific efforts are investigating the potential links between food safety hazards and NCDs (Velmurugan *et al.*, 2017).

With one climate change-related incident (ranging from small-scale to devastating) occurring every week, it is no longer a problem of the future but one that needs to be addressed today (Solly, 2019). Embracing scientific innovations is one way of mitigating the effects of climate change on food production systems. Investment in water utilization and retention technologies, production of crops that are resistant to stress conditions (floods, drought or infections such as bacterial blight) and those that can tolerate the density required for higher productivity, increasing food traceability aimed at preventing food loss due to contamination issues, prediction of extreme events and the development of early warning systems, more research on novel food production systems (**Chapter 3**) and many others are needed (Dhaliwal and Williams, 2019; Fabregas *et al.*, 2018; Lee *et al.*, 2019; Nkurunziza *et al.*, 2019; Oliva *et al.*, 2019; Reynoso *et al.*, 2019; Wu *et al.*, 2019; Zhou *et al.*, 2019).

It is also immensely important to maintain the current momentum of climate change awareness. Although there is scientific consensus on the causes of climate change, more needs to be done to disseminate the “best available science” to everyone, ranging from policy-makers to the wider public in order to promote civic engagement and public participation in tackling the various challenges that come with climate change (Petersen, Vincent and Westerling, 2019). Research on climate change and its impacts should be communicated in ways that foster wide acceptance of the findings (Cook *et al.*, 2016; Howe *et al.*, 2019). This publication aims to provide some perspectives on how climate change will affect food safety in communities worldwide, with the ultimate objectives of fostering greater public understanding of the issues and facilitating far-reaching solutions through stronger collaborative efforts among all relevant actors in food production systems. After all, food safety is everyone’s business.

SECTION III: INTERLINKAGES BETWEEN FOOD SECURITY AND FOOD SAFETY

At the World Food Summit of 1996, food security was defined as the condition when, “all people, at all times have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life” (FAO, 1996). Safe food is therefore a key dimension of food security. Although this publication focuses on the impact of climate change on food safety, it is also useful to view the broader context of climate change impacts on food security and to create an understanding of the interlinkages between food safety and food security, which is captured in the FAO publication *The future of food safety* (FAO, 2019a).

Worldwide, 14 percent of food is lost during the production stage before it reaches consumers. Part of this loss is attributed to food contamination issues (FAO, 2019b). In addition, WHO estimates that foodborne illnesses affect 600 million people a year, causing more than 420 000 deaths. Aflatoxins, major foodborne hazard, contaminate staple crops and are associated with various health risks including stunting in children and cancer (**Chapter 2.F**). In developing countries, children with high exposure to aflatoxins were found to be more likely to suffer from micronutrient (zinc and vitamin A) deficiencies (Watson *et al.*, 2016). Climate change is expected to cause decreases in the micronutrient content of various staple foods, with an estimated additional 125.8 million DALYs globally over the period of 2015 – 2050 which will result in increased burden of infectious diseases, diarrhea and anaemia (Ebi and Loladze, 2019; Smith and Myers, 2018; 2019; Weyant *et al.*, 2018; Zhu *et al.*, 2018). Combining these nutritional deficiencies with the additional burden of food safety hazards like aflatoxin contamination creates a dire situation (FAO and WHO, 2016). Another example of climate change affecting food safety and food security is illustrated by the effect that a combination of climate change and the presence of arsenic in paddy fields has on rice. This combination is expected to lead to a doubling of the toxic heavy metal content of rice and a 39 percent reduction in overall production by 2100, threatening food security and food safety mainly in developing countries (Muehe *et al.*, 2019).

World Food Safety Day (7th June) at FAO headquarters, 2019.

©FAO/Cristiano Minichello

The cost of unsafe food goes beyond human suffering. Food safety has significant impacts on trade and the economy as food is increasingly grown for the global market. It is estimated that unsafe food costs low- and middle-income countries about USD 95 billion in lost productivity each year. As global agricultural trade grows, unsafe food presents an increasing health risk for people in importing countries, especially countries such as the Small Island Developing States, which rely on food imports for a majority of their food supplies. International food safety standards must be met in order to maintain trade relations and prevent trade disruption due to food contamination (microbial and/or chemical). To emphasize these important facets of food safety, the UN organized two international high-level meetings in 2019 - the First FAO/WHO/AU International Food Safety Conference and the International Forum on Food Safety and Trade. While the former meeting focused on food safety strategies and approaches that contribute to achieving the Sustainable Development Goals (SDGs) in support of the UN Decade of Action on Nutrition, the latter was aimed at addressing the trade-related issues and challenges that are associated with food safety. Building more resilient food production and supply systems in the face of climate change was discussed at both meetings.

Efforts to deliver on the global imperative to eliminate hunger and food insecurity, which has been reiterated in several UN resolutions and documents, must go hand-in-hand with due consideration of food safety issues. It is vital that food safety be incorporated into realization of the SDGs, especially SDG 2 (zero hunger), SDG 3 (good health and well-being), SDG 6 (clean water and sanitation), SDG 12 (responsible consumption and production) and SDG 13 (climate action). Attainment of the SDGs can lead to holistic and durable solutions only when care of the environment is integrated into social and economic development.

© FAO/Munir Uz Zaman

Women collecting water from communal water pump during floods caused by Cyclone Aila in Bangladesh.

CHAPTER 2.A

FOODBORNE PATHOGENS AND PARASITES

Although foodborne diseases are a major public health issue in both developed and developing countries, the full extent of the chemical and biological contamination of food remains unknown and the number of foodborne disease cases are grossly underreported. In an effort to provide some quantification of the global foodborne disease burden, the WHO-based Foodborne Disease Burden Epidemiology Reference Group (FERG) published an estimate of the number of disease cases caused by 31 known hazards (including bacteria, viruses, parasites, toxins and chemicals). Among approximately 600 million cases of foodborne illness worldwide in 2010 – resulting in an estimated 33 million disability-adjusted life years (DALYs) – a majority (550 million) were due to diarrhoeal diseases caused by infectious agents, mainly norovirus, *Campylobacter* spp., *Vibrio cholerae*, *Shigella* spp., enteropathogenic *Escherichia coli* and enterohaemorrhagic *Escherichia coli.* In the African, Southeast Asian and eastern Mediterranean regions, the estimated DALYs lost to foodborne diseases were much higher than the global average. The 31 foodborne hazards also resulted in an estimated 420 000 deaths in 2010 (WHO, 2015). Some high-income countries – Australia, Canada, France, Greece, New Zealand, the Netherlands, the United States of America, the United Kingdom of Great Britain and Northern Ireland – have published their national estimates of foodborne diseases (Adak, Long and O'Brien, 2002; Gkogka *et al.*, 2011; Hall *et al.*, 2005; Havelaar *et al.*, 2012; Lake *et al.*, 2010; Scallan *et al.*, 2011; 2015; Thomas *et al.*, 2013; Vaillant *et al.*, 2005). The emergence and re-emergence of foodborne pathogens is also a growing concern for public health agencies, and the number of pathogens known to be transmitted by food is expanding (Mor-Mur and Yuste, 2009), which complicates calculating the extent of foodborne diseases.

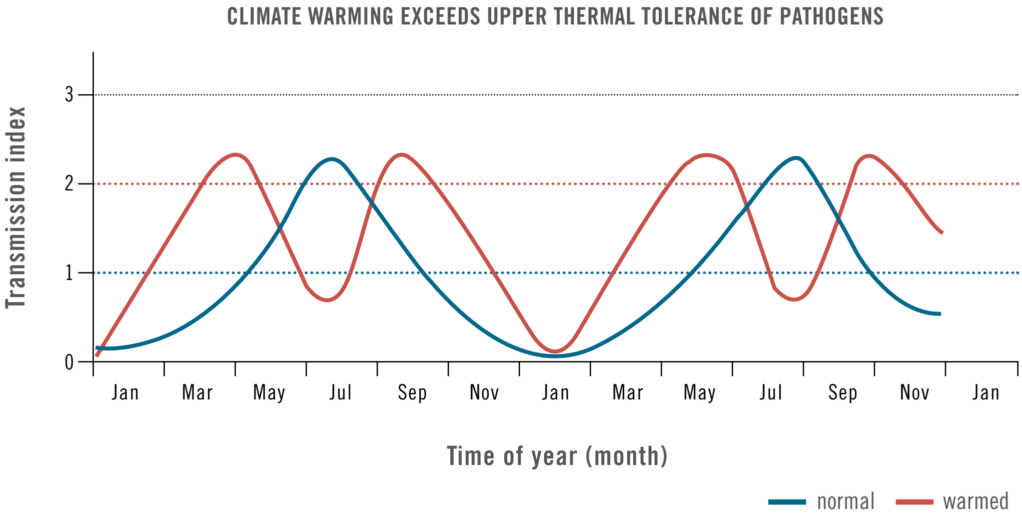
There is a tremendous economic cost associated with the burden of foodborne diseases. In the United States of America, the economic burden of foodborne diseases is approximately USD 14 billion per year and the majority of this cost is associated with foodborne pathogens such as *Salmonella* spp., *Campylobacter* spp., *Listeria monocytogenes*, *Toxoplasma gondii* and norovirus (Batz, Hoffmann and Morris, 2012; Scallan *et al.*, 2011). In addition to public health costs, there are other economic costs that an illness can impose on society, for instance the food production sector also incurs costs as a result of food safety incidents. Food-related businesses in the United States of America spend an estimated USD 7 billion per year in response to food safety incidents related to their products. These costs are associated with notification of consumers, removal of products from shelves and payment of damages resulting from lawsuits (Hussain and Dawson, 2013).

SECTION I: CLIMATE CHANGE AND FOODBORNE PATHOGENS

Growing scientific evidence supports the theory that climate-induced environmental changes will result in an increased net burden of food- and waterborne diseases (Carlton *et al.*, 2016; ECDC, 2012; Smith and Fazil, 2019). The level of impacts is likely to vary widely by pathogen and geographic distribution as climate change-induced temperature fluctuations and changes in precipitation patterns affect the persistence of pathogens in the environment by altering their rates of transmission, range and survivability (Tirado *et al.*, 2010). Altered and extended summer seasons affect the frequency of occurrences and the severity of seasonally variable foodborne diseases. The relationship between increased monthly temperatures and foodborne diarrhoeal episodes is well documented and has been reported in Australia, Israel and the Pacific Islands (McMichael *et al.*, 2003; Singh *et al.*, 2001; Vasilev *et al.*, 2004). Climate change can also alter the seasonal patterns of outbreaks. For instance, it has been predicted that there may be an emergence of a bimodal pattern of infection incidences that peak early and late in the summer season, with a decrease in mid-summer when temperatures are much higher than the pathogen's thermal optimum (**Figure 2**). It has been postulated that high temperatures related to climate change may lead to heat stress in livestock, resulting in increased shedding of enteric pathogens, which may overwhelm food control systems and enter the food supply (Khaitsa *et al.*, 2006; Pangloli *et al.*, 2008). Shedding of Shiga toxin-producing *Escherichia coli* due to heat-induced stress has been reported in cattle herds in Michigan, United States of America (Venegas-Vargas *et al.*, 2016).

Pathogens with low-infective doses (enteric viruses, parasitic protozoa, *Shigella* spp., enterohaemorrhagic *Escherichia coli*, *E.coli* O157:H7) and those that have high persistence in the environment (*Salmonella* spp.) are more likely to cause large outbreaks aided by environmental changes resulting from climate change; for example, rising temperatures encourage higher replication rates in *Salmonella* (Akil, Ahmad and Reddy, 2014; FAO, 2008). An analysis of trends in foodborne disease outbreaks in the Republic of Korea suggests that there is a strong positive relationship between foodborne pathogen infections caused by *Escherichia coli*, *Vibrio parahaemolyticus*, *Campylobacter jejuni*, *Salmonella aureus* and *Bacillus cereus* and changes in air temperatures and precipitation (relative humidity) (Kim *et al.*, 2015; Park, Park and Bahk, 2018). An IPCC report from 2007 states that

FIGURE 2. **WHEN CLIMATE CHANGE-INDUCED TEMPERATURES ARE MUCH HIGHER THAN THE PATHOGEN'S THERMAL OPTIMUM, THERE MIGHT BE A SHIFT IN THE NUMBER OF INFECTION CYCLES PER SEASON**



Source: Adapted from Altizier *et al*., 2013, *Science* 341: 514 – 519. With permission from AAAS.

increases in daily temperatures is very likely to result in increased numbers of food poisoning cases, particularly in temperate regions (IPCC, 2007). Studies from Germany (data collected over a period from 2001 to 2004) and the United States of America (data from a period of 1992 to 2001) found that an increase in the ambient temperature correlated with an increase in salmonellosis and campylobacteriosis cases with a delay of approximately two to five weeks (Naumova *et al.*, 2007; Yun *et al.*, 2016). Temperature also influences the contacts between food and pathogen-carrying insects such as flies and cockroaches, with higher insect activity associated with elevated temperatures (IPCC, 2007).

Changes in precipitation patterns are also likely to influence the incidence of foodborne diseases. The intake of various foodborne pathogens – *Salmonella* spp., *Escherichia coli* and norovirus – through the roots of various plants have been documented (Bernstein *et al*., 2007; Lopez-Velasco *et al*., 2012; Zheng *et al*., 2013). This process of internalization poses a threat to human health if food is consumed uncooked, as these pathogens cannot be removed by washing or disinfection methods (Hirneisen, Sharma and Kniel, 2012). A study that examined the effects of simulated water stress and excess water on the internalization of *Salmonella* in leafy green fresh produce found that the rate of intake increased under both conditions (Ge, Lee and Lee, 2012). Extreme rainfall events also increase the risks associated with waterborne diseases, especially where water treatment and management facilities are unable to handle the added water load. Compromised water quality poses a challenge to food safety in the food processing industry, while natural disasters such as flooding compromise water quality in affected areas, increasing the risk of human exposure to waterborne diseases such as cholera, especially in areas where basic public infrastructure for hygiene and sanitation are lacking or inadequate (IPCC, 2007).

While the link between climate change and the potential for changes in the seasonal variation of certain infectious diseases has been established, it is also vital to assess which pathogens are more climate-sensitive than others (Baker-Austin *et al.*, 2012; Fleury *et al.*, 2006; Harvell *et al.*, 2002; Kim *et al.*, 2015; Kovats *et al.*, 2004; 2005). This will facilitate the establishment of prioritized monitoring and control systems. McIntyre and co-authors (2017) found that more than half of the most important pathogens (including food- and waterborne pathogens) that affect human health in Europe are climate-sensitive. This implies that various climate-related environmental factors including extreme weather events, high temperatures (**Box 3**), rainfall, oscillations such as El Niño (Heaney, Shaman and Alexander, 2019), and drought will alter the distribution, incidence frequency and severity of these diseases. It was also noted that certain transmission routes of the vector-, food-, water- and soil-borne pathogens being studied had positive associations with multiple environmental factors and were therefore more likely to be affected by climate change (McIntyre *et al.*, 2017).

BOX 3

MELTING OF PERMAFROST AND RELEASE OF ONCE-FROZEN PATHOGENS

Warming of temperatures is leading to the thawing of older permafrost layers in the Arctic and Antarctic regions. As frozen soils melt, it is speculated that once-dormant ancient strains of viruses and spore-forming bacteria might revive and conceivably cause outbreaks in their immediate areas and beyond. However, the likelihood of such pathogens causing a pandemic remains quite low, according to scientists. A heatwave in 2016 caused an outbreak of anthrax in Yamal Peninsula in the Arctic Circle. Warm temperatures caused an anthrax-infected reindeer carcass, which had been buried in the permafrost, to thaw. More than 2 000 reindeer in the area became infected with anthrax, which led to a number of human cases in the region for the first time in 75 years (Guarino, 2016). It is feared that this will not be an isolated case. In 2014, scientists were able to revive an ancient giant virus (*Pithovirus sibericum*) from a piece of Siberian permafrost that was more than 30 000 years old. However, this virus is harmless to humans (Legendre *et al.*, 2014). A circumpolar network of experts has been established to assess emerging health risks resulting from climate change in the circumpolar north (Parkinson *et al.*, 2014).

SECTION II: IMPLICATIONS OF CLIMATE CHANGE FOR SELECTED FOODBORNE PATHOGENS AND PARASITES

SALMONELLA SPP.

There are a number of studies on the association between *Salmonella* infection and temperature (D'Souza *et al.*, 2004; ECDC, 2016; Naumova *et al.*, 2007). An increase of 1 °C in the weekly ambient temperatures in several European countries resulted in a 5 to 10 percent increase in salmonellosis cases (Kovats *et al.*, 2004). A study that focused on the association of salmonellosis with weather events in the United States of America found that for every 1 unit increase in extreme temperature events there was an increase of 4.1 percent in risks related to *Salmonella* infections; while a 5.6 percent increase in the salmonellosis risk was associated with a 1 unit increase in extreme precipitation events. The brunt of this increase is expected to be borne by coastal communities (Jiang *et al.*, 2015). It has been estimated that if no effective climate change measures are put in place, increasing temperatures will lead to an increase of approximately 50 percent in the morbidity burden (calculated as Years Lost due to Disabilities or YLDs) of *Salmonella* infections by 2030 in Australia (Zhang, Bi and Hiller, 2012).

CAMPYLOBACTER SPP.

In Israel, during the period 1999–2010, a 1 °C rise above a threshold temperature of 27 °C led to increases of 16.1 percent in *C. jejuni* infections and 18.8 percent in *C. coli*, in all age groups (Rosenberg *et al.*, 2018). An increase of 4.5 °C in the average temperature of Montreal, Canada is expected by 2055 and this is predicted to lead to a 23 percent increase in campylobacteriosis incidences, corresponding to more than 4 000 additional cases per year (Allard *et al.*, 2011). Climate change is resulting in longer survivability of insects due to milder winters and expanding the geographic range of vectors such as flies that carry *Campylobacter* (Cousins *et al.*, 2019; Goulson *et al.*, 2005). This is likely to lead to an increase in campylobacteriosis (Ekdahl, Normann and Andersson, 2005).

ROTAVIRUS

The incidence of rotavirus is usually associated with cooler and drier temperatures (Atchison *et al.*, 2010). According to a meta-analysis published in 2008, every 1 °C rise in temperature in the tropics was associated with a decrease of 4 to 10 percent in rotavirus-related diarrhoeal disease cases (Levy, Hubbard and Eisenberg, 2009). However, another study published in the same year found that for each 1 °C rise in temperature above a threshold of 29 °C, a 40.2 percent increase in incidences of diarrhoea due to rotavirus was observed in Dhaka, Bangladesh (Hashizume *et al.*, 2008). Although these are contrasting patterns, other factors such as population density must be taken into account when considering the severity of outbreaks. Research shows that for the transmission of rotavirus, a densely populated area is more sensitive to infection propagation than are areas that are sparsely inhabited (Martinez *et al.*, 2016). This makes densely populated cities in the tropics more vulnerable to rotavirus infections than rural areas that are sparsely populated.

When applicable, vaccines play an important role in reducing health threats from climate change, particularly in developing countries. However, although introduction of the rotavirus vaccine has succeeded in lowering the severity of cases, it does not show an impact on reducing the transmission rates of the pathogen, primarily because the vaccine is not widely available in developing countries (Restrepo-Mendez *et al.*, 2016).

VIBRIO SPP.

Vibrio spp. inhabit marine and coastal estuarine habitats and have been associated with warmer temperatures (Colwell, 1996). Several researchers have documented a relationship between cholera occurrence and El Niño Southern Oscillation (ENSO) events, which have a major impact on extreme weather patterns in different parts of the world (Anyamba *et al.*, 2019; Pascual *et al.*, 2000). Climate change is expected to increase the frequency and severity of ENSO events and their impacts (Cai *et al.*, 2014). A study published in 2017 found that between 2000 and 2014, the number of cholera cases during El Niño events increased by 50 000 in East Africa (Moore *et al.*, 2017). An association between cholera outbreaks and the changes in the environmental conditions caused by ENSO in Bangladesh has been shown (Cash *et al.*, 2014). An investigation into expansion of the geographical and seasonal ranges of *Vibrio parahaemolyticus* into Peru also found that the emergence of the disease was associated with the arrival of El Niño conditions (Martinez-Urtaza *et al.*, 2010; Abanto *et al.*, 2020). Warmer water temperatures are also associated with the emergence of outbreaks of *V. parahaemolyticus* in Alaska, United States of America (Martinez-Urtaza *et al.*, 2010; McLaughlin *et al.*, 2005).

V. cholerae has also been found to colonize soft turtles and marine fishes (Halpern and Izhaki, 2017; Wang *et al.,* 2017) and *V. parahaemolyticus* is a leading cause of seafood-related bacterial infections globally (Abanto *et al.,* 2020). Certain *Vibrio* spp. also, produce tetrodotoxin, a potent neurotoxin, which can be found in shellfish (Leão et al., 2018). As climate change affects the habitats and distribution of marine organisms, it may lead to more outbreaks by *Vibrio* spp. especially in countries where seafood is consumed raw or half-cooked (Morley *et al.,* 2018).

Some studies suggest that a pole-ward expansion of *Vibrio* spp. pathogens in mid- to high-latitude regions is partly due to climate change (Baker-Austin *et al.*, 2017; 2012). Additionally, in marine environments, widespread emerging pollutants such as microplastics (**Chapter 3**) can contain waterborne pathogens including *Vibrio parahaemolyticus* as part of their "plastisphere" (Kirstein *et al.*, 2016; Zettler, Mincer and Amaral-Zettler, 2013). With climate change altering ocean circulation patterns, the effects of this on the distribution of microplastics in the marine environment, and potentially on the spread of pathogenic bacteria, have yet to be investigated (Welden and Lusher, 2017).

A study published in 2016 showed that rapid growth of *Vibrio cholerae* (a 30- fold increase against background levels) in the Caribbean and sub-tropical Atlantic waters occurs in response to Sahara dust deposition events. This is attributed to the nutrients that are associated with the dust, especially iron, a deficiency of which can be a limiting factor for the growth of *Vibrio* spp. (Westrich *et al.*, 2016). With climate change projections suggesting an increase in the risk of drought conditions and dust emissions, this might be another environmental driver to be taken into account when considering *Vibrio*-associated infections (Dai, 2012; Middleton, 2019). It has also been suggested that aeroplanktonic adult flies (chironomids) may act as air-borne vectors for *Vibrio cholerae* and carry the bacteria between two bodies of water (Broza *et al.*, 2005). The authors of a study investigating three cholera outbreaks in Africa and on the Indian sub-continent noted a link between dominant wind direction and disease dissemination and postulated that this is because the wind aids the spread of the aeroplanktonic flies (Paz and Broza, 2007).

Vibrio spp. and plankton growth

Certain zooplankton such as copepods serve as marine reservoirs for *Vibrio cholerae* (Lutz *et al.*, 2013; Vezzulli *et al.*, 2010). These chitineous organisms are important grazers of algal blooms (**Chapter 2.B**). An association between increases in the abundance of *V. cholerae* O1 and of copepod populations in waterbodies was found in Bangladesh based on research carried out between 1987 and 1990 (Colwell, 1996). In addition, a relationship between increasing *Vibrio* populations (including human pathogens) and plankton growth with respect to a warming trend in sea surface temperature was shown in a study that examined historic (1958–2011) data from the Continuous Plankton Recorder (CPR), a biological monitoring programme. This phenomenon was also shown to have an impact on Vibrio-associated disease incidences in the region (Vezzulli *et al.*, 2016). Based on CPR data, it has been determined that climate change is likely to alter the distribution of the zooplankton populations in global oceans, potentially changing the prevalence of *Vibrio* infections in the world (Brun *et al.*, 2019). In addition, ENSO-related increases in rainfall are expected to increase the level of nutrients entering riverine and coastal ecosystems, triggering more plankton growth, which could promote an increase in *Vibrio* populations (Harvell *et al.*, 1999).

The association between the abundance of *Vibrio* spp. and coastal algal blooms is well documented (Epstein, 1993; Greenfield *et al.*, 2017; Turner *et al.*, 2014). *V. cholera* has been shown to proliferate alongside the dinoflagellate *Lingulodinium polyedra* ("red tide"), which produces yessotoxins (Mourino-Perez, Worden and Azam, 2003). Ciguatera poisoning cases preceded infections by *V. cholerae* in China, Hong Kong SAR according to a study that examined occurrence data for 1989–2001 (Kwan, Cheung and Kam, 2003). Algal growth tends to increase the pH in the surrounding waters owing to uptake of dissolved inorganic carbon during photosynthesis (bloom-induced basification) (Flynn *et al.*, 2015). It was shown as early as the 1960s that a positive relationship exists between elevated water pH and the onset of cholera outbreaks (Cockburn and Cassanos, 1960). In addition to *Vibrio cholerae*, coastal algal blooms have also been associated with other gram-negative bacteria such as *Pseudomonas* and *Escherichia coli* (Epstein, 1993).

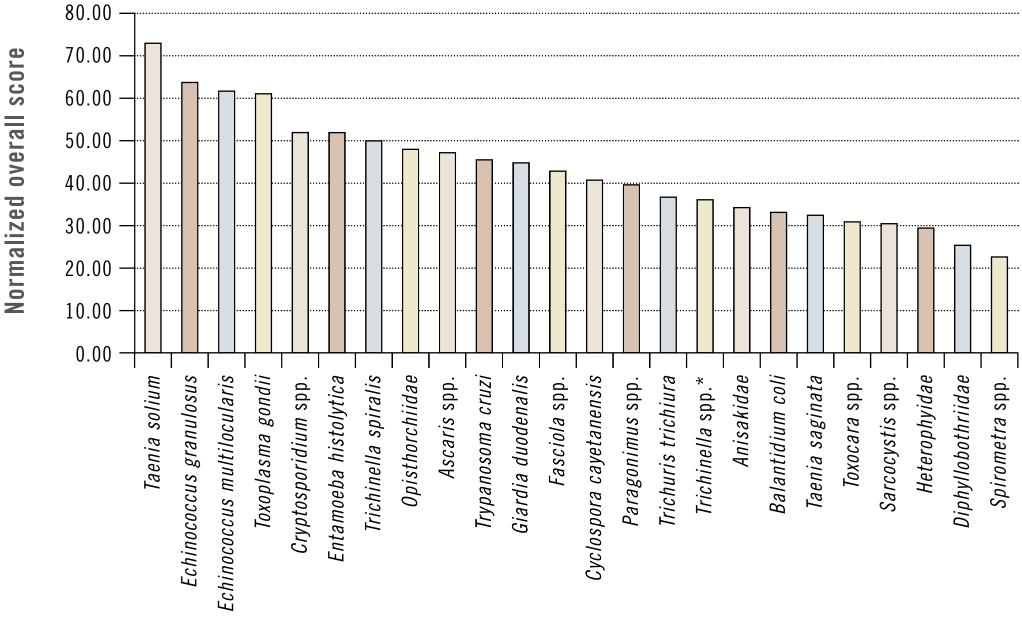
FOODBORNE PARASITES

Foodborne parasites can be transmitted by consuming raw or undercooked meat, wild game, fish or contaminated fresh, leafy green vegetables. The global ranking of foodborne parasites determined by the Joint FAO/WHO Expert Meetings on Microbiological Risk Assessment (JEMRA) Secretariat is shown in **Figure 3** (FAO and WHO, 2014). Climate change-associated environmental factors such as warmer temperatures and altered rainfall patterns have an effect on the abundance and migration of reservoir hosts and the survival and transmission rates of parasites (Short, Caminade and Thomas, 2017). Many foodborne parasites have complicated life cycles spanning multiple hosts, and there are dynamic relationships among parasites, hosts and their environments, which are likely to decline or increase according to the sensitivity to climate change of both hosts and parasites. Recent research shows that climate change may result in the migration of parasites to new hosts, destabilizing ecosystems (Carlson *et al.,* 2017).

Positive associations between rising monthly temperatures and giardiasis illnesses have been reported in New Zealand and the United States of America. An association between increased rainfall and a rise in cryptosporidium cases has also been noted in New Zealand (Britton *et al.,* 2010; Jagai *et al.,* 2009; Naumova *et al.,* 2007). A study conducted in Mexico found that temperature increase of 0.6 °C was associated with an increase in the prevalence of toxoplasmosis cases in 21 states of the country between 2000 and 2006 (Caballero-Ortega *et al.,* 2012). There are studies that suggest that warming oceans are playing a role in transporting parasites into new territories. For instance, *Toxoplasma gondii* has been found in polar bears and Arctic fox in the Norwegian Arctic archipelago of Svalbard, and beluga whales in western Canada (Iqbal *et al.,* 2018; Jensen *et al.,* 2009). These are cause for concern because the Inuit population depends on the Arctic animals for sustenance. Foodborne Chagas disease caused by *Trypanosoma cruzi* is another recent finding (Robertson *et al.,* 2016). Between 2000 and 2010 approximately 70 percent of Chagas disease cases recorded in Brazilian Amazon regions were foodborne (Alarcón, Noya and Robertson, 2015). The expansion of this tropical disease into temperate areas as a result of changes in the distribution of *Triatoma* vectors due to climate change-related environmental factors has been projected (Nichols *et al.,* 2018).

There is a predicted risk of increased infections caused by foodborne *Fasciola hepatica* in most of the United Kingdom of Great Britain and Northern Ireland, with a particularly high risk in Wales by 2050 due to climate change impacts on temperature and rainfall (Fox *et al.,* 2011). Risk modelling shows that climate change-induced warming temperatures may affect the geographical distribution of infections by the waterborne *Schistosoma* sp., with infection risk increasing by approximately 20 percent in most of eastern Africa (Rwanda, Burundi, eastern Zambia, most of Uganda, the United Republic of Tanzania and southwest Kenya) over the next few decades (McCreesh, Nikulin and Booth, 2015). Conversely, altered precipitation patterns may also give rise to hotter and drier climates in

FIGURE 3. **PARASITES SCORED ACCORDING TO CRITERIA RELATED TO THE QUANTITY AND SEVERITY OF GLOBAL DISEASES, THE GLOBAL DISTRIBUTION OF THE ILLNESSES, DISRUPTION TO TRADE AND THE LIKELIHOOD OF INCREASED HUMAN BURDEN**



(*Trichinella* spp.* includes *Trichinella* species except *T. spiralis*)

Source: FAO and WHO, 2014.

certain regions of Africa, which will decrease such infections by reducing the abundance of the intermediate host, freshwater snails (Stensgaard *et al.*, 2013). Similar changes in environmental conditions are predicted to cause a reduction in the habitats of snails that transmit *Opisthorchis viverrini*, a foodborne parasite, in northeast Thailand, which is expected to decrease the prevalence rates of infections from these parasites (Suwannatrai *et al.*, 2017). Regarding the effect of climate change on cestodes, there is some evidence to suggest that environmental factors may increase transmission of the foodborne *Echinococcus granulosus* and *E. multilocularis*. However, the extended time frame between infection and diagnosis makes it difficult to attribute climactic drivers to infections in humans (Utaaker and Robertson, 2015).

Although this section emphasizes disease-causing parasites, it is important to point out that there are a number of beneficial parasites that are vital to food webs and to the ecosystem in general. For instance, some parasites have beneficial roles in controlling diseases and cycling nutrients in soil. Carlson and co-authors (2017) have predicted that up to a third of all parasite species could disappear by 2070 as a result of climate change-related habitat loss. This could have unprecedented consequences for the global ecosystem (Carlson *et al.*, 2017).

SECTION III: INDIRECT EFFECTS OF CLIMATE CHANGE ON FOOD SAFETY

It is important to emphasize that prevention of microbial contamination is always preferable to reliance on methods of eliminating contamination. Accountability for food safety at all stages of the food chain is therefore vital. To that effect, it is also important to consider how climate change can affect food safety indirectly.

***Human behaviour*:** Prolonged warmer seasons influence consumers' behaviour and practices associated with food handling and storage, which can increase the risk of human exposure to foodborne pathogens (Tirado *et al.*, 2010). For instance, outdoor cooking and picnics in summer can create challenges related to temperature-safe food storage, cross-contamination between cooking vessels and the undercooking of meat (United States Department of Health and Human Services, 2019). A study published in 2018 examined data from more than 750 000 separate food facilities for the period between 2012 and 2016 and compared the ways in which meteorological conditions influenced the behaviour of regulatory workers in the United States of America. Researchers found that environmental stressors are associated with an increase in food safety violations and a decrease in food safety inspections (Obradovich, Tingley and Rahwan, 2018). The authors were able to extrapolate from these data and predict how future warming will affect food safety inspections and violations. They speculate that food safety inspections may decrease as areas experience higher temperatures. They also acknowledge that their data may have limitations and that they have not considered all uncertainties in their proposed models. For instance, in response to high temperatures food safety inspectors might choose to carry out fewer inspections and to focus on facilities where there is a higher risk of violations, rather than carrying out more inspections in facilities that pose a lower risk (Obradovich, Tingley and Rahwan, 2018).

***Water issues*:** Altered rainfall patterns and extended summer seasons are causing water crisis issues worldwide (Hofste, Reig and Schiefer, 2019). Water scarcity can have an impact on the transmission of foodborne pathogens such a *Listeria monocytogenes* by compromising hygienic conditions in food processing plants, for instance by affecting water usage patterns through hand hygiene of people who handle food and by causing inadequate sanitization of the machines used for food processing (Chersich *et al.*, 2018).

Water stress conditions will also affect food production. In the absence of sufficient water availability from municipal sources, farmers may resort to irrigating their crops with surface water that harbours a number of foodborne pathogens (Steele and Odumeru, 2004; Uyttendaele *et al.*, 2015). As climate change affects freshwater supplies, the recycling of sewage water into drinking water may become a norm in water-stressed cities. This method of circular economy has been adopted in Singapore and in several cities in the United States of America and Australia (Harris-Lovett and Sedlak, 2019; Monks, 2015; Woo, 2016). Although advanced technology is used to treat wastewater, strict quality monitoring for microbial and chemical contamination risks must be maintained. An emerging pollutant in potable reused water is antibiotic-resistant genes, which are not currently regulated. This pollutant arises from untreated medical waste, runoff from intensive agriculture and waste from pharmaceutical manufacturing. Antibiotic-resistant genes can be difficult to remove at wastewater treatment plants and can then be taken up by bacteria in the environment, perpetuating the issue of antimicrobial resistance (Harb *et al.*, 2019).

Rising sea levels and flooding caused by hurricanes threaten wastewater treatment plants and increase the likelihood of water borne disease outbreaks. Hummel and co-authors (2018) found that a sea level rise of 2 m under a worst-case scenario can affect the functioning of 394 wastewater treatment plants that provide water for 31 million people in the United States of America. Additionally, the frequency of tsunamis is expected to increase with sea level rise (Li *et al.*, 2018) and it has been postulated that tsunamis may have a role in the dispersal of ocean-living pathogenic waterborne microbes, such as *Cryptococcus gatti* from the Pacific Northwest, on to land (Engelthaler and Casadevall, 2019).

***Food storage*:** A rise in ambient temperatures will also have an effect on all aspects of the food cold chain, from initial chilling or freezing of food to transport, storage and retail display. Increasing ambient temperatures coupled with elevated storage temperatures will increase human exposure to food that is unsafe for consumption (James and James, 2010). Changes to the cold chain system will therefore be required as ambient temperatures rise. However, this often calls for increased energy consumption by food refrigeration systems. It has been estimated that when the ambient temperature increases from 17 °C to 25 °C there is a corresponding increase of about 11 percent in the average power consumed by food refrigeration systems in a small catering establishment (James and James, 2010). Generation of this energy contributes to increased production of CO_2. The total energy expended to keep an "unbroken" chain "from farm to fork" was found to be 19 292 Gigawatt hours per year (or 18 million tonnes of carbon) in Australia (Estrada-Flores and Platt, 2007). A properly functioning cold storage system also contributes to food security through reduced food losses. However, revamping of existing cold storage systems and installation of new ones, especially under climate change conditions, bring increased economic burdens, which can be a challenge for developing countries. In addition, extreme weather events that lead to power cuts increase the risk of food spoilage and contamination issues in storage facilities in supermarkets and homes. Marx and co-authors (2006) found an increase in diarrhoeal diseases following a power outage in the United States of America, which could be attributed to the consumption of spoiled foods. Additionally, thawing permafrost is also starting to cause the traditional ice cellars of Arctic communities to fail, which could lead to a rise in foodborne illnesses from food spoilage during storage (Yoder, 2018).

SECTION IV: ANTIMICROBIAL RESISTANCE

IV.I: ANTIMICROBIAL RESISTANCE AND FOODBORNE PATHOGENS

Antimicrobial resistance (AMR) has been recognized as an issue of global significance. Resistance is a naturally occurring phenomenon that evolved long before naturally occurring antibiotics were used in human medicine (D'Costa *et al.,* 2011). However, misuse and overuse of antimicrobials in humans and the widespread use of medically important antimicrobials in terrestrial livestock production, aquaculture and crop production have led to the emergence of pathogens resistant to antimicrobials (**Box 4**) owing to natural selection (Cabello *et al.,* 2016; Kirchhelle, 2018; Thanner, Drissner and Walsh, 2016). About 73 percent of global antimicrobial use is in meat production, and antimicrobial resistance in food-producing animals is rising. Research shows that antibiotics used for disease treatment failed in more than half the times in 40 percent of chickens and a third of pigs raised for human consumption in LMIC (Van Boeckel *et al.,* 2019). There are serious public health ramifications associated with AMR, with an estimated 700 000 people dying each year of drug-resistant diseases (including non-foodborne diseases) (IACG, 2019). Global consumption of antimicrobials in livestock production was estimated at 63 151 tonnes in 2010, with a rise of 67 percent – corresponding to 105 596 tonnes – predicted by 2030 (Van Boeckel *et al.,* 2015). Although direct causality is difficult to establish, a study conducted in seven European countries showed a strong association between the administration of eight classes of antimicrobials to livestock and the prevalence of AMR to these agents in commensal *Escherichia coli* in pigs, cattle and poultry (Chantziaras *et al.,* 2014). A strong correlation was also found between the prevalence of antibiotic-resistant *E. coli* isolates from humans and those isolated from poultry, pigs and cattle using surveillance data from 11 countries (Vieira *et al.,* 2011).

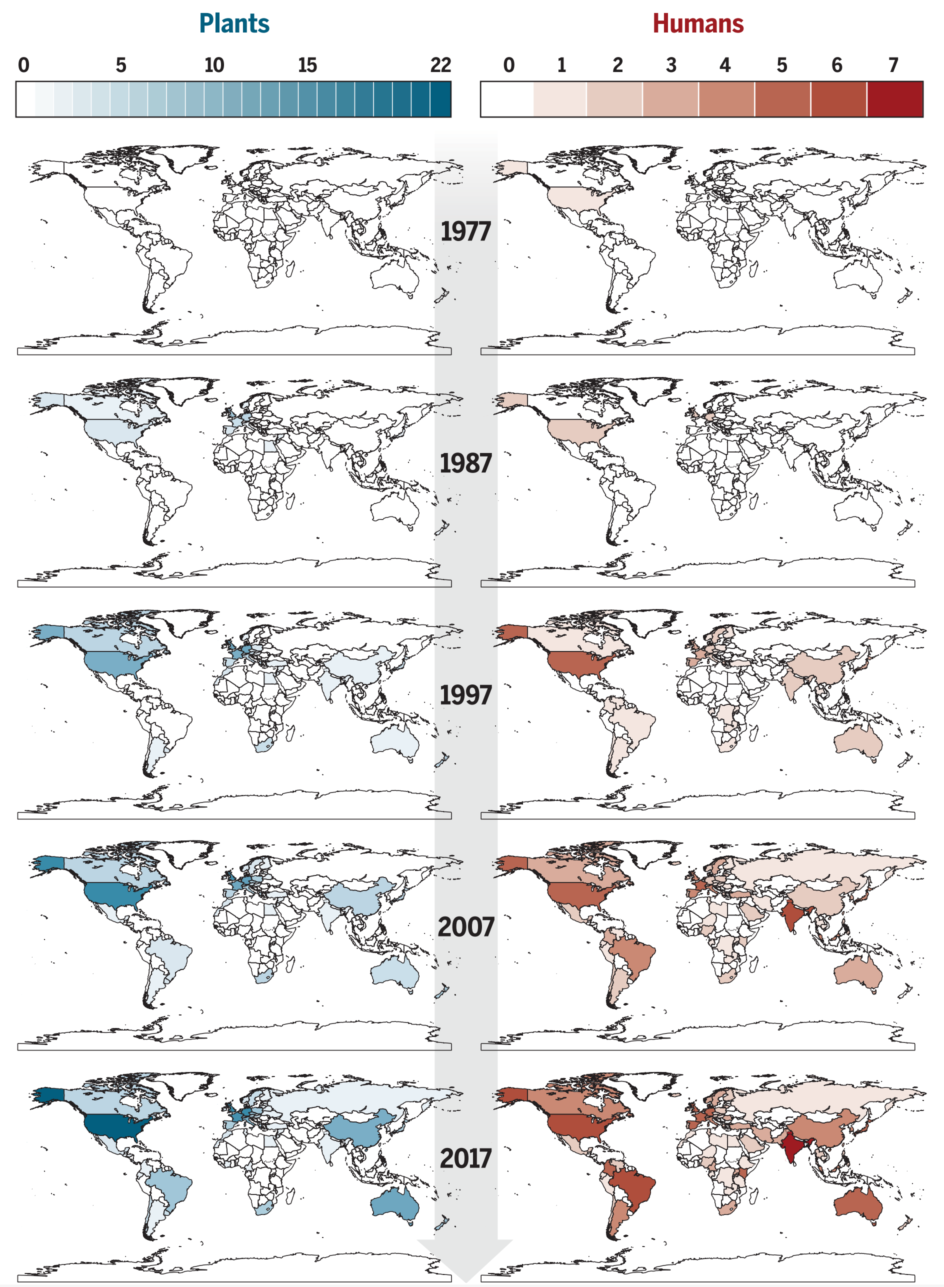
It is difficult to quantify the full potential costs incurred by AMR as it crosses sectoral boundaries and has layers of complications (Smith and Coast, 2013). The cost of treating patients suffering from antibiotic-resistant infections in 2014 was estimated to be USD 2.2 billion in the United States of America (Thorpe, Joski and Johnston, 2018). Another study looked at the effects of AMR on global working-age populations and estimated that the cumulative loss in global gross domestic product (GDP) due to the resulting disruption in the supply of effective labour will be between USD 2.1 trillion and USD 124.5 trillion by 2050, under conditions in which no progress is made in addressing AMR (Taylor *et al.*, 2014).

Food can be contaminated with resistant pathogens in many ways (**Box 5**). Food- and waterborne pathogens are increasingly showing resistance to clinically important antibiotics, including *Vibrio cholerae*, *Campylobacter* spp., *Listeria monocytogenes*, *Salmonella* spp., *Escherichia coli*, *Arcobacter* sp. (Dengo-Baloi *et al.,* 2017; Elmali and Can, 2017; Henderson, Herrera and Trent, 2017; Olaimat *et al.,* 2018; Poirel *et al.,* 2018; Wang *et al.,* 2019; 2014). Some *Salmonella* sp., such as *S. typhimurium* ST313, cause infections of the blood that can often be fatal, especially in regions where access to health care is limited. The extensively drug-resistant strain of

BOX 4

GROWING RESISTANCE TO FUNGICIDES

Azoles are widely used as fungicides in crop protection and as antifungal drugs in human and animal health care (ECDC, 2013; Meis *et al.*, 2016). The parallel global evolution of resistance to antifungals in clinical and agricultural settings is shown in the **Figure** below. Widespread use of antifungals in multiple sectors has been accompanied by a rapid emergence of resistance to azoles, with patient mortality approaching 100 percent (van Paassen *et al.*, 2016; Fisher *et al.*, 2018). In Colombia, azole-resistant *Aspergillus fumigatus*



Source: Adapted from Fisher *et al.*, 2018, *Science* 360: 739 – 742, with permission from AAAS. Map conforms to United Nations World map 4170 R18.1, Feb 20 has been found in agricultural soils where vegetable crops including carrots, potatoes, maize and peas are grown (Alvarez-Moreno *et al.*, 2019). It is postulated that climate change-derived warmer temperatures will likely increase the prevalence of fungal infections globally, making resistance to antifungals a grave concern (Garcia-Solache and Casadevall, 2010). In a recent study, researchers proposed that *Candida auris*, currently an urgent health threat globally, was able to adapt to climate change-induced warmer temperatures, which then enabled it to replicate at 37 °C, the average human body temperature (Casadevall, Kontoyiannis and Robert, 2019). According to the authors, this would make it the first instance of a pathogenic fungus emerging as a result of climate change.

S. typhimurium ST313 was recently isolated in the Democratic Republic of the Congo (Van Puyvelde *et al.*, 2019). Antibiotic-resistant foodborne pathogens are responsible for 430 000 cases per year in the United States of America (CDC, 2015). Recently, multi-drug-resistant *Salmonella* has been responsible for a number of outbreaks in the United States of America: *S. Infantis* in 2019 through raw chicken products; *S. Urbana* in 2017 through papayas; *S. Poona* causing an outbreak in 2015 *via* cucumbers; *S. Heidelberg* in 2014 through mechanically separated chicken; and many others (CDC, 2014; 2016; 2017; 2019).

IV.II: ANTIMICROBIAL RESISTANCE AND ITS RELATIONSHIP TO CLIMATE CHANGE DRIVERS

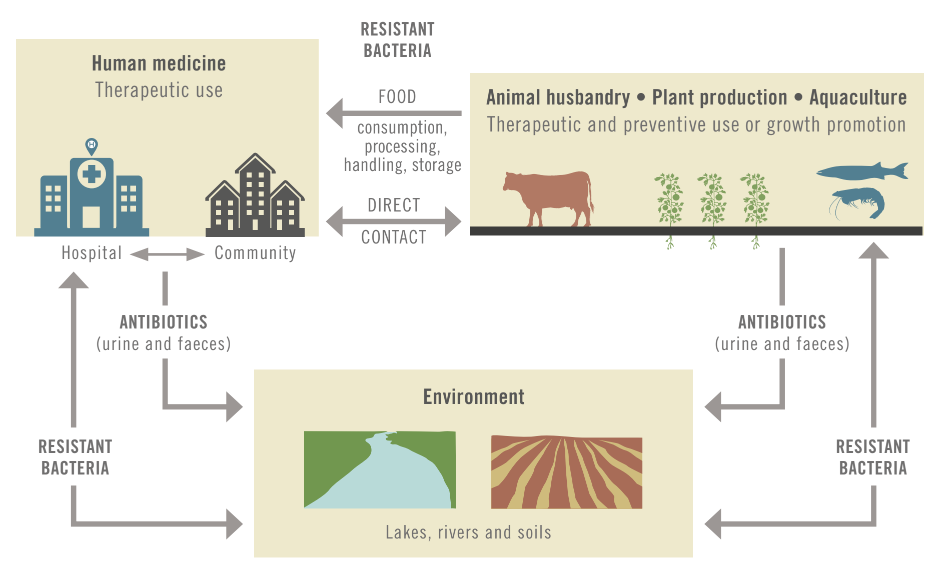
There is growing concern that antimicrobials are losing their effectiveness in many sectors, which could lead to an increase in antimicrobial use to fight infections (FAO, 2018). As pests and pathogens increase their geographic range due to climate change-associated environmental changes, it is likely that antimicrobial use will increase concomitant to the predicted disease burden, compounding the challenges related to AMR (Bebber, Ramotowski and Gurr, 2013; Bebber, 2015; FAO, 2018). In Florida, United States of America, the citrus industry is facing a continuing challenge from a bacterial infection (citrus greening disease), which was transmitted through the Asian citrus psyllid (*Diaphorina citri*) that arrived from China. In an attempt to control infections and stem the multi-billion dollar loss of citrus production, farmers sprayed their trees with antibiotics (streptomycin and oxytetracycline) that are usually used to treat human diseases (McKenna, 2019). Although the use of these drugs in agriculture (plant and animal) is not new, their use is expected to rise with the growing demand for food supplies. The high risk associated with emerging zoonoses and alterations in the survival and transmission of pathogens and parasites may lead to an increased use of veterinary drugs. This will result in higher veterinary drug residues in food of animal origin, thereby posing health issues for humans – with impacts on international trade – and contributing to challenges related to AMR (Beyene *et al.*, 2015; FAO/WHO, 2018a).

BOX 5

WHERE DO ANTIBIOTIC RESISTANT PATHOGENS APPEAR IN A FOOD CHAIN?

The full extent to which large-scale use of antimicrobials in plant production selects for the emergence of AMR in pathogens found in food of plant origin is still not well defined. Animal products may contain antibiotic-resistant bacteria owing to faecal matter contamination during slaughter or because of direct contact between animals and humans (**Figure** below) (Heredia and Garcia, 2018). Fresh vegetables are increasingly recognized as a vector for foodborne pathogens (Brandl, 2006; Lynch, Tauxe and Hedberg, 2009). Plants can carry antibiotic-resistant bacteria from irrigation water contaminated by human or animal faecal matter. Multiple outbreaks of diseases caused by *Escherichia coli* O157, *Salmonella* spp. and *Shigella* sp. in the United States of America and Europe have resulted from the consumption of leafy green vegetables (Allerberger and Sessitsch, 2009; Berger *et al.*, 2010; Herman, Hall and Gould, 2015). The soil also contains a large number of bacteria that harbour antimicrobial-resistant genes. Direct contact between the edible portions of plants and soil or soil splash can lead to the contamination of food with resistant organisms (FAO, 2018). Foodborne pathogens can also survive various food processing or preservation techniques because stress conditions can trigger a number of microbial adaptation mechanisms (Begley and Hill, 2015; Horn and Bhunia, 2018).

Non-pathogenic foodborne microorganisms also play a role in the transfer of mobile genetic elements that impart resistance to humans. For instance, *Escherichia cloacae*, a commensal microorganism found in the digestive tract of humans, can disseminate antibiotic resistance. This microbe is found on baby spinach leaves, and consumption of raw spinach (bagged and ready to eat) serves as a way of transferring resistance genes to the microbiome of the human digestive tract *via E. cloacae* (Ghaly *et al.*, 2017). Bacteria that are intentionally added to food during processing (starter cultures, probiotics, bio-preservation bacteria, etc.) may also have transferable resistance genes (Gueimonde, Sanchez and Margolles, 2013; Kastner *et al.*, 2006). *Enterococcus*, *Lactococcus* and *Lactobacillus* carrying multi-resistant plasmids have been isolated from dairy products (Gfeller *et al.*, 2003; Mathur and Singh, 2005; Verraes *et al.*, 2013).



Source: Adapted from Andersson and Hughes, 2014.

©FAO/Luis Tato

Collecting samples from poultry farms in Kenya to look for drug-resistant bacteria.

In 2018, MacFadden and co-authors showed that regions of the United States of America with increased average local temperatures had increased rates of AMR in three human pathogens (*Escherichia coli*, *Klebsiella pneumonia* and *Staphylococcus aureus*). A temperature increase of 10 °C was associated with an increase of 2.2–4.2 percent in the number of resistant infections (MacFadden *et al.*, 2018). Although this study cannot be used to suggest causation, environmental drivers related to climate change should be taken into consideration when predicting the scale of AMR issues globally. In a separate study, McGough and co-authors (2018) analysed country-level data on the prevalence of AMR in *Escherichia coli*, *Klebsiella pneumoniae* and *Staphylococcus aureus* in 28 European countries over the 17 years from 2000 to 2016. They found that countries that experienced an increase in average ambient temperatures over the 17 years also experienced higher prevalence of AMR in all the antibiotic classes under study, with the exception of resistance of *S. aureus* to methicillin (McGough *et al.*, 2018). It has been postulated that warmer temperatures may facilitate increased horizontal transfer of resistance genes. Increased plasmid transfer between *Escherichia coli* and *Pseudomonas putida* in response to a rise in temperature was reported in a study published in 2007 (Johnsen and Kroer, 2007). Extreme weather events that cause flooding, such as hurricanes, increase the chances of inundating areas that contain waste from animal farms where antibiotics are used for production. This enhances the spread of antibiotic-resistant bacteria into the surrounding environment.

SECTION V: CONCLUSIONS

Climate change and elongating food chains increase the likelihood of contamination issues arising from foodborne pathogens and parasites making it important to increase awareness of this in order to manage public health risks. When national and regional health authorities in various sectors, medical and scientific research communities, and the agrifood industry work together, more effective regulations and guidelines can be created that ensure better public health.

Cross-sectoral and integrated surveillance, monitoring and transparent data sharing are key aspects of anticipating and ensuring rapid mitigative responses to foodborne disease outbreaks. One of the suitable platforms is the International Food Safety Authorities Network (INFOSAN) that provides a channel for the rapid exchange of information about imminent threats of foodborne diseases among members. This enables countries to prepare risk management procedures in time to prevent the occurrence of foodborne disease outbreaks within their borders.

Today's intensification of food production to feed the growing population is associated with increasing dependence on agrochemicals such as antimicrobials. Prudent use of antimicrobials is essential in helping to address the problem of AMR. Based on a systematic review, it has been proposed that interventions that reduce the use of antimicrobials in food-producing animals will decrease the prevalence of antibiotic resistant bacteria in humans (Tang *et al.*, 2017). As AMR is a multi-sectoral issue, it is vital to promote the Global One Health approach, especially in settings where resources are limited. The interconnectedness among human, animal and plant health, given their shared environment, emphasizes the need for greater collaboration, communication and cooperation between medical professionals, veterinarians, plant pathologists and scientists with public health and civic officials.

© Associated Press/Felix Marquez

Fisherman walks among dead sardines on a beach in Chile. Severe algal blooms caused massive fish kills in 2016.

CHAPTER 2.B

ALGAL BLOOMS

Algal species can be broadly classified into microalgae (unicellular organisms) and macroalgae (multicellular, also called seaweeds) and together they produce more than half of the oxygen in the earth's atmosphere. Algal blooms denote an increase in the abundance of a single (or more) algal species in a given area. Algal growth reaches bloom proportions when a series of environmental factors occur in synchrony – temperature, salinity, light, turbulence, availability of micro- or macronutrients, availability of trace elements and, in the case of microalgae, interactions with populations of marine bacteria, viruses and algal grazers (zooplankton and herbivore fish) (Sison-Mangus *et al.*, 2016). A number of algal blooms occur periodically in oceans, seas or freshwater bodies, depending on the growth requirements of the various algal species in the area. They are essential primary producers in aquatic ecosystems, play an integral role in the cycling of carbon, sulphur and other elements, help to sustain commercial fisheries and have numerous other commercial applications in various fields (**Box 6**). It is estimated that of the approximately 5 000 algal species identified, about 300 are involved in causing blooms that are designated as harmful (Berdalet *et al.*, 2015; Goto-Azuma *et al.*, 2019; Moestrup *et al.*, 2009 onwards).

Over recent decades, increasing eutrophication, warmer seas, ocean acidification and food web modifications resulting from overfishing and other factors, have led to increased prevalence of harmful algal blooms (HABs) globally (Anderson *et al.*, 2008; Eriksson, 2011; Heisler *et al.*, 2008; Paerl and Huisman, 2008). In addition to marine animal mortality and impacts on human health, HABs also contribute to direct economic losses, destroy coastal resources and affect the livelihoods of coastal communities worldwide. Consumption of seafood and fish is the primary route for exposure to phycotoxins (algal toxins) in humans. A growing interest in increasing aquaculture and mariculture[1] facilities to meet the increased demand for food brings with it significant food safety concerns related to phycotoxins. The proliferation of HAB species may cause indiscriminate and large-scale fish

---

[1] Mariculture involves the cultivation of aquatic animals and plants in marine environment.

BOX 6

SELECTED USES OF ALGAL SPECIES

Several non-toxic micro- and macroalgal species have a number of potential applications in the biofuel, food, agriculture, pharmaceutical and nutraceutical industries as well as a potential role in environmental decontamination (Bilal *et al.*, 2018; Sharma and Sharma, 2017). The use of algal products as biodegradable food packaging is also being explored as an alternative to single-use plastics (Clancy, 2017; Hammon, 2019; Hitti, 2019; Hussey, 2014). The global algae products market is projected to be about USD 5.2 billion by 2023 (Kite-Powell, 2018). Microalgae are used in the production of omega-3 oils, livestock feed, biofertilizers and cosmetics, among many other applications (Joshi, Kumari and Upasani, 2018; Madeira *et al.*, 2017; Ryckebosch *et al.*, 2014; Uysal, Uysal and Ekinci, 2015). Another emerging application of microalgae is in "'bio-curtains", which are installed in urban landscapes that lack sufficient green cover in order to capture CO_2 from the air and produce oxygen through photosynthesis (Langley, 2019). The ability of algal blooms to sequester heavy metals might prove beneficial in efforts to decontaminate water bodies that contain high concentrations of toxic heavy metals such as methylmercury (Anastopoulos and Kyzas, 2015; Pickhardt *et al.*, 2002; Zeraatkar *et al.*, 2016). The quantities of macroalgae (brown and red seaweed) used in various applications increased by 176 percent between 1995 and 2012 (White and Wilson, 2015). *In vitro* research has shown that adding seaweed such as A*sparagopsis taxiformis* to rumen fluid can drastically reduce methane production by cows and sheep (Kinley *et al.*, 2016; Li *et al.*, 2018; Roque *et al.*, 2019). A team led by Prof. Kebreab at the University of California, Davis, United States of America tested the addition of *A. taxiformis* to the regular diet of dairy cows and found a 58 percent reduction of methane production. As it is difficult to obtain sufficient beneficial seaweed from wild capture, certain seaweed species are farmed in various parts of the world (FAO, 2018, White and Wilson, 2015). However, climate change is causing major damage to such production facilities. Since 2001, climate change has resulted in massive die-offs of the main species of seaweed, *Eucheuma cottonii*, in coastal regions of Zanzibar, United Republic of Tanzania, which is one of the world's largest producers of the seaweed product, carrageenan. Elevated temperatures in the Indian Ocean in combination with algal blooms in shallow waters reduced *E. cottonii* production by 94 percent in 2015, causing a huge economic loss (Ott, 2018).

It is important to point out that there are potential food safety considerations related to some algal applications. Food supplements that contain algae (blue-green algae supplements) are derived from algal species (primarily *Spirulina* and *Aphanizomenon flos-aquae*) that can coexist with other harmful strains of cyanobacteria (*Microcystis* sp.), thereby creating potential contamination issues for the supplements (EFSA, 2016). Certain macroalgal species that are inherently non-toxic can be considered toxic because they tend to accumulate heavy metals such as copper, lead, zinc and iron. Some of these species are therefore used as biological monitors of marine pollution (Chakraborty *et al.*, 2014; Medeiros, Mathieson and Rajakaruna, 2017).

mortality and contaminate or destroy shellfish beds (farmed and wild populations), inflicting massive losses on aquaculture and mariculture facilities. Over the last three decades, in the Republic of Korea, the loss to the aquaculture industry due to HABs was estimated at USD 121 million (Park *et al.*, 2013). In fact, according to "conservative" figures annual costs associated with marine HABs in Europe and Asia are estimated to be greater than USD 850 million and USD 1 billion respectively (Kudela *et al*., 2015). For United States of America, the annual costs are approximately USD 95 million (Kudela *et al.*, 2015). However, these costs are set to go much higher in the future as our reliance on marine resources increase.

HAB phycotoxins may bioaccumulate in fish and shellfish and induce toxic syndromes in humans who consume them, with symptoms ranging from skin, eye or ear irritations to more severe reactions such as liver and kidney damage and gastrointestinal, cardiovascular, respiratory and neurological conditions (Grattan, Holobaugh and Morris, 2016). Descriptions of different HAB species and their geographical distribution, the corresponding phycotoxins and toxic syndromes that they produce in humans and fish can be found in a publication by Lassus and co-authors (2016). Toxin production is specific to the algal species. For instance, not all species of *Pseudo-nitzschia* produce domoic acid toxins, and those that do, do not produce it under all bloom conditions (Bates *et al.,* 2018). In addition, certain HAB species can have significant harmful impacts even at densities that are below the biomass concentration required to constitute a visible bloom, for instance, certain *Dinophysis* spp. can be harmful at < 10^3 cells per litre (Reguera *et al.,* 2014). There are also reports of algal toxins becoming aerosolized and causing respiratory issues in humans (Cheng *et al*., 2005; Fleming *et al*., 2007; May *et al*., 2018; Wisniewska, Lewandowska and Sliwinska-Wilczewska, 2019). “Red tides” caused by the toxic dinoflagellate *Karenia brevis* are an annual event off the coast of Florida, United States of America. Kirkpatrick and co-authors (2010) found that aerosolized brevetoxins produced by *K. brevis* can be found 4 km inland from the beaches in Florida and there was an increase in admissions to hospital emergency rooms for respiratory illnesses when the algal blooms were present. Another route of exposure to algal toxins is the accidental ingestion of water containing toxins in recreational environments at the beach (Ralston, Kite-Powell and Beet, 2011). At present, no routine diagnostic tests are available for HAB-associated poisoning, and clinical diagnosis is based largely on symptoms presented and dietary history. There are also no known antidotes for many of these toxins, making symptom management the only care available to those suffering from the painful toxic effects (Grattan, Holobaugh and Morris, 2016).

Non-toxic algal blooms can also be considered harmful as they can result in economic losses in tourism, recreation and fisheries by causing mass mortalities of fish, which affect coastal communities and influence public health, for example by affecting the availability of safe drinking water. The geographic expansion of microalgal blooms poses a major threat to desalination plants that produce drinking water from seawater. Research suggests that a number of organic compounds that algae produce to promote aggregation and biomass formation are not removed by the usual pre-treatment processes involved in reverse osmosis plants. The organic matter can also cause obstruction problems for the operation of reverse osmosis plants (Villacorte *et al.,* 2015). This is an important issue that deserves attention as desalination plants are expected to be more widespread in the future, as cities get larger and suffers from climate-related water scarcity (Hofste, Reig and Schiefer, 2019).

ALGAL BLOOM EXPANSION

A number of HAB-forming species have expanded their geographic ranges over time. A well-known example is that of the causative species of paralytic shellfish poisoning (PSP) *Alexandrium tamarense* and *A. catenella*, which caused blooms mainly in the temperate coastal regions of Europe, Japan and North America in the 1970s. Over the last 20 years, these species have made their way into the Southern Hemisphere, forming toxic blooms off the coasts of Australia, New Zealand, Papua New Guinea and South Africa. In addition, new toxic species (*A. fundyense, A. minutum* and *A. cohorticula*) that also cause PSP have been identified off the coasts of Brunei, India, Thailand and the Philippines (Lassus *et al.*, 2016). *Alexandrium* spp. that cause PSP were also recorded, for the first time in sub-polar regions, off the coast of Greenland in 2012 (Baggesen *et al*., 2012). Each year, approximately 2 000 PSP cases are reported worldwide, with mortality of between 15 and 50 percent (Kadiri and Isagba, 2018; Van Dolah, Roelke and Greene, 2001).

The brown tide algae *Aureococcus anophagefferens*, formerly found only off the northeastern United States of America and South Africa, are now forming blooms along China's coastal areas (Zhang *et al.*, 2012). Although the brown tide does not produce toxins that are harmful to humans, it has decimated many fisheries because of its acute toxicity to bivalve species (Gobler, Lonsdale and Boyer, 2005). The habitat of the *Gambierdiscus* species, which causes ciguatera poisoning, is expanding from the warmer waters of the Caribbean Sea and the Pacific and Indian Oceans to several cases being reported in Europe since 2008, according to the EuroCigua project[2]. This trend is likely influenced by climate change, global trade in imported fish as well as the consumption of contaminated seafood during vacations abroad. Microplastics have also been indicated as potential carriers of HAB species (*Ostreopsis* sp., *Coolia* sp., *Alexandrium* sp.) in the marine environment (Masó, Garcés and Pagès, 2007; Yokota *et al.*, 2017; Zettler, Mincer and Amaral-Zettler, 2013). With climate change expected to affect the distribution of microplastics in the oceans, the ways in which this translates into changes in the geographic expansion of HAB species remains to be investigated.

In addition to microalgal species, there has also been a geographic expansion of certain macroalgal species (**Box 7**) in the oceans. Moreover, eutrophication, warmer and hypoxic oceans and overfishing are encouraging massive jellyfish blooms, which ease the grazing pressure of zooplankton on algal species, thus encouraging more growth and expansion of algae (Breitburg *et al*., 2018; Møller and Riisgård, 2007; Schmidtko, Stramma and Visbeck, 2017).

---

[2] More information on the Risk Characterization of Ciguatera Food Poisoning in Europe (EuroCigua) project is available at: http://www.aecosan.msssi.gob.es/AECOSAN/web/ciguatera/home/aecosan_home_ciguatera.htm

BOX 7

THE GROWING ISSUE OF MACROALGAE (OR SEAWEED)

Increasing quantities of *Sargassum* (mainly S. *natans* and *S. fluitans*) have been reported in the Atlantic Ocean and the Caribbean Sea over recent years (Butler *et al.*, 1983; de Széchy *et al.*, 2012; Gower and King, 2011; Langin, 2018; Smetacek and Zingone, 2013; Wang and Hu, 2016; 2017). *Sargassum* is found in abundance in the Sargasso Sea (North Atlantic). However, massive belts of it, which have been appearing in an area extending from West Africa to the Gulf of Mexico since 2011, do not originate in the Sargasso Sea (**Figure a**). Instead, research shows that this *Sargassum* grew off the coast of Brazil, near the mouth of the Amazon River, and then spread across the Atlantic (Gower, Young and King, 2013). Fertilizers and sewage run-off into the Amazon, heavy rains and the pattern of currents off West Africa – which is influenced by climate change-related factors – are suggested as being responsible for the bloom (Wang *et al.*, 2019). In 2018, the *Sargassum* biomass resembled an archipelago, extending approximately 9 000 km and containing more than 20 million tonnes of *Sargassum* biomass (**Figure b**) (Wang *et al.*, 2019).

FIGURE a EXPANSION OF *SARGASSUM* IN THE ATLANTIC OCEAN AND THE CARIBBEAN SEA, 2011-2018

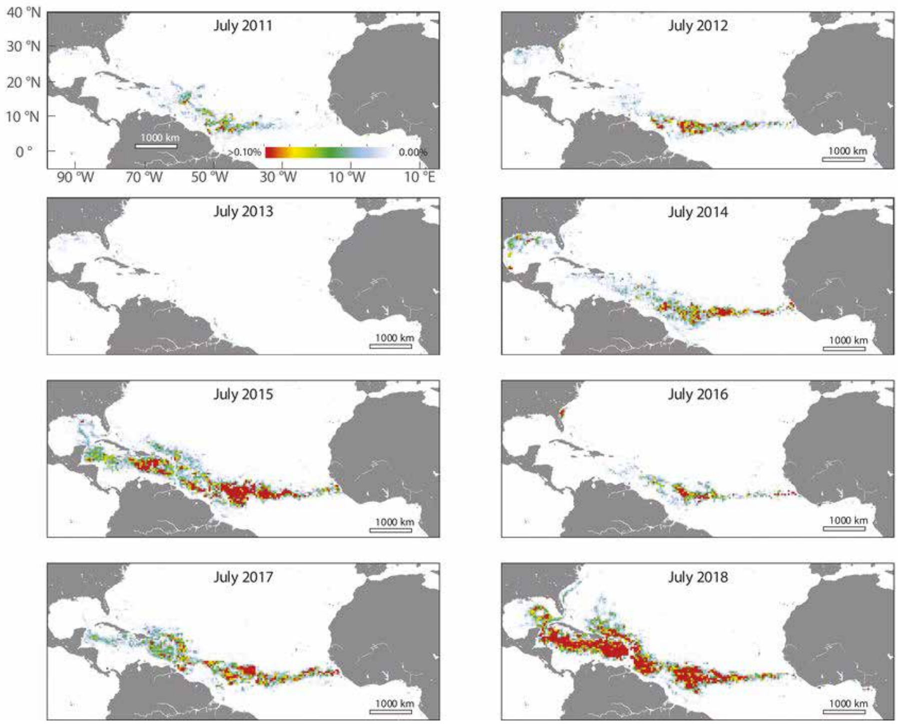
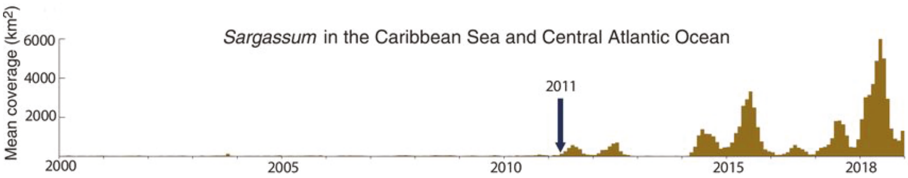


FIGURE b AREA COVERED BY *SARGASSUM* BETWEEN 2011 AND 2018.



Source: Wang *et al.*, 2019, *Science* 365: 83 – 87, with permission from AAAS. Map conforms to United Nations World map 4170 R18.1, Feb 20

This seaweed is an important ecological habitat for a number of marine animals, but in massive quantities it is deadly for the same animals and damages coastal ecosystems. Huge *Sargassum* blooms also adversely affect shore-based activities. In 2011, large quantities of *Sargassum* stretching for kilometres from the shores of western Kenya prevented fishing boats from going out to sea and entangled fishing nets, causing food shortages in the coastal villages that depend on fishing for their livelihoods (McDiarmid, 2011). When such a mass is not removed in time, it starts to wash ashore and decompose, producing noxious hydrogen sulphide. This led to huge losses for the tourism industry along the Caribbean shorelines. In 2018, Mexico spent USD 17 million on clearing 500 000 tonnes of seaweed from its Caribbean beaches, and Barbados declared a national emergency. Decomposing *Sargassum* also increases sea acidification and temperatures and creates oxygen-deficient areas. Studies have found high concentrations of arsenic and heavy metals in various *Sargassum* species, complicating the prospects for their potential application as animal feed, fertilizer or food for human consumption (Ma *et al.*, 2018).

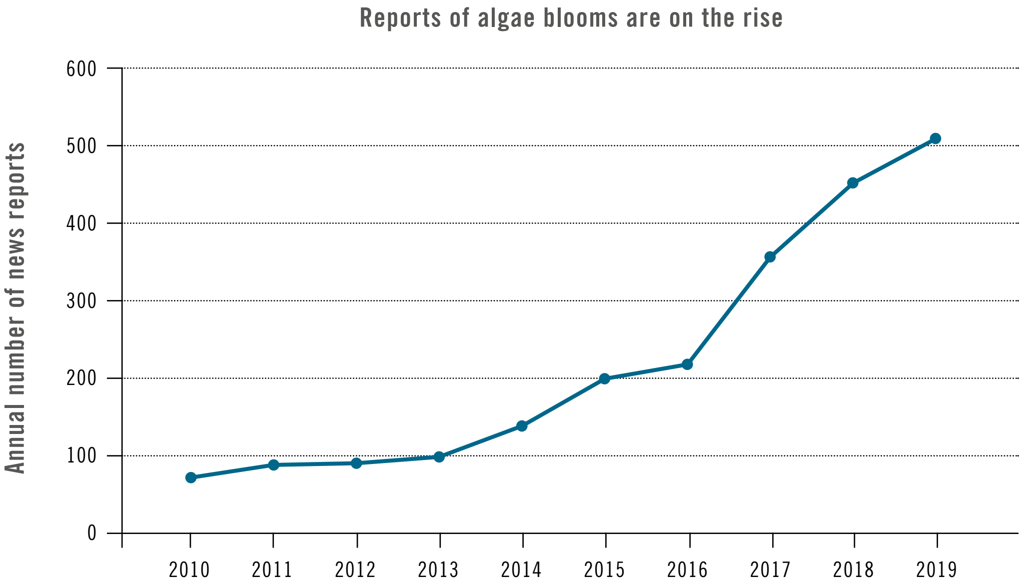
SECTION I: CLIMATE CHANGE IMPACTS ON ALGAL BLOOMS

There is growing understanding of how climate change can act as a potential catalyst in the intensification of algal blooms, resulting in potential risk to the environment and human health, particularly in coastal communities (Anderson, 2012). Projections of the effects of climate change on freshwater quality in the United States of America indicated that the mean number of days with harmful cyanobacterial blooms will increase from seven per year per water-body under current conditions to 16–23 days in 2050 and 18–39 days in 2090 (Chapra *et al.*, 2017). The Environmental Working Group,[3] based in the United States of America reported that algal blooms are appearing in more bodies of water, in larger quantities and earlier in the summer than previously recorded in the country. The numbers of algal blooms (toxic and non-toxic) that have appeared in the United States of America since 2010 are shown in **Figure 4**. Meanwhile, the global marine ecosystems will be required to adapt to “multifactoral” stressors under climate change, in addition to anthropogenic factors such as increased coastal discharges (Wells *et al.*, 2015). These stressors include temperature increase, sea-level rises, changes in precipitation patterns and light, ocean acidification, salinity, zooplankton grazing, alterations in ocean currents and coastal upwelling, enhanced stratification, and marine viruses and bacterial communities associated with phytoplankton (Lassus *et al.*, 2016; Sison-Mangus *et al.*, 2016). Together, these factors are most likely to affect the frequency, intensity and geographic extent of HABs through a range of complex relationships. They are also subject to species and strain variabilities. The following subsections discuss only a few of the climate change-associated factors arising from these multiple associations.

---

[3] Environmental Working Group, https://www.ewg.org/

FIGURE 4. **ESTIMATED NUMBER OF ALGAL BLOOMS IN THE UNITED STATES OF AMERICA SINCE 2010, BASED ON DATA COMPILED BY THE ENVIRONMENTAL WORKING GROUP**



Source: Environmental Working Group. Copyright © Environmental Working Group, www.ewg.org. Reproduced with permission

RISING TEMPERATURES IN GLOBAL WATER-BODIES

The upper sea surface is expected to experience most variation as the climate continues to warm. It is estimated that while the average global warming of the upper oceans (depth of about 75m) was 0.11 °C per decade from 1971 to 2010, in the lower layers (700 m depth) it was about 0.015 °C (Rhein *et al.*, 2013). Phytoplankton, including those that form HABs, will be among the first organisms to respond to changing conditions in the upper oceans (Irwin *et al.*, 2015). Temperature affects the rate of photosynthesis, motility and nutrient acquisition capability of phytoplankton (Wells *et al.*, 2015). The geographic range of warm water species is expected to increase, while cold water species are most likely to be pushed further towards the poles (Hallegraeff, 2010). This pole-wards shift of algal species, combined with decreasing sea ice cover in the Arctic and opening of new shipping lanes make these ecosystems vulnerable to species introduction, which can lead to increased frequency and duration of blooms by endemic algal species already present in the area. Coastal communities that still practice traditional fishing and hunting in the affected waters will feel the increase in exposure risk most acutely (Anderson, Richlen and Lefebvre, 2018). Ardyna and co-authors (2014) found that higher latitudes are starting to have two blooms a year instead of the single phytoplankton bloom in the spring which was the norm until a decade ago. Two phytoplanktonic blooms – a main one in spring and another in late summer or early autumn – are more common in seas at temperate latitudes. However, with rising temperatures in the Arctic causing a decline in the sea ice cover and a delay in sea ice freeze, most of the Arctic Ocean is now experiencing a secondary bloom in the fall (Ardyna *et al.*, 2014). HAB-causing species *Alexandrium catenella* and *Pseudo-nitzschia* are becoming increasingly common in the Arctic, with the frequency of PSP cases in Alaska being the highest in the world (Anderson Richlen and Lefebvre, 2018). In freshwater bodies, Ho, Michalak and Pahlevan (2019) studied bloom intensity trends in 71 lakes worldwide over three decades. They found that peak summer-time blooms were increasing in 68 percent of the lakes studied and suggested that lake warming may be a major factor in hampering eutrophication management efforts aimed at promoting lake recovery.

Warmer temperatures promote more growth of certain phytoplankton. A projected increase of 2.5–3.5 °C in sea surface temperatures in the Caribbean is expected to be associated with a 200 - 400 percent increase in ciguatera food poisoning cases in the region over the coming century (Gingold, Strickland and Hess, 2014). Long-term trends link warming sea temperatures to increases in blooms of *Pseudo-nitzschia* species and the prevalence of domoic acid contamination of shellfish, which subsequently raises human exposure risk (McCabe *et al.,* 2016; McKibben *et al.,* 2017). In 2015, a warm water anomaly (~3 °C above sea surface temperatures) during a heat wave caused a massive bloom of *Pseudo-nitzschia* off the northwest Pacific, extending from central California in the United States of America to almost the north of British Colombia in Canada. The resulting domoic acid toxicity caused a huge loss to the aquaculture industry in the areas affected, and several commercial fisheries had to be closed. The local Dungeness crab industry alone suffered losses of USD 48.3 million (Brown, 2016).

Certain algal species such as cyanobacteria tend to grow faster at temperatures above 25 °C, giving them a competitive advantage over other phytoplankton species in the area (Jöhnk *et al.,* 2008). Cyanobacterial blooms may also increase the water temperatures locally through intense light absorption, furthering this competitive advantage (Paerl and Huisman, 2008). In 2014, warmer temperatures led to the appearance of a large *Microcystis* (cyanobacteria) bloom in western Lake Erie, in the United States of America. The high level of microcystin toxin severely affected the quality of drinking water in the area (Lee, 2014). Other places where toxic cyanobacteria have affected water quality include Lake Taihu (China), Lake Okeechobee (United States of America) and Lake Victoria (Africa) (Cavicchioli *et al.,* 2019).

In addition to promoting phytoplankton growth, warming temperatures also widen the seasonal windows for certain HABs, enabling them to persist for longer periods and increasing the risk of humans consuming seafood contaminated with phycotoxins. Studies have found that blooms due to *Dinophysis* spp. now occur in the North Sea several weeks earlier than they did previously. They have also expanded their niche along the north and west coasts of the United Kingdom of Great Britain and Northern Ireland and Norway (Edwards *et al.,* 2006; Edwards and Richardson, 2004; Gobler *et al.,* 2017). Although warmer temperatures tend to support higher growth of certain phytoplankton, the increase in biomass is not proportional to higher toxin content. For example, while the increases in temperature lead to more cell growth and higher production of the diarrhoetic shellfish toxin in

Dinophysis spp., the yessotoxin production of *Protoceratium* sp. is higher in slow dividing cells at lower temperatures (Kamiyama *et al.,* 2010; Röder *et al.,* 2012). Widening of the seasonal window for *Alexandrium* sp. growth in Puget Sound has been estimated at approximately 30 days, which means that blooms will occur earlier in the year and stay for longer (Moore *et al.,* 2015). In addition, the life cycle of *Alexandrium* and certain other HAB-forming dinoflagellates, raphidophytes and cyanobacteria includes a resting cyst stage. Warming waters, among other factors, promotes earlier onset of the temperature "window" that is optimal for excystment (Hallegraeff, 2010; Wells *et al*., 2015).

The Continuous Plankton Recorder (CPR) is a plankton monitoring programme that has been operating since 1931. It provides the scientific community with a measure of the state of ocean plankton, mainly in the North Sea and the North Atlantic (Richardson *et al.,* 2006). Using decades of CPR data, it is possible to link warming of sea-surface temperatures and milder winters to a shift in the population of phytoplankton, with diatoms being replaced by dinoflagellates in the North Atlantic and the Baltic Sea (Edwards *et al.,* 2006; Hinder *et al.,* 2012; Spilling *et al.,* 2018). Warmer sea surface temperatures lead to decreasing amounts of surface nutrients, which tends to support the growth of the smaller dinoflagellates over the larger diatoms (Bopp *et al.,* 2005). As many HAB-forming species are dinoflagellates, this shift in the population may increase the likelihood of more HABs linked to dinoflagellates in certain parts of the world.

Ciguatera poisoning is a major foodborne illness of concern in the Pacific (WHO, 2015). Extreme weather events like hurricanes can impact reef ecosystems that can lead to increased abundance of *Gambierdiscus* spp. responsible for ciguatera poisoning (FAO and WHO, forthcoming). Research has found a strong correlation between ciguatera cases and climate oscillations such as ENSO and the Pacific Decadal Oscillation (Rongo and van Woesik, 2011). With studies suggesting an intensification of climate oscillations due to climate change, it is expected that this will most likely lead to more blooms of *Gambierdiscus* spp. (Fasullo, Otto-Bliesner and Stevenson, 2018; Liu *et al.,* 2017). In Rarotonga, Southern Cook Island in the South Pacific Ocean, the number of ciguatera poisoning cases increased from 204 per 10 000 population in 1994 to 1 058 in 2010. In 2016, a strong El Niño event combined with a positive phase of the Southern Annular Mode, which is considered an indicator of anthropogenic climate change in southeastern Pacific regions, caused consecutive blooms of *Pseudochattonella* cf. *verruculosa*, *Alexandrium catenella* and *Leptocylindrus danicus* in the Chilean fjords (Gillett, Kell and Jones, 2006; León-Munoz, Urbina and Garreaud, 2018). Gradual geographic expansions of *Pseudochattonella* cf. *verruculosa* towards the south and *Alexandrium catenella* towards the north led to their convergence, which was aptly named the "Godzilla" red tide event (Trainer *et al.,* 2019). This caused the largest mortality among farmed fish ever recorded, with the loss of 100 000 tonnes of Atlantic and Coho salmon and trout, corresponding to an export loss of USD 800 million (IOC, 2016; Trainer *et al.,* 2019).

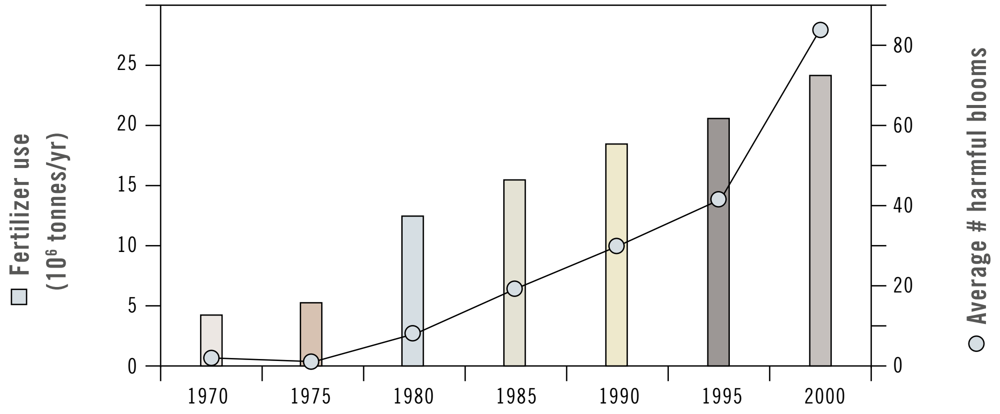
EUTROPHICATION AND PRECIPITATION CHANGES

Since the 1960s, agricultural production has seen increases of approximately ninefold in the use of synthetic nitrogen fertilizers and threefold in phosphorus application, and this usage is estimated to increase by 40–50 percent over the next 40 years (Sutton *et al*., 2013). Excessive fertilizer application leads to increased nutrient loading into aquatic systems, which is often cited as a leading cause of algal blooms (Anderson, Gilbert and Burkholder, 2002; Heisler *et al*., 2008). Depending on the growth requirements of the species concerned, nutrient enrichment can cause an increase in biomass of both toxic and non-toxic phytoplankton species in a given area, and even a modest increase of a HAB species can adversely affect the resident ecosystem (Glibert *et al*., 2010). The distribution of regions with more HABs resulting from nutrient enrichment is not uniform, but countries that are experiencing rapid population growth with corresponding increases in agriculture, livestock production and aquaculture operations will see an increase in the frequency and intensity of HABs (Anderson, 2012). The effects of eutrophication are exacerbated by various environmental factors driven by climate change such as heavy precipitation, rising sea surface temperatures and water column stratification (EASAC, 2013; Jiménez Cisneros *et al*., 2014; Martinelli and Howarth, 2006).

Nitrogen pollution is a growing major issue. Approximately 120 Tg of synthetic nitrogen is used in agriculture, including as feedstock, each year (Galloway *et al.,* 2008). Only 42–47 percent of the nitrogen added to agricultural lands is estimated to be harvested in crops while the rest is usually lost to the environment where it can find its way into waterbodies (Zhang, 2017). Nitrogen from other sources like sewage, livestock waste and fossil fuel combustion also finds its way to coastal areas, where it stimulates the initiation and persistence of HABs (Forster *et al.*, 2007; Howarth *et al*., 2005; Howarth and Marino, 2006; Park *et al*., 2019). The projected impacts of climate change on future precipitation patterns and nitrogen discharge under a "business-as-usual" scenario were shown to result in an 18 percent increase in nitrogen loading in the Mississippi–Atchafalaya Basin by the end of the 21st century, which will increase the likelihood of algal blooms in the area (Sinha, Michalak and Balaji, 2017). Phosphorus loading is often cited as the major cause of algal blooms in freshwater sources (Burkholder, 2002; Schindler, 1977). Using data from 2002 to 2010, Mekonnen and Hoekstra (2017) estimated that global human activity added 1.47 Tg of phosphorus per year to the world's major freshwater basins, with the contribution from agriculture growing by 27 percent over the study period (from 525 Gg in 2002 to 666 Gg in 2010).

India and China both have high fertilizer application rates and are predicted to receive heavy precipitation in the future owing to climate change impacts (Sinha, Michalak and Balaji, 2017). The increase in fertilizer use in China has been linked to blooms of *Prorocentrum* sp., *Karenia mikimotoi* and others, which are increasing in not only surface area but also duration (**Figure 5**). The total economic cost of HABs in China was nearly RMB 2.23 billion (USD 364 million) between 2008 and 2012 (Guo *et al*., 2013).

FIGURE 5 **RELATIONSHIP BETWEEN HARMFUL ALGAL BLOOMS (MEAN NUMBERS) AND FERTILIZER USAGE (MILLION TONNES PER YEAR) REPORTED ALONG THE EASTERN COAST OF CHINA.**



Source: Adapted from Heisler *et al.*, 2008, *Harmful Algae* 8:3 -13, with permission from Elsevier.

Climate change is also expected to exacerbate drought conditions in a number of regions worldwide (IPCC, 2014). Drought conditions and increasing demand for freshwater will have significant implications for the salinity of freshwater sources (Jeppesen *et al.*, 2015). During a severe drought in 2014, *Microcystis* caused a massive bloom in the San Francisco estuary, United States of America. The ability of cyanobacteria to tolerate high salinity and warmer temperatures helped them to out-compete other planktonic species in the area (Lehman *et al.*, 2017).

Other eutrophication sources

Aquaculture: While aquaculture contributes significantly to global food production and is expected to grow, it is also a source of nutrients that can lead to HABs mainly in poorly flushed areas. The fish consume a fraction of the feed used in aquaculture, while the remainder decomposes into nutrients, which when released can promote algal growth (Anderson, 2012). According to a recent estimate, nutrients from all forms of aquaculture operations is expected to increase sixfold by 2050 (Bouwman *et al.*, 2013).

Wildfires: The number of wildfires is increasing and is expected to increase further as a result of environmental factors related to climate change (Huang, Wu and Kaplan, 2015; Vachula, Russell and Huang, 2019). There will be a corresponding increase in firefighting efforts to control and suppress fires, which will include the use of fire retardants (long- and short-term), firefighting foams and wetting agents. Most retardants are a mixture of water, salts such as ammonium sulphates and diammonium phosphates – both of which are used in fertilizers – and other additives for thickening and preventing spoilage, with dye to impart colour (Kalabokidis, 2000). It has been speculated that these chemicals could reach freshwater sources or be washed out into coastal areas, where they could lead to algal blooms.

OCEAN ACIDIFICATION

Global oceans act as carbon "sinks" for approximately 40 percent of the CO_2 produced anthropogenically (Khatiwala, Primeau and Hall, 2009; Sabine *et al*., 2004). Currently, the surface pH of oceans has been reduced by 0.1 units (corresponding to an increase of approximately 30 percent in acidity) (Sosdian *et al*., 2018). Projections related to scenarios for the end of the century under current CO_2 emission levels from anthropogenic sources show a further decrease in pH of 0.4 units (Orr *et al*., 2005; Sosdian *et al*., 2018). Sensitivity to acidification-induced environmental conditions is expected to vary among planktonic species given their taxonomic diversity and different physiological characteristics for growth (Riebesell *et al*., 2018; Zingone and Oksfeldt Enevoldsen, 2000). Reports on the effects of ocean acidification on HAB toxicity and abundance are not uniform. One study found that higher CO_2 levels led to increased cellular toxin levels in *Alexandrium catenella* while another found decreasing cellular toxicity in *A. tamarense* under low pH conditions (Tatters *et al*., 2013; Van de Waal *et al*., 2011). Saxitoxin production in *A. ostenfeldii* was increased in the presence of low pH and elevated temperatures (Kremp *et al*., 2012). A two- to threefold increase in cellular domoic acid concentrations in *Pseudo-nitzschia fraudulenta* was found under conditions of low pH and limited phosphorus or silica conditions (Sun *et al*., 2011; Tatters, Fu and Hutchins, 2012). Low pH conditions coupled with phosphorus limitation was found to lead to increased karlotoxin production by *Karlodinium veneficum* (Fu *et al*., 2008). Under field experimental conditions of ocean acidification (more than 600 µatm of CO_2) *Vicicitus globosus*, which produces haemolytic cytotoxins, produced mass blooms that curtailed the development of coexisting species (Chang, 2015; Riebesell *et al*., 2018). This algae is reported to cause toxic blooms off the coasts of Asia, Brazil, Australia, Canada, Greece, New Zealand and the Russian Federation (Hiroishi *et al.*, 2005; Imai and Itoh, 1987). Riebesell and co-authors (2018) speculated that this competitive fitness is most likely also the case for a number of other HAB species, which will help facilitate their geographic expansion under conditions of ocean acidification. For HAB species such as *Heterosigma akashiwo*, a raphidophyte, an increase in photosynthetic growth rate and altered swimming behaviours were reported under conditions of low pH, while toxic cyanobacterial species such as *Nodularia spumigena* and *Aphanizomenon* sp. were not affected by increasing CO_2 levels (Fu *et al.*, 2008; Karlberg and Wulff, 2012; Kim, Spivack and Menden-Deuer, 2013).

It is important to point out that although some diatoms form harmful blooms, they also play crucial roles in the aquatic ecosystem. Diatoms use silicic acid to build silica cell walls (frustules), which allows them to sink into deeper waters and therefore act as important vectors for transporting carbon to the ocean depths as part of the oceanic carbon sequestration process. Recent research shows that ocean acidification hampers silica incorporation by diatoms and thus affects the carbon cycling mechanism (Petrou *et al.,* 2019). Any reduction in the carbon sequestration process could lead to an increase in CO_2 in the atmosphere, and therefore contribute to global warming (Hallegraeff, 2010).

Eutrophication followed by algal growth and degradation not only lowers the oxygen content of the water, it also increases the acidity owing to the production of CO_2 through microbial respiration. Numerous studies have shown how eutrophication increases the susceptibility of coastal regions to acidification. Cai and co-authors (2011) showed that eutrophication in the northern Gulf of Mexico and the East China Sea caused hypoxia and acidification of the subsurface waters. In 2014, Wallace and co-authors showed the connection between eutrophication and low pH in a number of estuaries in the United States of America. There are serious biological implications of the combined negative effects of hypoxia and acidification, and marine life bears the brunt of them (Gobler *et al*., 2014).

EXTREME WEATHER EVENTS

Climate change is expected to increase the frequency and severity of extreme events such as hurricanes, which can promote algal blooms by leading to massive discharges of nutrients and organic matter from watersheds into coastal waters (Wetz and Paerl, 2008). In 2003, conditions arising after Hurricane Isabel caused a massive bloom off Chesapeake Bay, United States of America (Miller, Harding and Adolf, 2006). A hurricane-induced phytoplankton bloom also occurs because of deep-water upwelling, when nutrients from deeper waters are brought to the surface, causing algal blooms within days of the passage of a storm (Pedrosa-Pàmies *et al.,* 2019). In 2007, Hurricane Gonu caused an algal bloom in the Arabian Sea (Wang and Zhao, 2008). It must be pointed out that hurricanes can also, help “dead” zones to recover in areas where warmer, oxygen-rich and fresher water sits on top of cooler, oxygen-deficient, saltier and denser water. Hurricanes Katrina and Rita, with their enormous wind speeds of more than 210 km per hour, dispelled the largest dead zone at the mouth of the Mississippi River in 2005 (Biello, 2008)**.** Other extreme events such as the marine heat waves in the Alaskan Sea in 2016 and the Southwest Atlantic in 2017 have also led to HABs (IPCC, 2019).

While the subsections in this section outlined how various climate change factors affect algal blooms, it is worth bearing in mind that the same environmental factors also affect shellfish and fish, which are the main routes of algal bloom-related poisoning in humans. Climate change perturbations may influence the metabolism of HAB toxins in marine organisms, which in turn will determine the human exposure to these toxins. Metabolism of saxitoxin by bivalve shellfish is affected by warming and acidification, which means that more of this toxin is available to move up the food chain, thereby increasing the risk of human exposure (Braga *et al.,* 2018).

SECTION II: DEAD ZONES – A CONSEQUENCE OF ALGAL BLOOMS

When algae (toxic or non-toxic) from blooms die and fall to the bottom of the ocean, microbial degradation of the algal biomass results in dissolved oxygen consumption in the area to reach levels at which the water can no longer support life. An increasing trend in nutrient loading in coastal zones has contributed to a considerable expansion of hypoxic areas in global oceans (Diaz and Rosenberg, 2008). It has been estimated that the open oceans have lost 2 percent, or 77 billion tonnes of their dissolved oxygen inventory over the past 50 years, which has serious ramifications for marine life (Breitburg *et al.*, 2018; Schmidtko, Stramma and Visbeck, 2017). Sea surface warming further reduces oxygen availability in aquatic ecosystems. In 2008, about 400 oxygen-minimum (where oxygen levels are less than 2 parts per million) or "dead" zones were reported globally **(Figure 6)**, up from 49 in the 1960s (Diaz and Rosenberg, 2008). Most of these zones are in waters that are major fishing areas – the Baltic Sea, the Black Sea, the Gulf of Mexico and the East China Sea.

Run-off from farms, combined with extreme drought conditions and diversion of water for irrigation upstream, led to massive algal blooms in the Murray-Darling Basin in Australia. The resulting hypoxic waters led to death of between 100 000 to a 1 million fish in early 2019 (Normile, 2019). An estimated ASD 10 million is

FIGURE 6 **GLOBAL DISTRIBUTION OF EUTROPHIC, HYPOXIC AND RECOVERING AREAS IN 2013.**

EUTROPHICATION AND HYPOXIA STATUS ● Eutrophic ● Hypoxic ● Areas in Recovery

Source: Adapted from Eutrophication & Hypoxia Map Data Set Accessed through Resource Watch. Map conforms to United Nations World map 4170 R18.1, Feb 20 expected to be spent on catching fish in selected drying pools and transferring them downstream on the Murray river, in preparation for another dry summer (Davies, 2019). In heavily populated cities such as Mumbai and Karachi, large quantities of sewage flow into the waterways. This, in combination with excessive fertilizer use and climate change-induced extreme weather patterns, has led to the formation of one of the world's largest dead zones in the Arabian Sea (> 2 million km^2) (do Rosario Gomes *et al.*, 2014). In the Western Hemisphere, the largest dead zone is in the Gulf of Mexico (> 20 000 km^2) and its formation is driven mainly by runoff from the Mississippi–Atchafalaya River system (Bianchi *et al.*, 2010; Rabalais, Turner and Scavia, 2002; Turner, Rabalais and Justic, 2008). In these dead zones, any marine life that cannot escape is suffocated, causing huge losses to coastal aquaculture facilities and to the entire marine ecosystem in the area. Annual global losses due to the damage caused to coastal services that depend on the aquatic ecosystem, including fisheries, by hypoxia related to coastal nitrogen and phosphorus pollution is approximately USD 170 billion (Sutton *et al.,* 2013). It has been estimated that sea floors have taken more than 1 000 years to recover from past climate-based deoxygenations. With climate change expected to drive the expansion of dead zones in the global oceans, it is bound to have serious ramifications in the future (Altieri and Gedan, 2015; Moffitt *et al.,* 2015).

SECTION III: CONCLUSIONS

MONITORING AND MITIGATION

With adequate regulations to ensure the design and implementation of appropriate monitoring and mitigation measures it will be possible to control HABs and prevent negative health effects and economic losses worldwide. The management of HABs falls into three broad areas: prevention, mitigation and control. The challenges of monitoring and forecasting HAB events is complex because of their high degree of heterogeneity (temporal and spatial) in terms of species composition, non-linear relationship between biomass and toxin production, and the numerous environmental factors that influence bloom dynamics. However, in order to achieve UN SDG 6 (clean water and sanitation) in full, it is important to establish global surveillance systems and develop accurate models for predicting algal bloom formation, especially under future climate change scenarios. Development of predictive models that link HAB formation with the occurrence of seafood intoxication outbreaks is also required.

Several approaches can be followed in the prediction of algal blooms, including utilizing artificial intelligence and deep learning models, and studying the impacts of climate change on HABs by using extreme weather events that mimic future climate change scenarios (Lee and Lee, 2018; Wells *et al.,* 2015). A recent review of a number of regional HAB observation and forecasting programmes carried out by Anderson and co-authors (2019) concluded that there was no "one-size-fits-all" approach and put forward suggestions on how to build a more effective integrated

HAB monitoring system for global oceans. The authors also emphasized the need to develop a holistic approach through multidisciplinary collaboration (Anderson *et al.,* 2019), such as the One Health Harmful Algal Bloom System used in the United States of America or the use of sentinel animals to identify and monitor HAB events (Backer and Miller, 2016; CDC, 2019).

Around the world, the coastal communities that are most at risk from HABs are in areas where no sustained monitoring programme or early warning system is in place (IPCC, 2019). Lack of appropriate regulatory frameworks in a number of countries often allows food contaminated with phycotoxins to reach the wider market. Greater investments are needed in the development of capacities for early detection, monitoring and data sharing in such countries. The number of countries that are adopting surveillance programmes to monitor the levels of toxic phytoplankton off their coasts is rising, reflecting the growing urgency of prevention and mitigation of HABs (Lassus *et al.,* 2016). In 2009, with support from the International Atomic Energy Agency, countries in Latin America and the Caribbean established a regional network for early warning of algal toxins in seafood (Cuellar-Martinez *et al.,* 2018). In recognition of the challenges that HAB brings, especially in light of climate change, international knowledge sharing partnerships have been established, including the collaboration between the European initiative on HABs, EUROHAB, and the United States Ecology and Oceanology of HABs (ECOHAB) initiative. Some other projects include the GlobalHAB programme, GEO Blue Planet, EuroCigua and the European Union's Climate Change and Emerging Risks for Food Safety (CLEFSA) project.

Although analytical tools for algal toxin detection exist, there is need for innovations in rapid and sensitive analysis (Zhang and Zhang, 2015). The major toxin groups are composed of a number of corresponding analogues with different toxicities, and assessment of the risks associated with some of these complex mixtures is covered in a joint FAO/WHO publication (FAO and WHO, 2016). There is need for technological advances that ensure timely and accurate detection of algal toxins in freshwater systems as these toxins are a safety threat to drinking water supplies, food and feed. It will be worthwhile to channel the lessons learned into regulations that require the managers of public drinking water supplies and coastal waters to test regularly for phycotoxins and cyanotoxins in areas that are becoming prone to blooms. Emerging tools such as omics approaches (genomics, transcriptomics, proteomics and metabolomics) can complement existing laboratory and field techniques for analytical detection and provide a means of developing a deeper understanding of the gene–environment interconnections in algal species (Anderson, 2012; McLean, 2013). It provides a means to analyse changes in the competitive fitness landscape by uncovering the mechanistic drivers that explain why certain species are more successful than others in adapting to environmental changes such as warmer temperatures and elevated CO_2 levels. This is especially important given the growing changes in environmental scenarios arising from climate change (Hennon and Dyhrman, 2019).

For instance, the expansion and future success of *Aureococcus anophagefferens* can be forecast by following an ecogenomics approach (Gobler *et al.,* 2011).

Regarding mitigation, the International Nitrogen Management System created as a collaboration project between UNEP and the Global Environment Facility has the aim of increasing the efficiency of nitrogen use in fertilizers and reducing total global nitrogen usage (Sutton *et al.,* 2013). Recent research shows that the breeding of wheat varieties that are more tolerant to symbiotic relationships with mycorrhizal fungi not only allows the plants to draw sufficient nitrogen and phosphorus from soil even under conditions of elevated CO_2 levels, but may also allow farmers to use less fertilizer (Thirkell, Pastock and Field, 2019). Possible strategies for mitigating (suppressing or destroying) HABs include mechanical, biological, chemical, genetic and environmental methods. Mechanical control methods include aeration to de-stratify water or the use of clay particles to aggregate HAB cells, followed by removal of the mass by sedimentation. The latter is utilized in the Republic of Korea, where HABs are a major issue for the aquaculture industry (Anderson, 2009, Haberland, 2016; Na, Choi and Chun, 1996; Sengco and Anderson, 2004). Chemical control of HABs includes adding blue dye to lakes to prevent penetration of the wavelengths required for algal photosynthesis, or dropping copper sulphate to prevent dinoflagellate blooms. The latter method was effective against algal species off the coast of Florida, United States of America in 1957, but copper sulphate also killed all the plant life in the area (Rousefell and Evans, 1958). Biological control by using algicidal bacterial species like *Shewanella* sp., predatory bacteria, filter-feeding fish or genetically altering specific algal gene expression followed by introducing these modified species into the environment are still limited to the laboratory settings (Gumbo, Ross and Cloete, 2008; Pokrzywinski *et al.,* 2017).

© Arief Adnari/Shutterstock.com

Polluted gold mine area in Indonesia.

CHAPTER 2.C

HEAVY METALS

Heavy metals are metallic elements that have densities much higher than that of water (Fergusson, 1990). Some of these metals are used in a variety of industrial, agricultural and technological applications. Although they are emitted into the environment *via* natural processes such as volcanic eruptions, wildfires and weathering, most heavy metal contamination in the environment comes from deposition of these elements from anthropogenic sources to the surface of the earth (Tchounwou *et al.*, 2012). Eventually rainfall can then facilitate the displacement of metals from the soil into community water supplies. Heavy metals are persistent, making remediation difficult and expensive.

Metal pollution has adverse effects on marine ecosystems and human health (Tracy, Weill and Harvell, 2019). The heavy metals that are of major public health concern are lead (Pb), chromium (Cr), cadmium (Cd), mercury (Hg) and arsenic (As), which are considered to be systemic toxicants even at low levels of exposure. Other metals such as cobalt (Co), copper (Cu), iron (Fe), nickel (Ni), magnesium (Mg), manganese (Mn), zinc (Zn) and selenium (Se) are considered to be micronutrients as they have essential biological functions, for instance as metalloenzymes. However, each metal has its own physicochemical properties and at certain levels of concentration exerts specific toxicological effects on metabolic processes in humans, including immunological, respiratory and chromosomal damage, oncological issues and many others (Jarup, 2003). In addition, the use of heavy metals in agriculture and aquaculture can promote the spread of antimicrobial resistance (AMR) through a co-selection process (Seiler and Berendonk, 2012). Heavy metals enter the human body mainly through diet, and some metals may bioaccumulate if certain food items such as seafood are consumed regularly.

The Joint FAO/WHO Expert Committee on Food Additives (JECFA) has established tolerable daily intake (TDI) levels for different metals (FAO and WHO, 2007; 2011a; 2011b; 2013). In addition, apart from dietary intake, studies show that children in urban areas are at risk of lead exposure from topsoil through inhalation and hand-to-mouth contact (Clay, Portnykh and Severnini, 2019; Mielke *et al.*, 2019).

SECTION I: CLIMATE CHANGE IMPACTS ON HEAVY METAL CONTAMINATION

Based on current available scientific literature, it is difficult to accurately account the short-term influence of climate change on heavy metal accumulation in the environment and the subsequent effect on food safety (for Hg, see **Chapter 2.D**). Alterations in rainfall intensity resulting from climate change are predicted to influence the transport of heavy metals by enhancing run-off from soil and increasing the leaching of heavy metals into water systems (Joris *et al.,* 2014; Wijngaard *et al.,* 2017). Arsenic contamination is a major concern in drinking water in a number of countries, including Bangladesh and India (Ahmad, Khan and Haque, 2018; Chakraborti *et al.,* 2018). WHO calculates that approximately 140 million people in more than 50 countries drink water with levels of As contamination that are far higher than the WHO provisional guideline value of 10 µg/ L (Ravenscroft, Brammer and Richards, 2009). A study that examined lifetime cancer cases in the United States of America attributed to contamination of community water systems in the period 2010–2017 found that As, along with disinfection chemicals, significantly enhanced the risk of cancer, contributing to 87 percent of the total number of estimated cancer cases (Evans, Campbell and Naidenko, 2019). The financial burden of cardiovascular disease and cancer resulting from As contamination in drinking water in the United States of America has been estimated at USD 10.9 billion a year (Greco *et al.,* 2019). The impact that climate change has on these numbers has yet to be investigated, but it is quite likely that heavy metal contamination of water supplies in several areas around the world will worsen as a result of climate change factors such as heavy precipitation patterns, acid rain and extreme weather events. The intensity and frequency of hurricanes are likely to increase because of climate change, resulting in flooding (Knutson *et al.,* 2019a; 2019b), which in turn can cause overflows from toxic waste sites and alter the distribution of contaminants in the area, causing damage to the environment and contributing to human health risks (Carere, Miniero and Cicero, 2011). For example, flooding in areas that store coal ash – a by-product of coal combustion that contains heavy metals such as As, Cr, Pb and Hg – can wash heavy metals into river systems (Dennis, Mufson and Eiperin, 2018).

An analysis published in 2016 described the heavy metal content of agricultural topsoil in Europe. It showed that 6.24 percent of agricultural land (137 000 km^2) required detailed assessment of contamination and remedial action (Toth *et al.,* 2016). Crops absorb heavy metals from the soil, leading to propagation of the heavy metal content along the food chain and thus affecting food safety and human health (Mahmood and Malik, 2014; Naseri *et al.,* 2015). China is facing high levels of heavy metal contamination in agricultural soils. According to a study published in 2015, 10.2 percent of arable land in China had high heavy metal contamination (mainly Hg and Cd), which affected almost 14 percent of the country’s grain production (Zhang *et al.,* 2015). A major crop that is known to take up and bioaccumulate As from the soil or irrigation water is rice, which is produced and consumed mainly in developing countries (OECD and FAO, 2018). Heavy metals accumulate not only in the plant itself but also in the grain that is consumed, thereby threatening the health of millions of people. One of the factors that governs As uptake is soil

©FAO/ Filipe Branquinho

Farmer working in the rice fields, Mozambique.

temperatures, which is expected to rise with climate change (Fang, Luo and Lyu, 2019; Qian *et al.,* 2011; Yeşilırmak, 2014). A study that looked at the association between As sequestration by the root system of rice under current and expected soil temperatures in Bangladesh found that the uptake of As by the plants increased under elevated soil temperatures (Neumann *et al.,* 2017). Recent research shows that the As content of rice may double in the future owing to the effect of increasing temperatures on soil processes. The combination of future climate conditions and increased As content in soil is predicted to reduce rice production by 39 percent by 2100, also severely affecting food security (Muehe *et al.,* 2019). In addition, there may be an association between increased As concentrations in rice grain and higher air temperatures, particularly during the late ripening stage of rice (Arao *et al.,* 2018).

Attention must be paid to how climate change can exacerbate the effects of anthropogenic activities on heavy metal contamination. Anthropogenic activities are the leading cause of acid rain, which promotes the mobilization and leaching of nutrients and heavy metals out of the soil into water systems, affecting agriculture and water safety (Zheng, Zheng and Chen, 2012). Overuse of nitrogen chemical fertilizers is currently one of the leading causes of soil acidification, which is a major issue in global croplands (FAO and ITPS, 2015; Guo *et al.,* 2010). Decreases in soil pH affect the bioavailability and mobilization of heavy metals (FAO and ITPS, 2015). Tian and Niu (2015) reported an average global reduction of 0.26 units in soil pH due to nitrogen addition. This increases the risk of heavy metals finding their way into the food chain after heavy precipitation episodes (Zeng *et al.*, 2011). Under drought conditions, which are expected to worsen in certain regions of the world as a result of climate change, populations living in areas that have heavy mining activities might experience toxicity effects resulting from inhalation or ingestion of airborne fine heavy metal particulate matter (IPCC, 2012; Thomas *et al.*, 2018). Drought conditions also tend to concentrate contaminants in water sources (Benotti, Stanford and Snyder, 2010).

Accelerated permafrost thaw caused by climate change may release historically trapped heavy metals such as As into aquatic ecosystems, compromising aquatic life and the safety of freshwater supplies (Yu *et al.*, 2019). Permafrost thawing also poses serious concerns in long abandoned mines at higher altitudes. In colder regions, in previous centuries, mine operators left the by-products of mineral processing – which are laden with heavy metals – in frozen structures reinforced by permafrost, rather than in constructed structures. Thawing permafrost is leading to acid drainage from these mines, which is resulting in the leaching of heavy metals into nearby soil and water systems, threatening the health and economy of countless communities downstream (Downing and Jacobs, 2014; Wilt, 2016)

A potential emerging source of heavy metal contamination is the use of certain nanoparticles. The marine ecosystem acts as a sink for nanoparticles, which are carried by precipitation and surface runoff. This has bioaccumulative effects on marine invertebrate species, potentially affecting the food chain (Canesi and Corsi, 2016; Conway *et al.*, 2014; Wang *et al.*, 2016). It should be noted that current understanding of nanoparticle-induced toxicity in humans is limited. Nanoparticles of titanium dioxide ($nTiO_2$) are one of the most common nanoparticles; others include Cu, Fe, Ag and zinc oxide (Shi *et al.*, 2019). Du and co-authors (2017) showed that under elevated CO_2 conditions there was higher bioaccumulation of $nTiO_2$ in rice grains, creating a potential food safety issue. The authors also found that under the same conditions the nutritional content and yield of rice decreased significantly, thereby affecting food security (Du *et al.*, 2017). Recent evidence suggests that high CO_2 levels can enhance the bioaccumulation of $nTiO_2$ in edible bivalve molluscs, posing a potential risk to consumers (Shi *et al.*, 2019). Although bivalves are filter feeders and tend to accumulate contaminants, they are also a traditional aquaculture species and provide 1×10^8 tonnes of seafood for consumers annually (FAO, 2014). Research shows that bioaccumulation of other heavy metals, including Cd, also increases in bivalve species under ocean acidification conditions because of increased uptake and reduced Cd exclusion (Shi *et al.*, 2016). Low pH has been shown to promote the formation of inorganic As (Arsenite), which is more toxic than the organic version (Sharma and Sohn, 2009). Bioaccumulation of heavy metals in fish tends to depend on factors such as fish age, size and trophic level in the ecosystem. While certain heavy metals such as Cd, Cr, Cu, Fe, Pb and Zn show a negative association between bioaccumulation and fish size, methylmercury shows the opposite trend (**Chapter 2.D**) (Canli and Atli, 2003). Similarly, bioaccumulation of As and Pb reduces with increasing trophic level, whereas Zn shows a positive association between bioaccumulation and trophic level (Chen *et al.*, 2000; De Gieter *et al.*, 2002). How these trends will be affected by alterations in the marine ecosystems resulting from climate change has yet to be investigated.

Another important source of heavy metal pollution is the waste from nuclear fuel cycles, which also finds its way into the oceans. Rising sea levels and melting glaciers can trigger seismic activity, causing devastating tsunamis and earthquakes (Masih, 2018). Such seismic activity can cause massive damage to nuclear facilities, as occurred during the Fukushima Dai-ichi nuclear power plant accident in 2011, which released large amounts of radionuclides into the environment. While nuclear power plants are a means of providing carbon-free electricity, such installations must be made climate-ready because they are often located near coastlines and are vulnerable to flooding. It is also important to consider the combined effects of climate variables and radionuclides on aquatic animals, as these will in turn affect the safety of the food chain. While it is known that radionuclides tend to bioconcentrate in marine biota, a study published in 2018 showed that low ocean pH increased the bioconcentration of radionuclide ^{57}Co in bivalves (Carvalho, 2018; Sezer *et al.,* 2018).

SECTION II: CONCLUSIONS

Heavy metal pollution and its effects on public health are a neglected area that requires urgent attention at regional and national levels, especially in the context of climate change. A number of physical, chemical and biological remediation approaches can be used to remove heavy metals from contaminated areas. Bioremediation is one of the more viable of these options in terms of both its low environmental impact and its cost-effectiveness (Khalid *et al.,* 2017). Bioremediation involves approaches such as phytoremediation, which utilizes plants that are hyperaccumulators to sequester heavy metals from soils, and is followed by methods such as phyto-mining to extract the metals from the plants (Ali, Khan and Sajad, 2013; Salt *et al.,* 1995). This process is, however, extremely time consuming. Bioremediation processes for wastewater treatment using microalgae are also attracting attention (Zeraatkar *et al.,* 2016). Today, the focus is on developing integrated approaches that use a combination of physical, chemical and biological processes to deliver more synergistic responses to heavy metal remediation efforts (Selvi *et al.,* 2019). For cases of radionuclide contamination, scientific innovations such as microrobots may, one day, be able to remove radioactive isotopes from nuclear plant wastewater and the environment in case of a spill or the potential use of cyanobacteria for bioremediation (Ying *et al.,* 2019; Mehta *et al.,* 2019). Despite the progress of scientific innovations in remediation, unless more stringent regulatory standards for heavy metal management are introduced, contamination will continue to cause environmental deterioration and harmful health effects, especially under climate change conditions.

© FAO/ Miguel Riopa

Worker putting ice on swordfish before fish auction begins in Spain.

CHAPTER 2.D

METHYLMERCURY

WHO considers mercury to be one of the top ten chemical contaminants of public health concern (Sheehan *et al*., 2014). While all forms of mercury – elemental (Hg^0), inorganic (Hg^+ and Hg^{2+}) and organic (methylmercury CH_3Hg^+ and dimethylmercury[4] CH_3HgCH_3) are toxic, methylmercury (MeHg) is especially so as it bioaccumulates in the aquatic food web and is a developmental neurotoxicant. Another form of organic mercury, dimethylmercury, once absorbed gets distributed in the tissues of vertebrates and can cause neurological symptoms (EPA, 2004). MeHg can cross the placenta and the blood–brain barrier, making it especially dangerous for developing foetuses as *in utero* exposure endangers the development of the peripheral and central nervous systems (Campbell, Gonzalez and Sullivan, 1992; Rodier, 1995). This exposure leads to various neurological complications in later life that include delayed development, speech impairment, seizures and mental retardation (Sheehan *et al.*, 2014). The high toxicity of MeHg was first recognized in the 1950s in Minamata, Japan where people suffered from severe disabilities and died from eating seafood contaminated with mercury (at concentrations as high as 50 mg/kg) that bioaccumulated in the food chain (Fujuki, 1980; Harada, 1968). The Minamata Convention on Mercury, which was adopted in 2013, is a global treaty established to protect human health and the environment from the toxic effects of anthropogenic mercury release. Other large-scale MeHg-related incidents occurred in Niigata (1960s), Japan and Iraq (1970s) (Bakir *et al.*, 1973). MeHg exposure has both health and financial implications (**Box 8**). It is estimated that more than 75 000 newborn babies face an increased risk of learning disabilities from *in utero* exposure to MeHg in the United States of America every year (EPA, 2018). In adults, research shows that even at low doses MeHg increases vulnerability to cardiovascular effects (FAO and WHO, 2007; Karagas *et al.*, 2012; Nishimura *et al.*, 2019; Roman *et al.*, 2011). In China, 7 360 deaths due to fatal heart attacks were reported as a result of consumption of various foods containing MeHg in 2010 (Chen *et al.,* 2019).

---

[4] Dimethylmercury is found in the global oceans at detectable levels. In seawater, dimethylmercury decomposes to form methylmercury (Mason and Fitzgerald, 1996, Black, Conaway and Flegal, 2009)

BOX 8

CURRENT AND PROJECTED COSTS ASSOCIATED WITH MeHg EXPOSURE

Calculation of the health costs associated with MeHg exposure have been carried out based on the loss of intelligence or IQ points, which has a corresponding loss in economic productivity over the lifetime of children exposed to MeHg. Trasande and co-authors (2016) published data from sites contaminated with mercury in 15 countries. The data showed that among the 262 230 children born in the selected areas during the year under study, MeHg exposure resulted in the loss of 72 160 IQ points. An additional 1 310 cases of intellectual disabilities were identified per year, estimated to represent 16 501 lost DALYs. In total, an annual economic loss of USD 77.4 million was calculated from the selected sites. From analysis of data on mercury concentrations in the hair of women and girls of reproductive age from the DEMOCOPHES project,[5] Bellanger and co-authors (2013) found that the amounts were highest in southern Europe and the lowest in eastern Europe. The authors also estimated that in the European Union (EU) between 1.5 and 2 million children (35 percent) were born each year to women whose exposure to MeHG exceeded the reference limit of 0.58 µg/g, and about 900 000 (17 percent) were born to women whose hair mercury content exceeded 1.0 µg/g. It was calculated that the total benefits from preventing MeHg exposure in the EU would be an additional 600 000 IQ points per year, corresponding to about EUR 9 billion per year (Bellanger *et al.*, 2013). A policy-to-impacts study estimated that by 2050, United States of America can save USD 339 billion in lifetime benefits and USD 104 billion in cumulative economy-wide benefit by reducing emissions, based on the global policies under Minamata Convention on Mercury (Giang and Selin, 2016).

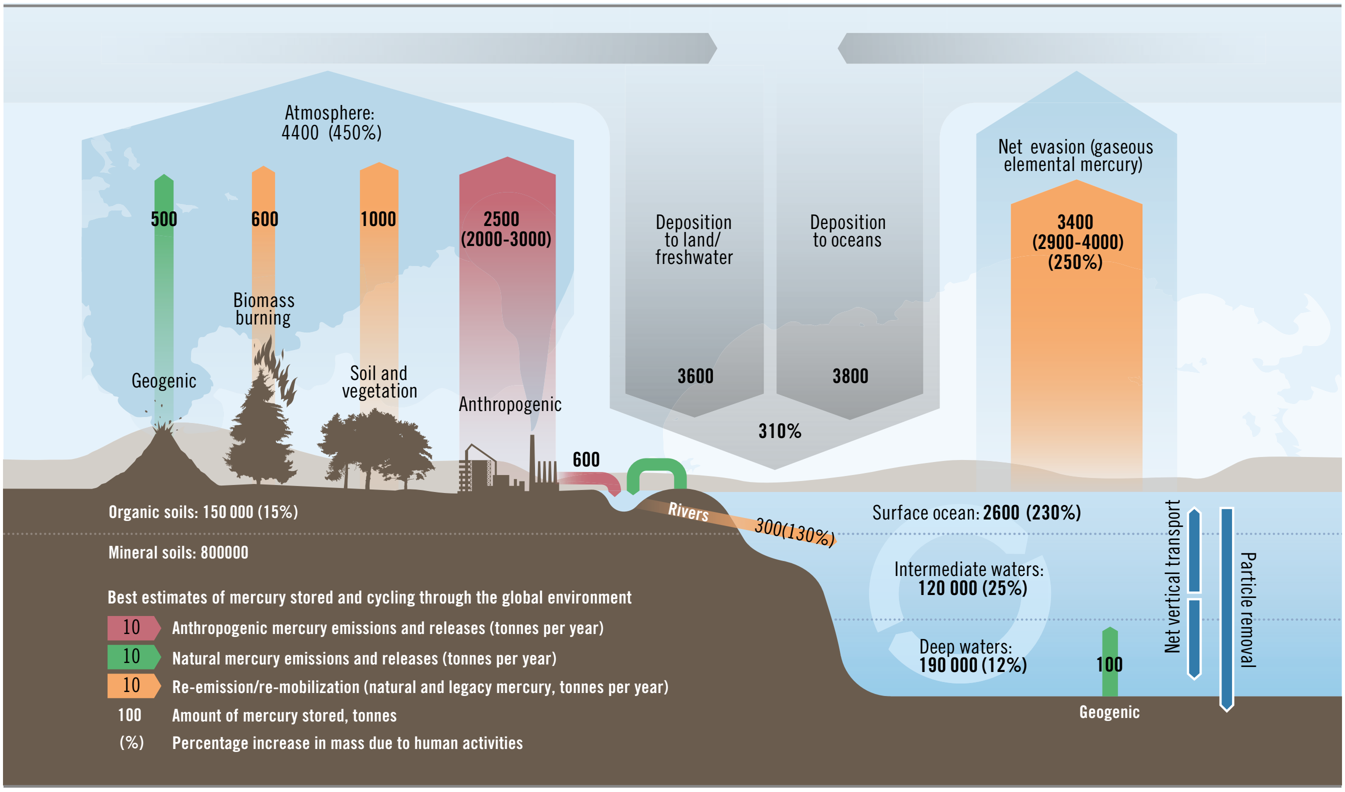
The Joint FAO/WHO Expert Committee on Food Additives (JECFA) and the European Food Safety Authority (EFSA) Panel on Contaminants in the Food Chain (CONTAM) have both carried out health risk assessments for methylmercury in food (FAO and WHO, 2007; CONTAM, 2012).

Emissions from anthropogenic sources contribute substantially to the release of mercury into aquatic ecosystems globally (AMAP and UNEP, 2013). The total amount of mercury that is released into the environment (**Figure 7**) from natural sources, anthropogenic sources and re-emissions has been estimated to be between 80 and 600, between 2 000 and 3 000 and between 4 000 and 6 300 tonnes per year by different authors (Gworek *et al.*, 2016; AMAP and UNEP, 2013). The amounts and distribution of atmospheric mercury globally are changing because of a modest lowering of emissions from North America and Europe accompanied by a concomitant increase in emissions from Asia and developing countries resulting from rapid industrialization (**Figures 8 and 9**). Global mercury emissions from anthropogenic sources in 2015 were approximately 20 percent higher than the concentrations in 2010 (UNEP, 2019). With an atmospheric lifetime of between 6 and 24 months, elemental mercury, which is released in gaseous form from various sources, is widely dispersed around the globe, reaching even remote areas where there are no atmospheric releases, such as in Arctic regions (AMAP and UNEP, 2015; Selin, 2011).

---

[5] Information on the project is available at http://www.eu-hbm.info/democophes.

FIGURE 7 **GLOBAL MERCURY CYCLING**



Source: Adapted from UN Environment Programme, 2019.

Research shows that methylation of mercury in the oceans (**Box 9**), which influences human exposure to methylmercury *via* the aquatic food chain, is proportional to the amount of mercury deposited into the aquatic ecosystem from various sources, (Harris *et al.*, 2007; Mason *et al.*, 2012). The concentration of mercury present in the ocean surfaces has increased by a factor of three or more compared with pre-anthropogenic conditions. This accounts for an estimated 290 ± 80 million moles (5.8 ± 1.6 million kg) of mercury of anthropogenic origin in oceans worldwide, with the highest concentrations in the Arctic and North Atlantic oceans (Lamborg *et al.*, 2014). Over recent years, numerous publications have highlighted the concentration of MeHg in various waterbodies including the Pacific, Arctic and Atlantic oceans, the Mediterranean Sea and the Antarctic Ocean (Bowman *et al.*, 2015; 2016; Cossa, Averty and Pirrone, 2009; Gionfriddo *et al.*, 2016; Heimburger *et al.*, 2010; 2015; Kim *et al.*, 2017; Munson *et al.*, 2015).

The bioaccumulation of MeHg in the aquatic food chain is a major concern, as ocean and freshwater fish are generally the largest source of foodborne mercury exposure in humans and 80–100 percent of total mercury content in fish corresponds to MeHg (EFSA, 2012). The concentration of MeHg in fish depends on the fish's diet, age and ranking in the food chain (FAO and WHO, 2010; Lepak *et al.*, 2019). While the average concentration of MeHg in fish is about <0.4 µg/g, apex predatory fish tend to contain methylmercury concentrations that are far higher than the surrounding seawater, sometimes by more than a million times

(Dietz *et al.*, 2000; Gilmour and Riedel, 2000; Krabbenhoft and Sunderland, 2013). Numerous studies have calculated the MeHg content of fish from various oceans (Afonso *et al.*, 2013; Storelli *et al.*, 2003a; 2003b; 2005).

In seafood other than fish, MeHg constitutes between 50 and 80 percent of total mercury levels (FAO and WHO, 1972). Other critical sources of MeHg exposure for humans include rice and poultry (Feng *et al.*, 2008; Meng *et al.*, 2014 Yin *et al.*, 2017, Zhang *et al.*, 2010). A survey of commonly marketed rice-based infant cereals from the United States of America and China showed that they contained high concentrations of MeHg, indicating another potential pathway for MeHg exposure in children (Cui *et al.*, 2017). Breastmilk can also be a source of mercury in infants (da Cunha, Costa and Caldas, 2013). The vulnerable population groups most at risk from MeHg exposure are women and girls of reproductive age, pregnant or lactating women, breastfed infants, young children and people with high fish consumption.

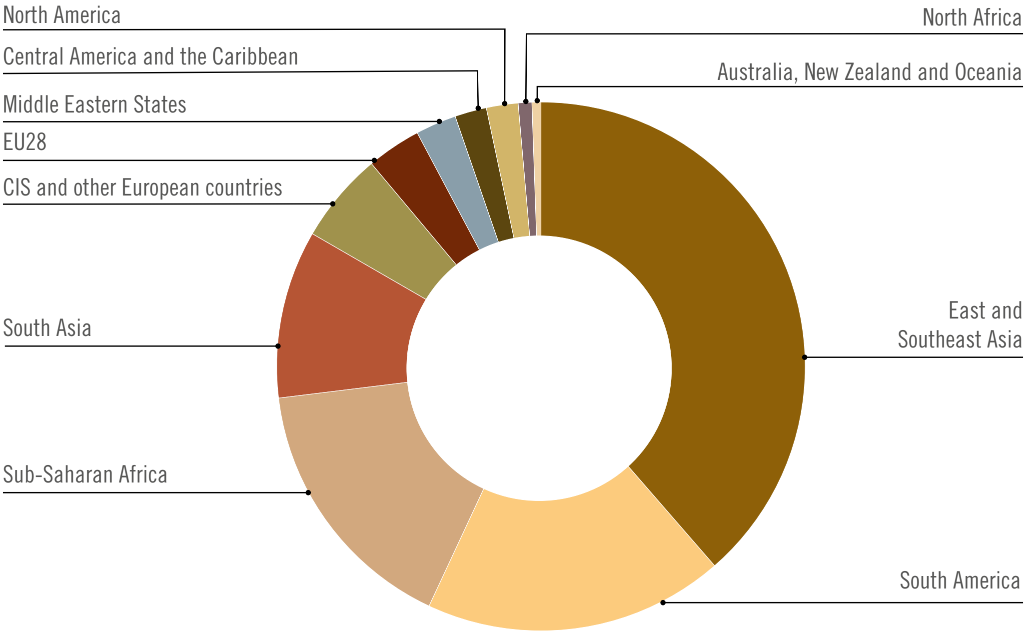
BOX 9

METHYLATION MECHANISMS AND SITE DISTRIBUTION

The transformation of mercury emissions into MeHg takes place mainly in aquatic systems. Inorganic mercury is converted into methylmercury through methylation by anaerobic bacteria of the *Deltaproteobacteria*, which are involved in sulphate and iron reduction in nature (Obrist *et al.*, 2018; Parks *et al.* 2013). The conserved gene pair (*hgcAB*) that codes for methylation of inorganic mercury has also been identified in a number of methanogenic archaea, and it has been found that methanogens can produce MeHg at rates that are close to those achieved by members of *Deltaproteobacteria* (Gilmour *et al.*, 2018). Conversion of elemental mercury (Hg^0) to MeHg by certain bacterial species has been discovered. Hu and co-authors (2013) suggest that communities of methylating and non-methylating bacteria may work together to convert Hg^0 into MeHg under anaerobic conditions. This finding poses challenges for mercury clean-up operations, as a potential method of tackling MeHg contamination is to convert inorganic mercury into its volatile elemental form, which is based on the assumption that the elemental mercury would bubble out of water and dissipate.

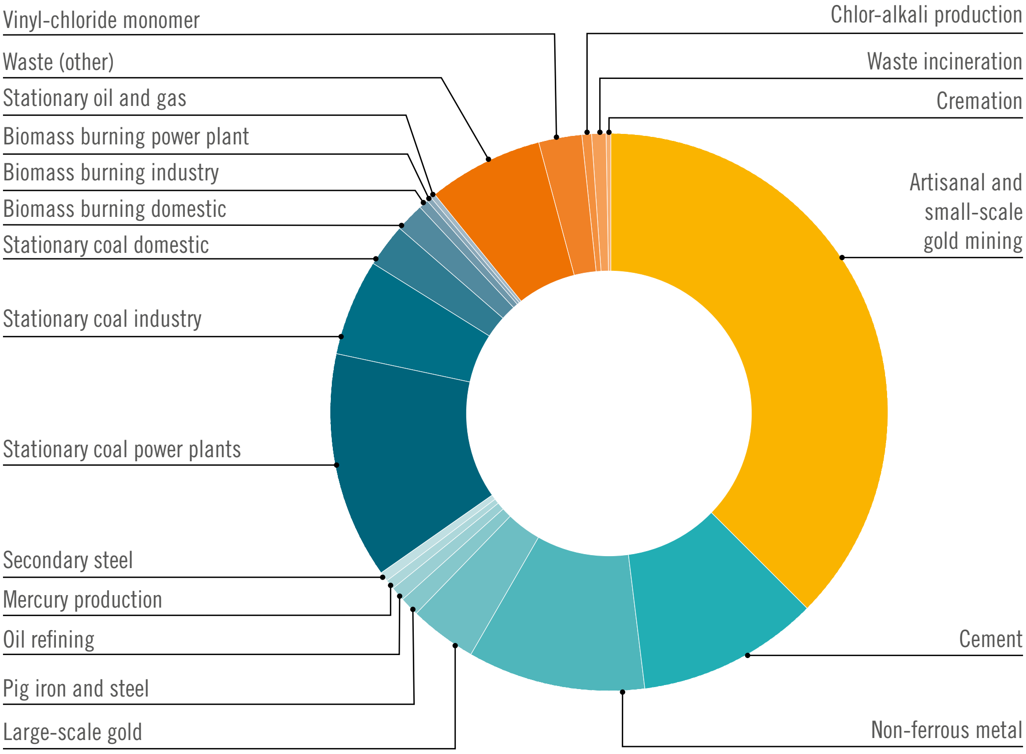
Anthropogenic causes such as the overuse of sulphate-rich fertilizers and their subsequent runoff into wetlands can also increase the methylation of mercury by sulphate-reducing bacteria, leading to higher concentration of MeHg in freshwater fish (Bates *et al.,* 2002). As the sulphate-reducing bacteria help to decompose organic matter, the process releases nitrogen and phosphorus, causing eutrophication in neighbouring water systems (Myrbo *et al.,* 2017). To date, most of the microorganisms that methylate mercury have been isolated from aquatic sediments and wetlands. However, based on the global distribution of *hgcAB* genes and other methylating microbes, as estimated through the use of metagenomics approach, new areas where MeHg could be released into the terrestrial and aquatic food webs have been identified. These areas include the coastal "dead zones" that result from algal blooms, thawing permafrost soils, the digestive tracts of invertebrates and rice fields (Liu, Zhuang and Zhuang., 2017; Podar *et al.*, 2015). The potential for mercury methylation of inorganic mercury by methanogens in the human gut microbiome remains unknown although *Methanobrevibacter luminyensis*, isolated from human faeces, was found to contain *hgcAB* genes and could methylate mercury (Podar *et al.*, 2015). However, it must be borne in mind that in any given system, there is always an interplay between methylation and demethylation processes that determine the net concentration of MeHg in the area (Avramescu *et al.*, 2011; Lu *et al.,* 2017). The effects of climate change on the bacterial species responsible for demethylation of mercury in aquatic environments has yet to be investigated.

FIGURE 8 DISTRIBUTION OF GLOBAL MERCURY EMISSIONS FROM ANTHROPOGENIC SOURCES INTO THE ATMOSPHERE IN 2015 BROKEN DOWN BY REGION



Source: Adapted from UN Environment Programme, 2019.

FIGURE 9 PROPORTIONS OF ATMOSPHERIC MERCURY EMISSIONS FROM VARIOUS SECTORS GLOBALLY IN 2015



Source: Adapted from UN Environment Programme, 2019.

SECTION I: CLIMATE CHANGE IMPACTS ON METHYLMERCURY CONTAMINATION

It is reasonable to expect that climate change will affect the bioaccumulation of MeHg in the marine ecosystem, which is linked to the food chain (Alava *et al.*, 2018). Not enough is currently known about the biomagnification of MeHg in terrestrial ecosystems and how the related risk applies to the human food web (Tsui *et al.*, 2019). The following paragraphs focus on climate change-induced environmental factors and their impact on MeHg concentrations in the marine ecosystem.

RISING TEMPERATURES

Methylation of mercury is temperature-dependent (Dijkstra *et al.*, 2013; Downs, Macleod and Lester, 1998). A study from 2005 showed how ocean warming rates of 0.4 °C and 1.0 °C around the Faroe Islands could facilitate average increases in methylation of mercury concentrations of 1.7 and 4.4 percent respectively, which translate into increased exposure for humans. It has been estimated that concentrations of MeHg in different fish species could increase by 3–5 percent for every 1 °C rise in the water temperature (Booth and Zeller, 2005; Reist *et al.*, 2006). Warmer temperatures have been linked to increased MeHg accumulation in European seabass (*Dicentrarchus labrax*), a commercially important species (Maulvault *et al.*, 2016).

In the oceans, large amounts of mercury are driven deeper into the water through current patterns that push cold, salty and denser water away from surface shallow waters. This helps to reduce greatly the amount of mercury available to enter the food chain (Lamborg *et al.*, 2014; Sunderland and Mason, 2007). With anthropogenic mercury levels predicted to rise over the coming centuries, combined with warming oceans, the ability of deeper waters to sequester mercury may be overwhelmed, leading to higher concentrations of the neurotoxicant in surface waters and, consequently, in the food chain (Stern *et al.*, 2011; Streets, Zhang and Wu, 2009). Schartup and co-authors (2019) predicted that a warming trend in the Gulf of Maine would increase the MeHg levels in resident tuna by 30 percent between 2015 and 2030, and in fact, mercury levels rose by 3.5 percent every year from 2012 to 2017. This has been attributed to fish having higher metabolisms in warmer waters leading them to consume more prey, which in turn results in higher accumulation of MeHg (Schartup *et al.*, 2019). The same authors also found an association between overfishing and higher concentrations of MeHg in predatory fish. In some areas, overfishing is forcing predatory fish to change their prey to fish species that contain higher concentrations of MeHg than the species that constituted their original diets and had lower MeHg levels (Schartup *et al.*, 2019). Changes in diet are also caused by rising seawater temperatures, which alter the distribution of prey fish (Cheung *et al.*, 2009).

© Anke Sundermeier/Pixabay

Tuna caught by fishermen in Sri Lanka.

CHANGES IN PRECIPITATION, AND DROUGHT

Increased local precipitation resulting from climate change will enhance the deposition of inorganic mercury in lakes and oceans, potentially leading to more methylation of mercury. Changes in precipitation will also result in a 20–30 percent increase in the amounts of organic matter deposited in various aquatic areas around the globe because of large-scale runoffs (IPCC, 2013). Research shows that dissolved organic carbon is a strong driver of increases in MeHg concentrations in estuarine and coastal ecosystems (Taylor *et al.*, 2019). It has been estimated that an increase of 15–20 percent in the organic matter content of flows from land into seas could enhance the MeHg concentration in plankton sevenfold (Jonsson *et al.*, 2017). However, several other studies have pointed out that although eutrophication enhances the concentration of methylmercury in aquatic systems, algal blooms tend to decrease the biomagnification of MeHg through the dilution of mercury by the algal cells (Achá *et al.*, 2018; Pickhardt *et al.*, 2002; Razavi *et al.*, 2015).

A study evaluated the effect of drought, a potential effect of climate change, on the level of MeHg accumulation in different fish species in the Paraíba do Sul River basin in southeastern Brazil. The authors reported that there was a 20 percent increase in MeHg concentrations in the muscle tissues of fish compared with to levels from the previous year that did not have drought conditions (Azevedo *et al.*, 2018).

OCEAN ACIDIFICATION

Research shows that lowering pH values increases the microbial uptake of mercury, particularly in the presence of dissolved organic carbon (Kelly, Rudd and Holoka, 2003; Le Faucheur *et al.*, 2011). With the pH of the oceans likely to decrease in the coming decades owing to rising CO_2 levels, this factor will play a role in the concentration of MeHg levels in fish and, consequently, in humans (Caldeira and Wickett, 2005).

WILDFIRES

A 19 percent increase in global fire emergencies resulting from various factors related to climate change has been estimated (Huang, Wu and Kaplan, 2015). Research shows that under a "business-as-usual" climate scenario, regions that are prone to wildfires (including the United States of America and Australia) may see increases in the intensity of heatwaves and wildfires due to the effects of El Niño and La Niña (Fasullo, Otto-Bliesner and Stevenson, 2018). Globally, wildfires tend to release large amounts of mercury that is stored in terrestrial ecosystems into the atmosphere, from where it is likely to find its way into the food chain (Freidli *et al.*, 2009; Webster *et al.*, 2016). Kumar and co-authors (2018) found that climate change effects could lead to a 14 percent increase in global emissions of mercury due to wildfires between 2000 and 2050.

THAWING OF PERMAFROST

According to a study published in 2018, the Arctic permafrost contains 1 656 ± 962 Gg of mercury, amounting to approximately ten times the total amount of mercury released into the atmosphere from anthropogenic sources to date. The likelihood of this mercury being released into the environment as ice starts to melt due to global warming is high (Schuster *et al.*, 2018). A recent study shows that mercury from previously frozen soils is converted into MeHg in the Arctic region, exposing local wildlife and indigenous communities to contamination risks (Fahnestock *et al.*, 2019). Over the past couple of decades, a warming trend has been observed in the permafrost of Scandinavia and Svalbard in Europe (European Environmental Agency, 2017). Another study published in 2017 found that melting Himalayan glaciers had a role in the downstream transportation of mercury. Authors have also found that the hydrodynamic erosion of bedrock is another source of the mercury that is released into rivers (Sun *et al.*, 2017). Thaw slumps (equivalent to landslides) caused by rapid thawing of permafrost are another source of downstream MeHg concentration (St. Pierre *et al.*, 2018). An additional risk factor is the release of carbon along with mercury as the permafrost thaws because this can create additional sites for methylation (Stern *et al.*, 2011).

SECTION II: CONCLUSIONS

Remaining aware of the effects of climate change on MeHg contamination in our environment will allow countries to prepare and take appropriate precautionary and mitigation measures. Full implementation of the Minamata Convention is necessary to achieve long-term results in the control of mercury emissions. More attention needs to be paid to capacity building, awareness raising and focusing on science-based solutions. Scientific research can help to bring about effective implementation of the different actions included in the convention. This can be carried out by enhancing understanding of the cost-effectiveness and efficacy of various mercury control measures, identifying sources of exposure for vulnerable populations, improving modelling to facilitate the evaluation of impacts from variations in mercury emissions and developing more cost-effective sampling and analytical methods (Selin *et al.*, 2018). More research is also needed to understand the complex associations and where they exist among the various foodborne hazards that can originate in global oceans. For instance, while mercury exposure can cause a range of adverse biological effects on marine copepods (zooplankton species), research shows that ocean acidification can significantly alleviate mercury toxicity. This can ensure fecundity and survival in the presence of MeHg under ocean acidification conditions (Wang, Lee and Li, 2017). As various *Vibrio* species are found attached to the chitineous copepods in the oceans, the effect of ocean acidification on the survival of copepods in the face of rising Hg deposition in aquatic systems, and the association of this effect with the distribution of *Vibrio* species in the oceans in a changing climate remains to be investigated.

Effective monitoring of current mercury levels should be accompanied by the development of future solutions. Expanding and harmonizing mercury monitoring systems would facilitate a standardized approach to monitoring of mercury levels at the global level. Efforts already under way include the recent establishment of the Asia-Pacific Mercury Monitoring Network (Sheu *et al.*, 2019). It is critical that regions undergoing rapid industrialization and urbanization and those with high seafood consumption strive to establish well-coordinated monitoring systems at the national and regional levels to minimize the exposure risks for public health (UNEP, 2016). It is often difficult to obtain accurate knowledge about conditions in developing countries because of a lack of data and the high costs associated with data collection and analysis. According to a recent review of global mercury monitoring networks published by UNEP (2016), there is room for improvement in Africa, Asia and Latin America and the Caribbean. Above all, there is need for greater global support and stronger collaboration among various sectors to bring about far-reaching solutions to the issue of rising mercury emissions.

© FAO/Sven Torfinn

Farmer in the midst of a desert locust swarm feeding on crops in Kenya.

CHAPTER 2.E

PESTICIDES

Pesticide[6] use has boosted crop production since the time of ancient civilizations. The first recorded pesticide usage dates back to 4 500 years ago when Sumerians applied elemental sulphur to protect their crops from insects. Synthetic pesticides are designed to disrupt critical biological pathways in pests, thereby reducing their survival. With the large-scale production of synthetic pesticides starting in the 1940s, the intensification of agriculture really started. According to FAOSTAT, approximately 4.2 million tonnes of pesticide active ingredients were used in the world's croplands in 2017 and the global pesticide market has been estimated at USD 45 billion per year (FAO, 2019; Pretty and Bharucha, 2015). While pesticide use has increased over the decades, crop losses have not decreased significantly (Epstein, 2014; Oerke, 2006). An estimated 20–40 percent of global crop production is lost to pests[7] (Oerke, 2006). However, pesticide use enables farmers to boost agricultural production despite these losses. Global food demand has been rising with population growth and so has reliance on pesticides (the "pesticide treadmill" effect described by Robert van den Bosch[8]). Pesticide application is on an upwards trend in both developed and developing countries (Schreinemachers and Tipraqsa, 2012). It has been estimated that a 1 percent increase in crop output per hectare is associated with a 1.8 percent increase in pesticide use (Schreinemachers and Tipraqsa, 2012). Increased population pressure has led to the expansion of agricultural land as well as crop intensification, with more crops now being grown on a single piece of land. Both of these phenomena are linked to increased pesticide use. Over the last decade in France, a rise in the productivity of farmland has occurred along with an increase in pesticide use (Stokstad, 2018).

---

[6] The term "pesticide" covers the following groups: herbicides, insecticides, fungicides, rodenticides and plant growth regulators.

[7] According to the FAO/WHO International Code of Conduct on Pesticide Management, a pest is defined as: "any species, strain or biotype of plant, animal or pathogenic agent injurious to plants or plant products, materials or environments and includes vectors of parasites or pathogens of human and animal disease and animals causing public health nuisance".

[8] Author, *The Pesticide Conspiracy*.

An overreliance on pesticides accelerates the evolution of pesticide resistance, which has its origins in a number of biochemical mechanisms (Gould, Brown and Kuzma, 2018; Hawkins *et al.,* 2018). In the United States of America, the quantities of glyphosate –a broad-spectrum systemic herbicide – applied to soybeans per hectare more than doubled between 1995 and 2015. There are at least 38 weed species in 37 countries that are resistant to this herbicide, creating a growing concern (Beres *et al.,* 2018; Heap and Duke, 2018). Multi-herbicide resistant weeds in Australia pose a serious and costly threat to wheat production, with famers forced to resort to alternative means to deal with the challenge (Walsh and Powles, 2014). Increased use of neonicotinoid pesticides threatens the health of honey bees, other pollinators and beneficial insects and their predators (Di Bartolomeis *et al.,* 2019; Douglas *et al.,* 2020). The economic value of pollination by insect pollinators in human food production has been calculated to be USD 206 billion a year (Gallai *et al.,* 2009). In addition, a strong correlation has been found between the large-scale use of neonicotinoids and the collapse of fisheries in Lake Shinji, Japan, suggesting that such adverse effects are probably also occurring in other regions globally (Yamamuro *et al.,* 2019).

Overuse and misuse of pesticides, especially those that are slow to degrade, have caused environmental deterioration through soil degradation, biodiversity loss from the toxic effects on non-target species, reduced water quality, severe damage to animal and human health and economic consequences. The use of clordecone in the Caribbean islands of Guadelope and Martinique provides examples of some of these problems (Multigner *et al.,* 2016). In 2016, the first systematic testing for neonicotinoids in the rivers of the United Kingdom of Great Britain and Northern Ireland showed high levels of contamination in half of the 16 rivers surveyed, and the study identified imidacloprid, clothianidin and thiamethoxam as three insecticides of greatest concern (Shardlow, 2017). A 2019 study of 29 waterways in ten EU countries showed contamination from a mixture of pesticides, in addition to veterinary drugs (Casado *et al.,* 2019). Such scenarios pose serious problems because quantitative techniques for assessing the risk exposure to a mixture of pesticides are still in their infancy. Humans are exposed to pesticide residues predominantly *via* their diets - crops that are either treated with pesticides or have absorbed pesticide residues from the soil and irrigation water; livestock and fish that have bioaccumulated the chemicals from their environments and feed; and contaminated drinking water (Carvalho, 2017; Kim, Kabir and Jahan, 2017). Risk assessments of pesticide residues have been carried out by the Joint FAO/WHO Meeting on Pesticide Residues (JMPR) and various national authorities.

Pesticides have been linked to a number of health issues – endocrine disruption, cancer, reproductive disorders, Parkinson's disease, damage to the nervous system and even epigenetic changes (Blair *et al.,* 2015; Kim, Kabir and Jahan, 2017; Sabarwal, Kumar and Singh, 2018). There is some preliminary evidence that pesticides alter the composition of gut microbiota (Licht and Bahl, 2019; Yuan *et al.,* 2019). The adverse effects of this dysbiosis in downstream pathways have yet to be investigated. Some initial evidence suggests that co-exposure to herbicides and antibiotics can potentially lead to higher resistance levels in bacteria (Kurenbach *et al.*, 2018). Direct environmental exposure to pesticides (*via* spray drift, volatalization and handling) is harmful, especially to people applying pesticides, who experience high exposure to the chemicals. Prenatal exposure to chlorpyrifos (an organopesticide) as a result of pregnant women living in proximity to areas where pesticides are applied, affects the neural development of children (Sagiv *et al.*, 2019). Children can also be exposed to pesticide residues through breastmilk. Pyrethroids, used widely in agriculture and urban environments, have been found to be toxic to aquatic organisms and are shown to bioaccumulate in human breastmilk (Brander *et al.*, 2016; Corcellas *et al.*, 2012; Feo *et al.*, 2012; Sereda, Bouwman and Kylin, 2009).

SECTION I: CLIMATE CHANGE IMPACTS ON PESTICIDE USE AND SUBSEQUENT EFFECTS

Although there is no conclusive scientific evidence that directly links increased pesticide use and climate change, it is reasonable to expect that climate change will affect pesticide application, and consequently have downstream effects on the environment and human health. Climate change is expected to change the geographic distribution, life cycles, population dynamics and trophic interactions of various agricultural insect pests globally (Lehmann *et al.*, 2018). To combat this, the frequency and volumes of pesticide use may increase. A study published in 2018 shows that under current climate change projections, pesticide use in China will increase by between 1.1 and 2.5 percent by 2040, 2.4 and 9.1 percent by 2070, and 2.6 and 18.3 percent by 2100 (Zhang *et al.*, 2017). As temperatures increase and precipitation patterns change, there may be a corresponding shift in crop production locations. Cho and McCarl (2017) found that climate variations led to shifts – primarily towards the north and higher elevations – in crop production areas in the United States of America between 1970 and 2010. Such shifts in agricultural production areas are also expected to change the pattern of pesticide use, bringing risks of pesticide exposure to new regions. There is also growing evidence suggesting that climate change may reduce the sensitivity of weeds to certain herbicides (Matzrafi, 2019).

In addition to the effects that it will have on the distribution and utilization of pesticides that are currently in use globally, climate change will also affect the remobilization of obsolete[9] and banned pesticides from global inventories. These pesticides, which were once in general use, have been banned because of their serious toxicological effects on people and the environment. Poor storage conditions and management practices often cause damage to pesticide stocks, resulting in leakage into the surrounding environment (Rodríguez-Eugenio, McLaughlin and Pennock, 2018). Climate change is likely to influence how pesticides from storage sites end up in aquatic environments, posing serious concerns about the presence of pesticide residues in food and water.

---

[9] Information on FAO's Programme on the Prevention and Disposal of Obsolete Pesticides is available at http://www.fao.org/agriculture/crops/obsolete_pesticides/en/.

ELEVATED TEMPERATURES

Warmer temperatures encourage faster growth rates in plants and their pests – insects and pathogens (Delcour, Spanoghe and Uyttendaele, 2015). Viticulture is one of the sectors that is suffering from the effects of warmer temperatures and humidity, which promote the growth of fungal infections such as downy mildew (*Plasmopara viticola*) and powdery mildew (*Eysiphe necatrix*) on grapes (Chakraborty, Tiedemann and Teng, 2000). These are being addressed by more frequent fungicide applications, such as in Germany's Moselle region, increasing human exposure to the chemicals (Ruiz, 2019).

Pesticide use tends to be far higher in areas that experience warmer temperatures. In the United States of America, the frequency of insecticide sprays against Lepidoptera insect pests in maize ranges from 15 to 30 applications per year in Florida (warmer climes), compared with zero to five applications in New York (cooler climes) (Hatfield *et al.,* 2011). It is possible for aphids to produce five additional generations a year when temperatures increase by 2 °C (Newman *et al.,* 2003; Roos *et al.,* 2010). This may encourage more applications of insecticides to control pest populations.

ALTERATIONS IN PEST (INSECT) DISTRIBUTION AND POPULATIONS

Climate change is expected to affect the global distribution of pests. In response to global warming, crop pests and pathogens have been moving towards the poles at a rate of 2.7 (± 0.8) km per year since 1960 (Bebber, Ramotowski and Gurr, 2013). *Burkoholderia glumae*, which causes bacterial panicle blight in rice, has been expanding its range with warming temperatures. It has been predicted that a temperature increase of 3 °C could result in a very serious case of bacterial panicle blight disease, the severity of which can lead to a loss of rice production equivalent to the food needs of about 4 million people a year in the United States of America (Shew *et al.,* 2019). The Colorado potato beetle (*Leptinotarsa decemlineata*) has been expanding towards higher latitudes in Eurasia, in parallel with its host plants from the Solanaceae family, which grow in warmer areas (Wang *et al.,* 2017). The ability of pests to adapt and persist in the face of climate change can be associated with genetic changes like the pair of circadian clock genes -period (*per*) and pigment dispersing factor receptor (*Pdfr*)- identified as genes that can potentially be selected for by the European corn borer moth (*Ostrinia nubilalis*) for adaptation in the face of climate change (Kozak *et al.,* 2019). Elevated temperatures will not only provide opportunities for the migration of pests into new areas, but will also, boost the population numbers and metabolic rates of indigenous pests, leading to losses in crop production (Coakley, Scherm and Chakraborty, 1999). With a global average temperature increase of 2 °C, the median increase in the loss of crop yields due to pests is estimated to be 46 percent (59 megatonnes) for wheat, 19 percent (92 megatonnes) for rice and 31 percent (62 megatonnes) for maize (Deutsch *et al.,* 2018). Based on their modelling results, Deutsch and co-authors (2018) suggested that France, China and the United States of America will most likely experience the greatest crop losses due to pest population increases as temperatures get warmer. Currently, large swarms of desert locusts are decimating croplands and pasture across the Horn of Africa and beyond, seriously threatening food security in the entire region. This insect upsurge is associated with an El Niño-like event in the Indian Ocean that caused cyclones and heavy rains in 2018-19, creating favourable conditions for growth (FAO, 2020). The only response to this crisis is the large-scale aerial spraying of pesticides to control the infestation.

As pest distributions change, it is very likely that agricultural land will see increases in pesticide use, giving rise to more food safety concerns. For instance, the geographic niche of the fall armyworm (*Spodoptera frugiperda*) has recently expanded from the Americas to Africa and Asia. Taylor and co-authors (2018) studied insect–crop dynamics with respect to climate variations in the United States of America and suggested that climate change is very likely increase the pest pressure, which is expected to result in an increase in pesticide applications in order to maintain productivity. It has been speculated that in some regions, certain restricted pesticides that have proved effective against specific pests may even be reintroduced, thereby posing a very serious concern (Macdonald, Harner and Fyfe, 2005). Possible use of illicit and/or adulterated pesticides with reduced efficacy during pest outbreaks could further exacerbate these concerns.

It is also worth noting that differences in the optimum temperatures of crop pests and their natural predators may reduce the ecological interactions of the pests and predators, which might result in higher pest populations with a likely corresponding increase in pesticide use (Furlong and Zalucki, 2017). Elevated temperatures, accompanied by rising CO_2 levels, can cause a dilution of pesticide concentrations in plants, thereby promoting reductions in the sensitivity of pests to pesticides and potentially prompting increased pesticide application to compensate (Delcour, Spanoghe and Uyttendaele, 2015). Climate change may lead to more generations of pests per year, which – in combination with prolonged exposure to pesticides over longer growing seasons – may make pests more resistant to pesticides (Matzrafi, 2019). The withdrawal of pesticides has been linked to higher incidences of mycotoxin contamination from *Fusarium* species in maize (Reboud *et al.,* 2016). In a desperate effort to maintain low levels of fungal infections and insect damage in food grains during storage, under conditions of increased temperature and humidity, pesticide use may increase (Gottlieb *et al.,* 2018).

INCREASED DISPERSAL INTO THE ENVIRONMENT

Volatilization allows pesticides to travel through the air to be deposited in areas that are far away from the location of application (vapour drift). This can cause damage to wildlife, plants and subsequently human health. Warmer temperatures and direct exposure to sunlight influence the dispersal rate of pesticides through a combination of increased volatilization and degradation. To compensate for this loss of concentration, it can be expected that larger quantities of pesticides against various pests will be applied, leading to higher risk of human exposure (Noyes *et al*., 2009). The Arctic regions have seen the deposition of several volatilized pesticides, some of which are no longer in use today mainly due to their highly toxic effect on the environment. Over recent decades, warming in these regions has started to cause these persistent highly hazardous pesticides to be released back into the atmosphere, posing potential risks to human health and the environment (Ma *et al.*, 2011).

ELEVATED CO_2 LEVELS

Over the years, a number of articles have been published that elucidate the relationship between rising CO_2 levels and nutritional deficits in plants, especially in staple crops (Loladze, 2014; Smith and Myers, 2018; Zhu *et al.*, 2018). An increase in CO_2 levels affects the carbon to nitrogen ratio in plants by raising their sugar content, which leads to increased feeding by insects in an attempt to meet the carbon to nitrogen ratios that they require (Hatfield *et al.*, 2011; Loladze, 2014). In response to this, more pesticide use is expected along with higher risks of human exposure to pesticide residues. A combination of elevated CO_2 levels and temperatures has been linked to increased damage to rice from the brown planthopper (*Nilaparvata lugens Stål*) (Pandi *et al.*, 2018). Rising CO_2 levels have also been linked to decreasing pesticide efficacy. The control efficacy of triazophos against *N. lugens* in transgenic *Bacillus thuringiensis*-modified rice decreased significantly under elevated CO_2 levels (Ge *et al.*, 2013). C3 plants may undergo anatomical and physiological changes under increasing CO_2 concentrations, which interferes with the foliar uptake of herbicides (Ramesh *et al.*, 2017). Higher CO_2 levels in the atmosphere could also promote the growth of certain weeds by facilitating more photosynthesis and increasing the root biomass, thereby making it harder to control the weeds and necessitating the increased use of herbicides (Rodenburg, Meinke and Johnson, 2011).

PRECIPITATION AND DROUGHT

The efficacy of soil-applied herbicides is affected by changes in precipitation patterns (Rodenburg, Meinke and Johnson, 2011). An increase in rainfall can increase herbicide dilution and leaching into groundwater or runoff from the soil, leading to greater contamination of water bodies in surrounding areas. To compensate for this loss of concentration the application of herbicides may be increased. Regions affected by drought may also experience increased risk of exposure due to higher concentration of contaminants in water sources as water levels drop (Boxall *et al.*, 2009). It has been shown that drought conditions influence the uptake of herbicides by changing the foliar morphology of plants and decreasing the effective volume of herbicides available owing to increased volatilization (Patterson, 1995; Ramesh *et al.*, 2017).

THAWING OF PERMAFROST

The previous large-scale use of organochlorine compounds such as polychorinated biphenyls as pesticides, among other applications, has led to the deposition and persistence of these compounds in remote regions, including polar and mountainous areas. This is mainly a result of long-range atmospheric transport and the resistance of the compounds to environmental degradation. Traces of endosulphan (**Box 10**) found in the Himalayan mountains had arrived from the Indian subcontinent (Li *et al.*, 2006). There is evidence that these trapped contaminants are being remobilized from their frozen global inventories as a result of climate change-induced melting of the permafrost (Cabrerizo *et al.*, 2013; Miner *et al.*, 2018; Potapowicz *et al.*, 2019). This will not only enhance the distribution of such persistent pollutants into various aquatic ecosystems, but also affect bioaccumulation in fish and other marine animals, resulting in higher exposure risk for coastal communities and others that depend on these animals for sustenance.

BOX 10

THE STORY OF ENDOSULPHAN

Endosulphan is a broad-spectrum organochlorine insecticide first registered in 1954 in the United States of America. It is an endocrine disruptor and was found to be genotoxic and to cause severe adverse neurological and reproductive effects in humans. It was also shown to be extremely toxic to the marine environment, causing massive fish die offs. After almost 60 years of use, a global ban on the manufacture and use of endosulphan was negotiated under the Stockholm Convention on Persistent Organic Pollutants in 2011. At the time of the ban, endosulphan was the second most used pesticide around the world, with application on more than 60 crops to control insect pests. Countries have developed effective crop-specific, pest management strategies and today, the use of endosulphan has been nearly fully phased out from agriculture, setting an important example and precedent for future global bans on highly hazardous pesticides.

SECTION II: CONCLUSIONS

PREDICTION, MONITORING AND MITIGATION

As agriculture becomes more dependent on pesticides, food production systems become more vulnerable to crop losses and the effects of contamination from pesticide pollution. Even organic farms now face issues with pesticide contamination. Neonicotinoid contamination has been found in 93 percent of organic fields in Switzerland, suggesting the spread of the chemicals through wind and water sources (Humann-Guilleminot *et al.*, 2019). Pesticide resistance is a growing concern, particularly resistance to glyphosate and insecticidal Bt-toxins in transgenic crops. Jørgensen and co-authors (2018) found that pesticide (insecticide and herbicide) resistance was dangerously close to exceeding “planetary boundaries” beyond which large-scale issues related to human health and agricultural crises are likely to arise. As food security and food safety concerns grow, it is important to explore means of reducing dependence on synthetic pesticides in agriculture and to promote prudent use. Integrated pest management[10] approaches involve biological control mechanisms such as the use of plant extracts, pheromone traps, predators and microbes, depending on the type of pest. Raising awareness of the biodiversity of soil and its importance is critical. The use of beneficial soil microbes to provide plants with protection against environmental stressors is gaining attention. Application of unique combinations of soil bacteria can provide similar benefits as some commercial pesticides, for instance in protecting rice against the rice leaf-folder pest (*Cnaphalocrocis medinalis* Guen.) (Saravanakumar *et al.,* 2007). Some soil microbes have been shown to increase crop yields and plant growth, promote drought resistance and water retention and prevent foliar pathogen entry (Ceballos *et al.,* 2013; Kumar *et al.,* 2012; Marasco *et al.,* 2012). These terminologies will help small farmers, particularly those with limited resources, who are willing to try alternatives to synthetic pesticides and seek to adapt to climate change. The increased resistance of insect pests to insecticides is leading some farmers to explore biological control methods such as the utilization of predatory insects in pepper production in Almeria Province, Spain. Such biocontrol measures are also included in the "pest-smart" interventions[11] that are an element of agroecology (FAO, 2015). Countries in Africa (Ethiopia, Ghana, Kenya and South Africa) have adopted specific biopesticide legislation and engaged with commercial biopesticide companies in an effort to make biological control measures more viable. Biocontrol measures are also expected to be affected by climate change conditions, but there is as yet insufficient research to demonstrate the specific effects.

More robust monitoring of pesticide concentrations in soil, water and the food chain around the globe are needed, especially under climate change conditions. Low- and middle-income countries tend to suffer from a lack of appropriate regulations for the prudent use of pesticides, insufficient capacity to enforce national laws, inadequate facilities for proper pesticide storage and disposal, lack of good management practices and monitoring capacities and an absence of awareness of the hazards related to the overuse of pesticides (Brodesser *et al.,* 2006). An FAO survey of pesticide regulatory units in low- and middle-income countries found a severe lack of adequate human resources compared with the situation in member countries of the Organisation for Economic Co-operation and Development (OECD), where appropriate resources for pesticide management are available (FAO, 2010). In addition, pesticides that have been banned in certain developed countries are sometimes sold to developing countries, exacerbating the issues related to pesticide misuse. In order to support member countries in addressing some of these issues, FAO collaborated with WHO to establish the International Code of Conduct on Pesticide Management, which is

---

[10] FAO defines integrated pest management (IPM) as: "careful consideration of all available pest control techniques and subsequent integration of appropriate measures that discourage the development of pest populations and keep pesticides and other interventions to levels that are economically justified and reduce or minimize risks to human health and the environment. IPM emphasizes the growth of a healthy crop with the least possible disruption to agro-ecosystems and encourage natural pest control systems".

[11] Information on the "pest-smart" approaches of the Centre for Agriculture and Biosciences International (CABI) – Southeast Asia and the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS) in Southeast Asia is available at https://ccafs.cgiar.org/.

a voluntary framework, designed to be used within national legislation. The code provides standards for the optimum management of pesticides throughout their life cycle, from production to monitoring, surveillance and proper disposal (FAO and WHO, 2014). In addition to monitoring pesticide use, it is also extremely important to educate farmers on the dangers of using banned pesticides and to promote prudent use of pesticides as well as the use of protective clothing while spraying.

Predictive modelling approaches that identify new areas of expansion by pests based on various climate change scenarios will help to ensure that appropriate prevention and mitigation measures are put in place to avoid or mitigate damage caused by insects and vector-borne diseases. Taylor and co-authors (2019) used a modelling approach to anticipate the future "thermal niche" of the vector *Diaphorina citri*, which transmits Huanglongbing disease, and found that areas that are currently free of the disease, such as the Iberian Peninsula and California, will have thermal conditions that are conducive to the spread of Huanglongbing for seven months a year under the authors' climate change scenarios. Widespread application of better pest management techniques in which the use of pesticides is reduced in favour of biocontrol agents such as natural predators will be possible when pest–predator relationships are better understood under various farming scenarios, such as the relationship between aphids and syrphid flies in Pakistan (Faheem *et al.*, 2019). Efforts to modify current modes of pesticide application are being explored, although most of these efforts so far have been limited to laboratory settings. One way of reducing pesticide use is to enhance the retention of sprayed pesticide on plant surfaces (Damak *et al.,* 2016). Technological innovations such as genome editing and RNA interference might have potential future applications as pest biocontrol measures (Cohen, 2019; Lopez *et al.*, 2019; Swevers and Smagghe, 2012; Vogel *et al.,* 2018). Precision agriculture methods such as the use of drones to spray pesticides at optimum times can improve efficiency by ensuring accurate targeting and reducing human occupational-related exposure risks from pesticides (FAO and ITU, 2018).

The book *Silent Spring*, authored by Rachel Carson (1962), played a critical role in educating the public about the observed and potential toxic effects of using organophosphate and organochlorine pesticides, leading to calls for safer pesticides and better regulations. Today, in the face of a growing population and armed with the knowledge of the benefits and costs of using pesticides, it is even more vital that humanity works with nature and not against it.

© Chris Steele-Perkins/ Magnum Photos

Farmer inspects maize heads in Nepal.

CHAPTER 2.F

MYCOTOXINS

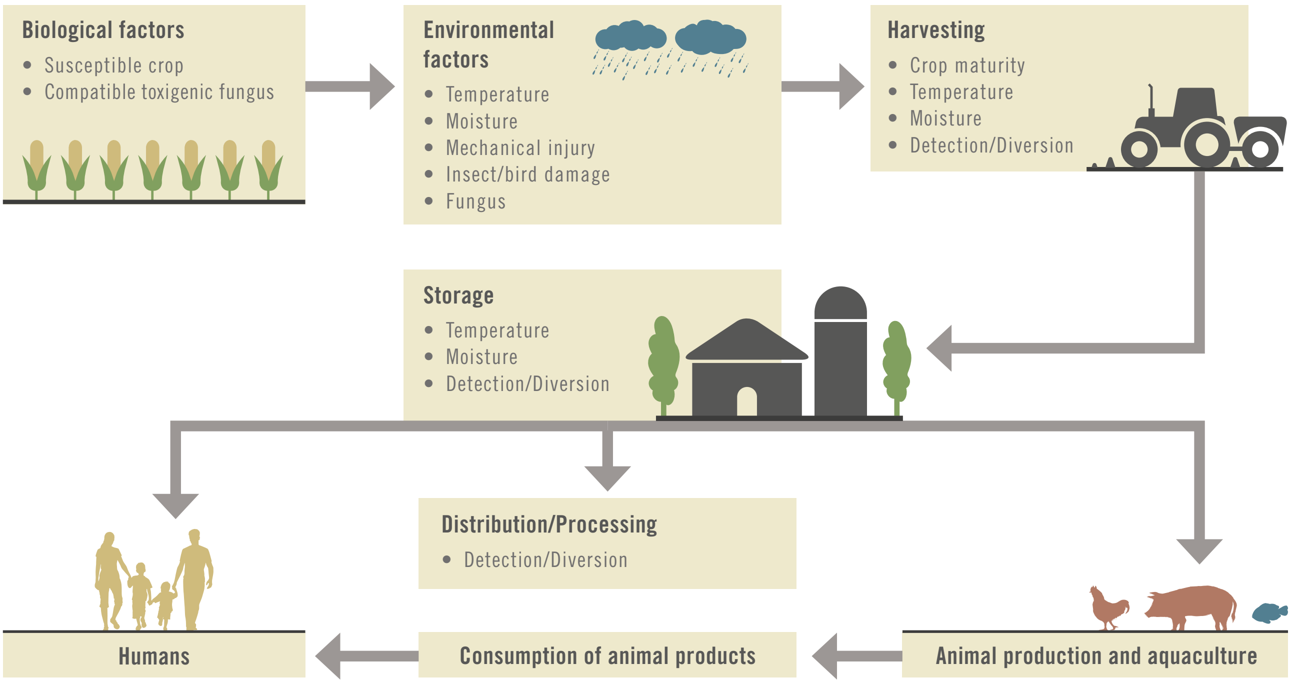
Mycotoxins are secondary metabolites of fungi (**Box 11**) that grow in or on crops and are known to cause human and animal diseases. Too much or too little water during the growing season, temperature variations, pests, and unhygienic conditions for drying and storage are among the major factors that contribute to the proliferation of fungal infections, and subsequently to mycotoxin production. Human exposure to these toxins is through the food supply (**Figure 10**). The global population primarily depends on a few starch and oilseed crops, all of which are susceptible to mycotoxins (Khoury *et al.*, 2014). This makes mycotoxins a major food safety hazard (Pitt and Miller, 2017). The major toxigenic species found in food and feed are in the following genera: *Aspergillus*, *Fusarium*, *Penicillium* and *Claviceps* (Bennett and Klich, 2003). The five most agriculturally important mycotoxins – aflatoxins, ochratoxin A, fumonisins, deoxynivalenol and zearalenone – accounted for 55, 29, 61, 58 and 46 percent respectively of occurrences in cereal grains according to reports collected worldwide from 2006 to 2016 (Lee and Ryu, 2017). A similar picture emerged from feed samples submitted for analysis (Gruber-Dorninger, Jenkins and Schatzmayr, 2019). In general, mycotoxins are not eliminated during food processing, except by dilution, contributing to the seriousness of the food safety issue that they pose (Bullerman and Bianchini, 2007). In terms of health risks, aflatoxins are carcinogenic and are associated with the most global DALYs (636 869) due to liver cancer as reported by the Foodborne Diseases

BOX 11

CONSERVATION OF FUNGAL SPECIES UNDER THREAT OF CLIMATE CHANGE

It should be noted that while certain fungal species are harmful to humans, a vast majority of both micro and macro fungal species have very important roles in ecosystems (including in the cycling of nutrients, decomposition and carbon sequestration, bioremediation and prevention of desertification) as well as applications in the food and pharmaceutical industries. Climate change conditions threaten the survival of a large number of beneficial fungal species globally, and more intensive research is required to understand the mechanisms involved. Close attention should be paid to the conservation of fungi as a way of maintaining a healthy global ecosystem for the future (Willis, 2018).

FIGURE 10 **FACTORS AFFECTING THE OCCURRENCE OF MYCOTOXIN CONTAMINATION IN THE FOOD SYSTEM**



Source: Adapted from CAST, 2003.

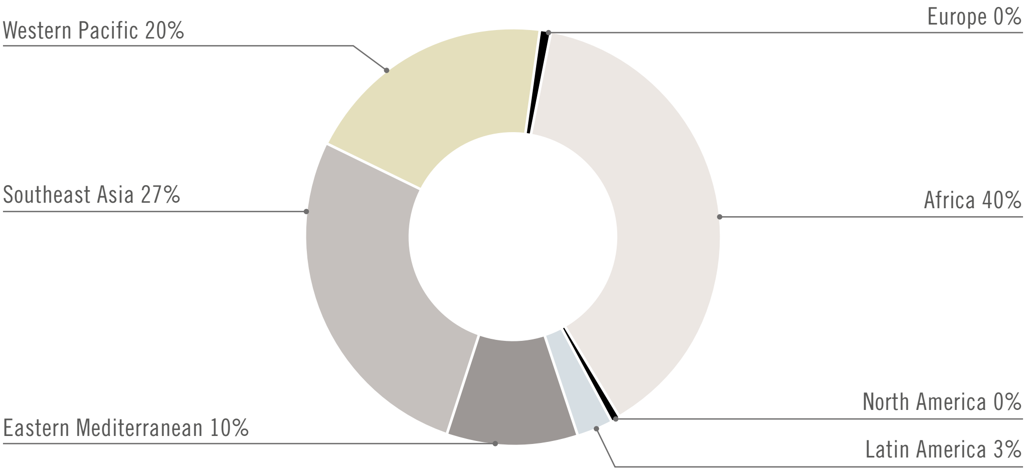
Burden Epidemiology Reference Group of WHO (IARC, 2012a; WHO, 2015). Co-exposure to aflatoxins and hepatitis B virus infection causes between 5 and 28 percent of global hepatocellular carcinoma cases per year. Most cases appear in areas (**Figure 11**) where there is poor regulatory control of the aflatoxin content in food (Liu and Wu, 2010). In developing countries, children suffering from high exposure to aflatoxins can also suffer from micronutrient deficiencies (Watson *et al.*, 2016). Other mycotoxins exert toxic effects on the kidneys, reproductive system, immune system and the gastrointestinal system (IARC, 2012b; Alshannaq and Yu, 2017). Exposure to fumonisins and aflatoxins or a combination of both has been linked to stunting in children in low- and middle-income countries (LMICs) (Chen *et al.*, 2018; Chen, Riley and Wu, 2018b; FAO and WHO, 2016; IARC, 2015; Watson *et al.*, 2018). The Joint FAO/WHO Expert Committee on Food Additives (JECFA) is responsible for evaluating the various health risks from these toxins. Codex standards, internationally accepted as the reference for global food supplies and trade, are set according to JECFA assessments. Based on the latest FAO survey, carried out in 2003, about 100 countries have established maximum limits for mycotoxin levels in human food and Codex maximum level (ML) values[12] exist for

---

[12] The General Standard for Contaminants and Toxins in Food and Feed (CODEX STAN 193-1995) can be viewed at http://www.fao.org/fileadmin/user_upload/livestockgov/documents/1_CXS_193e.pdf.

a few mycotoxins in selected food items (FAO, 2004). While several countries have regulations for the major mycotoxins, a lack of sufficient data on the occurrence and toxicity of lesser-known mycotoxins makes it difficult to design regulations for them, for instance for the various modified and emerging mycotoxins (**Box 12**).

FIGURE 11 **GLOBAL DISTRIBUTION OF LIVER CANCER CASES THAT CAN BE ATTRIBUTED TO AFLATOXINS**



Source: Adapted from Liu and Wu, 2010, *Environmental Health Perspectives* 118:818 - 824.

BOX 12

MODIFIED AND EMERGING MYCOTOXINS

While "parent" mycotoxins exist in a free state in food and feed, they can also be modified to create compounds that have different chemical structures, physico-chemical properties and biochemical mechanisms of action from those of the parent. Such modifications can occur in the host plants, through fungi other than the mycotoxin-producing species concerned, during food processing or through metabolic processes in humans and animals (Freire and Sant'Ana, 2018; Humpf, Rychlik and Cramer, 2019; Rychlik *et al.*, 2014). Derivatives of mycotoxins such as deoxynivalenol and zaeralenone can be deconjugated to their parent compound during digestion, thereby contributing to overall exposure to mycotoxins (Berthiller *et al.*, 2013; Dall'Erta *et al.*, 2013; Gratz *et al.*, 2018; Gratz, Duncan and Richardson, 2013; Vidal *et al.*, 2018). Certain mycotoxins are classified as "emerging" by some European researchers. These mycotoxins include fusaproliferin and moniliformin, which have been reported in Serbian maize (Jajic *et al.*, 2019), and enniatins and beauvericin (Jestoi, 2008). Both modified and emerging mycotoxins co-occur with "traditional" ones (Kovalsky *et al.*, 2016). Research on the occurrence, co-occurrence, mechanisms of transformation and bioavailability, and toxicity of modified and emerging mycotoxins is needed. The chemical diversity of mycotoxins and the lack of suitable certified reference materials make risk analyses and the setting of standards difficult. The effects of climate change on the production and distribution of modified and emerging mycotoxins, and the subsequent impacts on human health, remain to be investigated.

Another safety issue that is attracting attention is assessment of the health risks associated with co-exposure to multiple mycotoxins and the prioritization of the most prevalent combinations (Assunção, Silva and Alvito, 2016). Aflatoxins and fumonisins are common contaminants found in cereals and cereal-based foods. The recent co-exposure assessment of aflatoxin B1 and fumonisin B1 in food by JECFA showed that the interaction between the two mycotoxins posed a major concern for human health (FAO and WHO, 2016). Some mycotoxin combinations commonly found in food and feed globally are summarized in the literature (Lee and Ryu, 2017; Smith *et al.,* 2016). Using *in vitro* methods, Smith and co-authors (2016) suggested that some combinations showed synergistic, additive or antagonistic effects. However, as noted by Alassane-Kpembi and co-authors (2017), many of the studies suggesting material interactions between mycotoxins suffer from important methodological problems. The potential increased hazards of food and feed contaminated with more than one mycotoxin other than fumonisins and aflatoxins remain to be determined. In addition to food, animal feed is also often contaminated with more than one toxin. A recent study of feed samples submitted for analysis reported that 64 percent of the samples, mainly from sub-Saharan Africa, Southeast Asia and South Asia, was co-contaminated with two or more mycotoxins (Gruber-Dorninger, Jenkins and Schatzmayr, 2019). When mycotoxins are present above the regulated or guideline concentrations, losses in animal protein and the contamination of animal products such as milk affect human health and nutrition status (Gruber-Dorninger, Jenkins and Schatzmayr, 2019). The introduction of novel feed sources, including food waste, has also contributed to alterations in the prevalence patterns of various mycotoxins (Miller, 2016a). Mycotoxins are also a growing concern for the global aquaculture industry owing to a shift towards more plant-based feed (Gonçalves *et al.,* 2017). Apart from exposure to multiple mycotoxins, research gaps also, remain in scientific understanding of combined exposure to mycotoxins and other food safety hazards like marine bio-toxins and heavy metals, which are all expected to be affected by climate change (Luo *et al*., 2019; Yang *et al*., 2017).

In addition to causing food safety concerns, mycotoxin contamination in food and feed is also a major barrier to international trade. Mycotoxins generated some of the most frequent notifications (with 569 reports) by the European Commission's Rapid Alert System for Food and Feed (RASFF) network in 2018, affecting trading relationships (RASFF, 2018). A lack of appropriate regulatory limits for mycotoxin contamination, in a number of countries, lead to the rejection of food in international markets and causing economic loss. Without adequate quality control in place, this contaminated food is largely consumed in the producing country, increasing health risks in the domestic population, especially among children and immune-compromised people. Strict and more harmonized control of mycotoxins is needed as international trade can be considered as one of the major drivers for the dissemination of mycotoxins into areas that are outside the range of its natural occurrence.

SECTION I: CLIMATE CHANGE IMPACTS ON MYCOTOXIN CONTAMINATION

Increased climate variability - higher temperatures, severe droughts, unseasonal rain during harvest times and extreme weather events that cause flooding - is expected to increase the risk of mycotoxin accumulation in fields and after harvest, including in commercial and traditional storage facilities (Miller, 1995; Paterson and Lima, 2017; Vermeulen, Campbell and Ingram, 2012). As the food chains to global markets grow longer, the risk of aflatoxin and ochratoxin production in food may increase as a result of inadequate storage and transport conditions across changing climate zones. Mycotoxin contamination also has serious economic implications along food value chains, and these are expected to worsen as the climate changes. Mitchell and co-authors (2016) estimated that under current climate change conditions, the maize industry in the United States of America may more frequently face losses of the levels seen in 2012 (USD 1.68 billion) because of aflatoxin contamination. In addition, it is important to point out that various methods employed to mitigate mycotoxin contamination are also subject to climate change conditions (**Box 13**).

BOX 13

MITIGATORY METHODS FOR MYCOTOXIN CONTAMINATION AND CLIMATE CHANGE

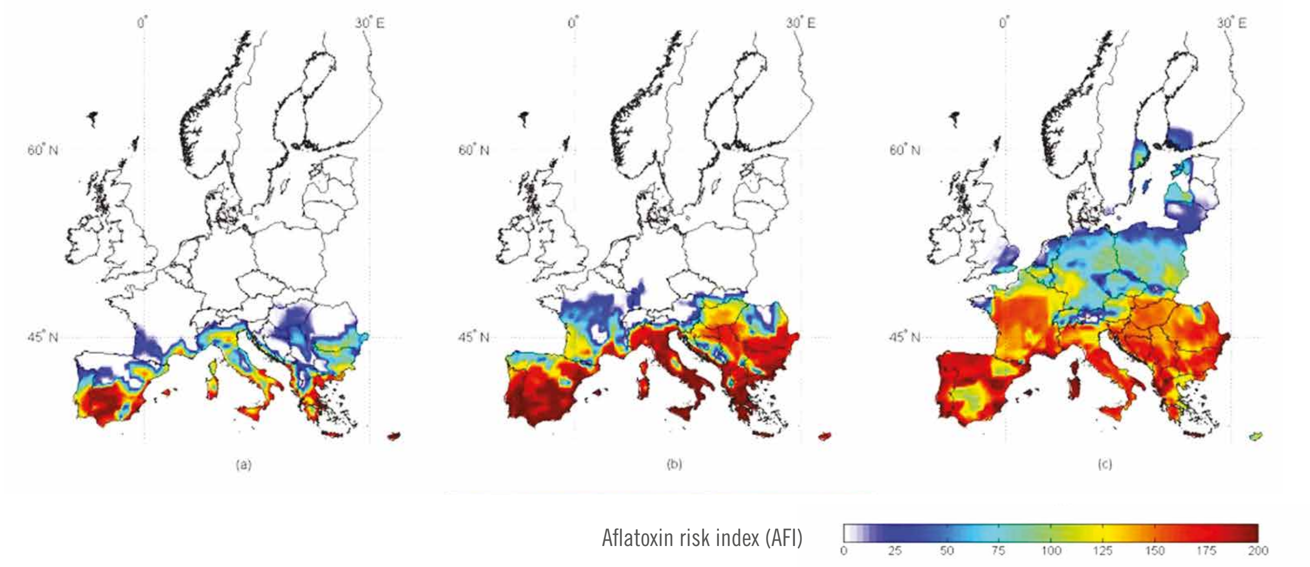
In addition to following good agricultural practices, there are a number of pre- and post-harvest measures (FAO and WHO, 2016) – including biological and chemical processes and the selection of appropriate packaging materials for storage (such as Purdue Improved Crop Storage or PICs bags) – that prevent and mitigate mycotoxin contamination (Udomkun *et al.,* 2017). Among the various mitigation measures, biological control agents will face similar climate change conditions as the fungal pathogens of interest. Non-toxigenic fungal strains of *Aspergillus flavus* that out-compete toxigenic strains are applied to commercial crops such as groundnuts, maize, pistachios and cottonseed during pre-harvest. Various country-specific fungal biocontrol agents are currently in use in Kenya, Nigeria, Senegal and the Gambia (Udomkun *et al.,* 2017). However, it must be noted that all fungal species will be affected by climate variability, which will influence the effectiveness of this mode of control in the long term. In addition, the recent discovery of the sexual states of toxigenic *Aspergillus* species raises the possibility of recombination with the non-toxigenic biocontrol species under environmental stressors induced by climate change (Moore, 2014). Pre- or post-harvest inoculation of susceptible crops with bacterial species that include *Bacillus, Trichosporon, Sphingomonas, Pichia, Stenotropomonas* and lactic acid bacteria has been shown to promote microbial degradation of mycotoxins (Patriarca and Pinto, 2017; Schatzmayr and Streit, 2013; Udomkun *et al.,* 2017). However, the practical effectiveness of this method, especially under climate change scenarios, is yet to be determined. A more recent biocontrol method is the use of enzymes rather than microbes because of the lower safety concerns, ease of use and higher specificity of enzymes (Gonzalez Pereyra, Martinez and Cavaglieri, 2019). Scientific efforts to design novel enzymes that can degrade aflatoxins are also under way through the online science crowdsourcing platform, FoldIt Aflatoxin Challenge. It will be important to address the issues that exists around detoxification of aflatoxins, for instance, the uncertainty about the toxicity of the breakdown products. Gene technologies such as the use of RNAi, multi-omic approaches and the production of mycotoxin-resistant crop varieties by genetic engineering are also viable options for control, especially under the threat of climate change (Bhatnagar-Mathur *et al.,* 2015; Pandey *et al.,* 2019; Pellegrino *et al.,* 2018). However, the applicability and regulatory acceptance of these methods require further investigation.

Climate change has already altered the distribution of toxigenic fungi and the appearance of mycotoxins in crops, such as the migration of the major mycotoxins (deoxynivalenol, ochratoxin A, aflatoxin, fumonisin and zearalenone) into areas that lack appropriate capacity for surveillance and risk management (Balbus *et al.,* 2013; Miller, 2016a; 2016b). Aflatoxins, once considered solely an issue with imported food, have now become a chronic problem in some parts of Europe (Battilani *et al.,* 2016; Moretti, Pascale and Logrieco, 2019). Climate change can affect the degree to which various regions of the world are suitable or unsuitable for crop production, further influencing the distribution of fungal pathogens (Zhang and Cai, 2011). Based on modelling studies, Ramirez-Cabral, Kumar and Shabani (2017) predicted that the major maize producing areas between the tropics of Cancer and Capricorn may become unsuitable for production under scenarios of future changes in climate. At the same time, cooler regions in northern Europe and North America may become suitable for maize production (Ramirez-Cabral, Kumar and Shabani, 2017). This will in turn affect the migration of the pests and fungal pathogens of maize into areas that have remained outside their regular habitat. In areas where mycotoxins become a problem, farmers may – where they can – change to crops that are less susceptible to infections, which may result in food crops that do not meet the needs of the region (Wilson, Dahl and Nganje, 2018).

ELEVATED TEMPERATURES

Although rising temperatures in some areas of the world may exceed the thermal optimum for certain toxigenic fungi, warming in the temperate regions may see a rise in fungal damage. The risk of aflatoxin contamination, particularly in maize and groundnuts, is expected to increase as fungal species expand their geographic regions into higher latitudes owing to rising temperatures. A study published in 2016 modelled the patterns of aflatoxin occurrence in maize and wheat under climate change scenarios of +2 °C and +5 °C over the next 100 years in Europe (**Figure 12**). They found that aflatoxin B1 is likely to become a major food safety issue in maize, especially in Eastern Europe, the Balkan Peninsula and the Mediterranean regions, under a +2 °C scenario, which is the most probable case over the coming years. Aflatoxin contamination of maize was predicted to be likely under the +5 °C scenario even at latitudes of 60° north (Battilani *et al*., 2016). *Fusarium graminearum*, which is found mainly in warmer central and southern Europe, has been reported to emerge as the dominant *Fusarium* species in various regions of northern Europe (the Netherlands, Germany, Poland and the United Kingdom of Great Britain and Northern Ireland) by replacing the more common *F. culmorum* (Moretti, Pascale and Logrieco, 2019)*.* Predictions of the level of deoxynivalenol in wheat in northwestern Europe (the United Kingdom of Great Britain and Northern Ireland, France, the Netherlands, Scandinavia and central Europe) in 2040 suggested that toxin concentrations might reach 2 mg/kg for winter wheat and between 3 and 14 mg/kg for spring wheat (van der Fels-Klerx *et al.,* 2012). In Hungary, rising aflatoxin contamination in maize has been attributed to potential climate change-induced environmental factors (Dobolyi *et al.,* 2013). It has also been speculated that

FIGURE 12 **MAPPING OF AFLATOXIN CONTAMINATION RISKS IN MAIZE UNDER THREE CLIMATE SCENARIOS (CURRENT, +2 °C AND +5 °C) IN EUROPE.**



Source: Reprinted from Battilani *et al.*, 2016, *Scientific Reports* 6:24328. This work is licensed under the Creative Commons BY 4.0 License. Map conforms to United Nations World map 4170 R18.1, Feb 20

increases in temperatures may lead to a shift in the types of mycotoxin produced by any given fungal species, from those that are currently dominant to other related compounds. Four decades ago, zearalenone was common in maize produced in the United States of America and Canada, but since temperatures have increased, deoxynivalenol has emerged as the dominant toxin in crops that are damaged by *F. graminearum* (Miller, 2016a). A serious emerging threat arises from the recent discovery of the sexual states of the aflatoxigenic species, which until recently were only known to reproduce asexually (Carbone *et al.*, 2007; Moore *et al.*, 2009). As temperatures rise across the temperate agricultural belt, these regions may become more prone to aflatoxin contamination. Sexual recombination often arises from environmental conditions that produce stress in fungal species. As climate change continues to alter environmental stressors, it may increase the likelihood of recombination events in *Aspergillus* spp., thereby greatly increasing the need to monitor these strains and document any impacts on pathogenicity or reproductive capabilities due to climate change (Moore, 2014).

PEST DAMAGE

Climate change is expanding the geographic range of crop pests (Bebber, 2015) (see also the section on "Alterations in pest (insect) distribution and populations" in Section I of **Chapter 2.E**). Insects can carry fungal spores, which are introduced into the interior of plants when the insects feed. Plants that are stressed by pest damage are more predisposed to fungal infections. Insect damage by *Sesamia nonagrioides*

© Jaromir Chalabala/Shutterstock.com

Peanuts being sold on the street in India.

Lefebvre was found to be a good indicator of fumonisin contamination in maize cultivated in the Mediterranean region (Avantaggiato *et al.*, 2003). Withdrawal of pesticides (herbicides and insecticides) from maize crops has been linked to a marked increase in mycotoxin contamination (of up to sixfold in nivalenol) by *Fusarium* species (Reboud *et al.*, 2016). Control of pests can therefore reduce fungal contamination in crops. In the United States of America, maize that was genetically modified for insect resistance was found to have lower levels of fumonisins due to reduced pest damage (Cappelle, Munkvold and Wolt, 2019). Based on data for 2006, this resulted in benefits to United States consumers of about USD 23 million because of mycotoxin reduction (Wu, 2006). Pest damage to crops can also occur under inadequate storage conditions, which encourages fungal growth and mycotoxin production (Chulze, 2010).

RISING CO_2 LEVELS

Elevated CO_2 conditions have been shown to have an impact on disease susceptibility and the development and severity of infections by *F. graminearum* on wheat and *F. verticillioides* on maize (Vary *et al.*, 2015; Vaughan *et al.*, 2014). Bencze and co-authors (2017) reported higher deoxynivalenol content in wheat resulting from infection by *F. culmorum* under elevated CO_2 levels, leading to food safety concerns.

PRECIPITATION CHANGES

Drought induces stress conditions in plants making them more susceptible to fungal infections (Kebede *et al.*, 2012). In 2012, extreme drought conditions in Serbia resulted in aflatoxin contamination in about 70 percent of the maize produced that year (Kos *et al.*, 2018). In 2003, for the first time, severe drought and higher than normal temperatures in six regions of northern Italy resulted in a switch from infection by *F. verticilloides* and fumonisin contamination in maize to aflatoxin production by *Aspergillus* section *Flavi.* Aflatoxin M1 was also found in milk and other dairy products as a result of animals being fed contaminated feed. The lack of preparedness or appropriate knowledge to deal with the issue created substantial challenges for efforts to control the spread of the fungal species (Giorni *et al.*, 2007). Mycotoxin contamination is also one of the major risks associated with grains after flooding, which results in long periods of moisture and stress for the plants (FDA, 2018). As climate change amplifies the intensity of hurricanes, changes normal precipitation patterns and causes sea levels to rise, flooding will affect storage facilities and standing crops, increasing the risks related to mycotoxins.

SECTION II: CONCLUSIONS

Mycotoxins present a massive challenge to the achievement of food security in countries that are currently food-insecure, especially because mycotoxin contamination occurs in staple crops. Climate change is likely to continue to exacerbate the impacts of this food hazard for the reasons explained in this chapter. The full impact of mycotoxin exposure is grossly underestimated owing to poor coordination in national monitoring systems and a lack of resources for accurately detecting mycotoxin levels, especially in countries where levels of mycotoxin contamination in food and feed are high and the health issues related to exposure are severe. The inability of farmers from developing nations to switch production from crops that are vulnerable to mycotoxins to those that are not as susceptible emphasizes the importance of accurate prediction capacities in regions that include sub-Saharan Africa. In regions where resources are lacking, raising the awareness of farmers and food handlers regarding methods of preventing and mitigating mycotoxin contamination, organizing small producers into cooperatives, using resistant crop varieties and diversifying diets must be priorities (Achaglinkame, Opoku and Amagloh, 2017; Misihairabgwi *et al.*, 2019). Effective partnerships between resource-limited and developed countries are strongly encouraged as a way of helping to provide the necessary knowledge, training and investments for building capacities (laboratories, adequate storage facilities, etc.). In countries where mycotoxin regulations are insufficient or where they exist only for export food commodities, there is an urgent need to create and enforce harmonized legislation on the control of mycotoxins in food and feed destined for both domestic consumption and export (Medina *et al.*, 2017; Misihairabgwi *et al.*, 2019). According to social network models of maize trade, nations with identical or near-identical aflatoxin standards tend to trade more with each other. This implies that nations that either lack or have relatively loose regulations tend to receive goods with higher levels of aflatoxin contamination and have fewer trading partners. This creates serious health risks for the countries' populations in addition to major economic loss (Wu, 2015). Such burdens may increase under climate change as nations work to ensure timely responses and adaptation to changing food chains.

PREDICTION AND MONITORING OF MYCOTOXINS UNDER CLIMATE CHANGE

Accurate prediction and monitoring of mycotoxin occurrence will vastly improve efforts to reduce the entry of mycotoxins into the food chain and promote the prudent use of fungicides on cropland. DONcast is a predictive tool developed for farmers and designed to predict deoxynivalenol (DON) concentrations in wheat at the provincial level (Hooker, Schaafsma and Tamburic-Ilincic, 2002). The African Postharvest Losses Information System (APHLIS) helps to map aflatoxin risks across sub-Saharan Africa based on climate data from the early-warning tool, Anomaly Hotspots of Agricultural Production (ASAP) (Rembold *et al.,* 2019; 2011). Chauhan and co-authors (2015) have developed predictive models for aflatoxin risk, which are integrated into the advanced Agricultural Production Systems sIMulator (APSIM) system allowing users to simulate the likely aflatoxin risk associated with various environmental parameters. The high variability of conditions required for the production of specific mycotoxins can make it difficult to develop precise models (Garcia *et al.,* 2009). More studies on how fungal pathogens and pests acclimatize to various climate change conditions and their effects on other colonizing mycobiota as well as on the plant–pest/pathogen interface are needed. This will help to determine appropriate targeted responses for pathogens of interest under specific climactic conditions. Raising awareness of the health effects and prevention of mycotoxin contamination is also critical for the effective management of mycotoxins. The Partnership for Aflatoxin Control in Africa (PACA) has been raising awareness of mycotoxin issues at pan-African workshops that target a broad audience – from policy-makers to farmers and is helping African countries to build their capacities to prevent and control aflatoxins.

Overall, interconnected approaches are needed to meet the challenges associated with mycotoxin contamination, especially under conditions of climate change (UNEP, 2016). There is need for greater commitment –to research and development, implementation of innovative technologies particularly for predicting infection hotspots, involvement of the health sector in promoting practical interventions for mycotoxin management, coordination and transparent sharing of information among monitoring networks for mycotoxins and establishment of best practice guidelines and stringent regulations for mycotoxin control. Such steps should not be taken by individual sectors in isolation but must be followed in a holistic, multidisciplinary process in which all relevant stakeholders in the value chain – from farmers to researchers, along with the policy-makers and the health sector – are fully engaged in the issues.

© aerocaminua/ Shutterstock.com

Loading of grain into a cargo ship for export.

© The Ocean Cleanup

© Alex Traksel/Shutterstock.com

Top: cleanup efforts at the Great Pacific Garbage Patch; bottom: lab grown meat or cellular agriculture.

CHAPTER 3

EMERGING ISSUES AND INTELLIGENCE GATHERING

Foodborne disease outbreaks cause significant human health impacts and economic losses, and – as previous chapters have described – food safety is vulnerable to climate change. With ongoing changes in climate affecting food production and supply systems in complex ways, it is important to invest in approaches that help food safety authorities to remain informed of potential challenges before their occurrence. The knowledge gathered can be transformed in ways that foster greater preparedness for emerging issues and promote effective prioritization for resource allocation and financial investments. In line with this, among the objectives of the FAO/WHO/AU Food Safety Conference in 2019 was identifying strategies that address future food safety issues and alerting policy makers to emerging issues and trends in food production systems.

In order to remain aware of emerging challenges, the FAO uses foresight-based techniques, which are a fairly new concept in the food safety arena. Foresight is not about predicting the future: it is a forward-thinking, structured approach for the gathering and interpretation of intelligence, which is subsequently used to develop proactive strategies for identifying and addressing issues prior to their occurrence. Part of the process involves taking a broad overview across a wide spectrum of interrelated sectors to look for emerging concepts or trends for a mid- to long-term period through horizon scanning. The information collected is used to build scenarios which are then explored to identify the opportunities and threats of each scenario. The approach allows an exploration of highly uncertain issues in advance of their possible occurrence and promotes better preparedness for emerging issues. FAO's Future of Food and Agriculture series provides long-term analyses of global food and agriculture systems in order to enable member countries to foresee challenges in their respective agrifood sectors and to facilitate mobilization efforts before the realization of worst-case scenarios (FAO 2017a, 2018).

Foresight measures are not a substitute for traditional surveillance and monitoring systems. Rather, these techniques are meant to complement information sourced from surveillance systems in order to provide a holistic view of the scope of potential issues that may require risk management measures. Climate change adaptation measures are also increasingly emphasizing on the establishment of robust early warning systems. Foresight provides a unique blend of broad-spectrum intelligence that will support early warning systems by facilitating the prioritization of resources and the development of relevant strategies (FAO, 2015). Some of the emerging issues and concepts that are influenced by climate change and are currently under FAO's purview are described in the following sections. They include emerging pollutants, certain novel food and food production systems, geoengineering measures and technological advancements.

MICROPLASTICS

Discarded post-consumer plastic debris, microfibres from textiles, fishing gear and other mass-produced plastics in the natural environment face a combination of biotic and abiotic factors that results in their degradation into smaller pieces (Geyer, Jambeck and Law, 2017; Henry, Laitala and Klepp, 2019). Microplastics (less than 5 mm in diameter) are an emerging pollutant found ubiquitously in the environment – from deep seas, rivers and lakes to mountains and the atmosphere (Allen *et al.,* 2019; Ambrosini *et al.,* 2019; Choy *et al.,* 2019). As climate change melts glaciers and alters ocean currents, these phenomena are expected to contribute to changes in the distribution of microplastics in the environment (Ambrosini *et al.*, 2019; Welden and Lusher, 2017). In order to understand the widespread effects of microplastics in full, it is important to quantify the abundance of microplastics in a given environment (Rivers, Gwinnett and Woodall, 2019). In 2014, van Sebille and co-authors estimated that there were 236 000 tonnes of microplastics, mainly in the north Atlantic and north Pacific oceans, but the authors consider this number to be an underestimation of the true scale of the problem (van Sebille *et al.,* 2015). Because of the ubiquitous nature of microplastics humans can be exposed to them from multiple sources, including food (sea salt, fish, etc.) and drinking water (Carrington, 2017; FAO, 2017b; Kim *et al.,* 2018; WHO, 2019; Wright and Kelly, 2017). Estimations of the health impacts posed by microplastics are uncertain as assessing the true concentrations of exposure to this pollutant is extremely challenging (Wright and Kelly, 2017; WHO, 2019). In addition, it is difficult to quantify the "carrier" effect of microplastics as they harbour various chemicals and microbes. Evidence shows that the colonizing microbial community, or "plastisphere", that lives on waterborne microplastics can include pathogenic *Vibrio parahaemolyticus*, biofilm-producing bacterial species, antimicrobial-resistant bacteria (even in remote locations such as Antarctica) and harmful algal bloom species (Kirstein *et al.,* 2016; Lagana *et al.,* 2019; Masó *et al.,* 2007; Rodrigues *et al.,* 2019). Fish exposed to a combination of mercury and microplastics have been shown to have increased bioaccumulation of the toxic heavy metal (Barboza *et al*., 2018). Adsorption of heavy metals, antibiotics and organic pollutants on microplastics has also been shown (Li, Zhang and Zhang, 2018). Large-scale operations are being put in place to capture the massive plastic "patches" in the oceans.

NOVEL FOOD PRODUCTION SYSTEMS

A number of novel food sources and food production systems are emerging – a development that can be attributed to increased awareness of the need to reduce environmental "footprints", especially under climate change impacts.

Climate change is causing mass migration from rural areas into cities as a direct consequence of extreme weather events and disasters. This trend is expected to grow and, as cities expand, there is an urgent need to think about means of providing food that is safe and nutritious for the growing urban populations. Initiatives such as vertical farming, rooftop farms and floating cattle farms[13] might become part of the urban agricultural landscape (Al-Kodmany, 2018). Appropriate measures of urban agriculture will shorten food chains and may reduce food safety risks. Vertical farming is gaining popularity in several cities as it allows producers to choose from a range of options for growing food in urban spaces – hydroponics, aeroponics, aquaponics and many others. Diminishing arable lands and unpredictable weather patterns are also driving some farmers to complement land-based agricultural methods with these innovative techniques, which have the advantages of reducing the impact on natural environments, requiring fewer agrochemicals, avoiding risks from wildlife, reducing water utilization, avoiding the need to respond to unpredictable weather conditions, utilizing food waste as compost (when appropriate) and enhancing traceability. However, these ways of food production can be energy-intensive and restrictive in the types of plants grown, for instance, cereals cannot be grown. Food safety risks can arise from the use of soils sourced from urban areas, which may contain contaminating chemicals, and of grey water for irrigation, especially for leafy green vegetables that are often consumed raw. Hygiene concerns also arise from the risk of workers bringing in contaminants from outside the facilities. Improperly controlled environmental conditions can encourage bacterial growth, requiring the use of antibiotics. In addition, such methods are vulnerable to extreme weather events such as hurricanes.

The combination of growing populations, rising sea levels, sinking islands, higher likelihood of extreme weather events and vulnerable coastal communities calls for innovative solutions. The United Nations Human Settlements Programme (UN-Habitat) recently unveiled a concept for potential floating "satellite" cities in an attempt to promote off-shore settlements that are built to withstand extreme events such as hurricanes and tsunamis. However, such concepts face many challenges that include scale and the financial investment needed to produce sufficient and safe food under space restrictions.

---

[13] Information on floating farms is available at https://floatingfarm.nl/.

© FAO/ Patrick Durst

Bamboo borers (*Dinoderus minutus*) cooked and prepared for sale at a local market in Thailand.

NOVEL FOOD SOURCES

Cellular agriculture – through which food products are produced from cultures of cells taken from plants, animals, fungi or microbes – is gaining increasing attention. Since the first taste test of *in vitro* or "clean" meat in 2013, more research into cell-based meats has been carried out (Arshad *et al.*, 2017; Zaraska, 2013). Cell-based methods are also being explored for seafood (Rubio *et al.*, 2019). These techniques are still in their early stages of development and whether large-scale production of such products is a viable option remains to be explored. The method has advantages such as reduced use of antibiotics or the need for less land for production. However, the techniques prompt food fraud-related concerns and require the establishment of appropriate processes for quality control. In addition, although originally expected to have a lower carbon "footprint", Lynch and Pierrehumbert (2019) suggest that cultured meat production does not appear to offer a more sustainable solution than meat from traditional cattle production.

The use of food waste as a food source and the "personalization" of meals are among the benefits of 3D-printed food. Using extrusion 3D printing technology to print edible macronutrients has been tested with success (Perez *et al.*, 2019). Although 3D printing is not yet available on a commercial scale, various 3D food printers are available on the market. The issue needs careful consideration, particularly because there are numerous food safety concerns that are yet to be addressed. For example, the temperature fluctuations that are part of the extrusion process in 3D printing may promote the growth of microbial pathogens. More research into the storage and shelf-life of 3D-printed food and the addition of food additives to improve the "printability" of certain ingredients is needed.

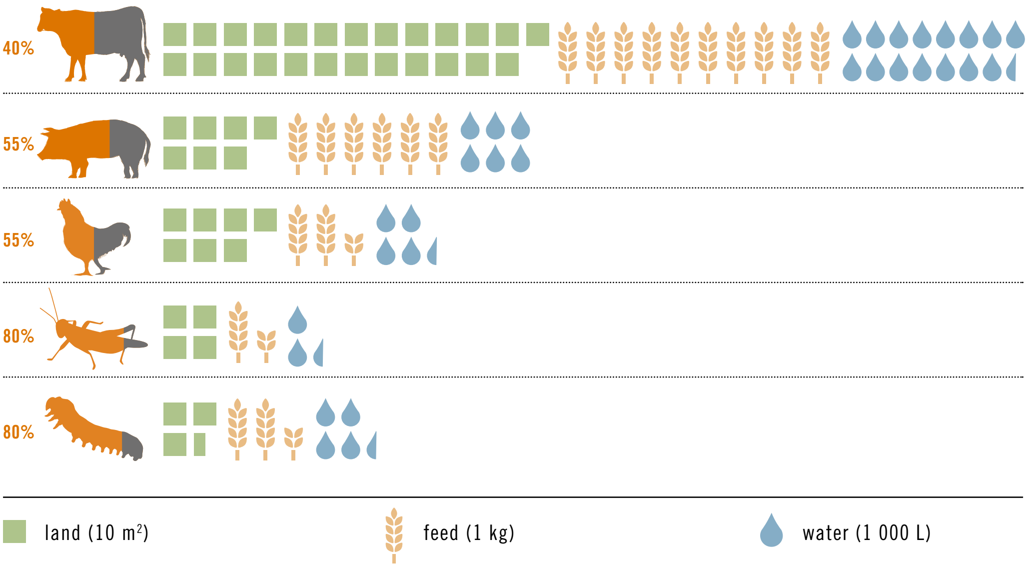
Insects (**Box 14**) are rapidly emerging as an alternative source of food and feed (Smetana *et al.*, 2016). While insect consumption, or entomophagy, has been practised in various countries for generations, the establishment of a global market for farmed edible insects is relatively recent but steadily growing. Sufficient nutritional content, high feed conversion efficiency, rapid growth, environmental sustainability (**Figure 13**) and the use of food waste as substrate for insects are some of the major advantages of farming of edible insects (FAO, 2013). However, this "mini livestock" raises food safety issues that require attention, including microbial (bacterial, viral and fungal) hazards, chemical hazards (pesticides, antibiotics and heavy metals), the inherent toxic compounds that insects produce, potential allergenicity, a lack of sufficient cross-border regulatory oversight among others (EFSA, 2015).

BOX 14

DECLINE OF INSECT POPULATIONS THREATEN ECOSYSTEM COLLAPSE

Insects are immensely important in maintaining terrestrial ecosystems. Global warming, declining forest cover and the overuse of pesticides have been attributed to a dramatic decline in beneficial insect populations in countries that include Germany, Puerto Rico and the Netherlands, sparking fears of ecosystem collapse (Cardoso *et al.*, 2020; Hallmann *et al.*, 2017; Lister and Garcia, 2018; van Strien *et al.*, 2019). Additionally, intense droughts and wildfires associated with El Niño events are also having an impact on insect populations in areas with high biodiversity like the Amazon Rainforest (França *et al.*, 2020).

FIGURE 13 **QUANTITIES OF WATER, LAND AND FEED NEEDED TO PRODUCE 1 kg OF THE LIVE ANIMAL. ALSO SHOWN IS THE PERCENTAGE OF EACH ANIMAL THAT IS EDIBLE.**



Source: Adapted from Doberman, Swift and Field, 2017, *Nutrition Bulletin* 42:293 - 308. This work is licensed under the Creative Commons BY 4.0 License.

Thorough characterization of food safety hazards is a critical factor when deciding on the future applicability of such innovations. More research is needed in order to fully understand the various food safety issues associated with novel foods. In addition, the regulations in place for the applications described in this section are inadequate in terms of production facilities, food safety inspections, quality control, labelling and other issues. Food fraud is also a potential issue with some novel foods. For instance, laboratory-cultured meat may be sold as meat from livestock, or *vice versa*.

GEOENGINEERING (OR CLIMATE ENGINEERING)

Geoengineering focuses on large-scale human interventions that can counteract some of the effects of climate change. Under the umbrella term of “geoengineering”, CO_2 capture followed by long-term storage are among the efforts that seek to mitigate climate change. The idea of fertilizing oceans with iron to stimulate the natural carbon sink is not new (Martin and Fitzwater, 1988). The basic concept being that iron-deficient phytoplankton species will see a rapid burst of growth when iron is dumped into the ocean. This will facilitate the sequestration of CO_2 from the air and its effective capture when algal blooms die and sink to the ocean floor. However, the risks associated with such large-scale perturbations must be fully explored before this method is applied at a large scale. Iron fertilization experiments in the north Pacific were found to promote growth of the HAB species, *Pseudonitzschia*, and neurotoxic domoic acid was found in sea water samples taken from the area, jeopardizing the aquatic food chain (Trick *et al.*, 2010). In addition, recent studies show that such efforts could sequester far less carbon than previously thought (Costa *et al.,* 2016). The establishment of proper governance of climate engineering experiments is needed.

TECHNOLOGICAL ADVANCES AND DIGITALIZATION

The importance of food traceability has grown over recent years. As food production and distribution chains try to keep up with changing consumer preferences and the demands of the food trade, adherence to food safety standards can become lax, which is likely to cause food safety outbreaks (Hodges and Kimball, 2005). These factors, in combination with climate change conditions, threaten to disrupt food chains and the integrity of food quality by increasing the risk of foodborne diseases. Innovations such as digital technologies that allow improvements in traceability along food supply chains are needed, especially in view of the climate change conditions discussed in this chapter.

Blockchain is an emerging technology that has the potential to serve this purpose in the global food supply chain (Kamilaris, Fonts and Prenafeta-Boldú, 2019). The integration of blockchain technology with the Internet of Things (IoT) can be used in the monitoring of supply chains in real time while enhancing traceability based on the Hazard Analysis Critical Control Point (HACCP) system. Despite the advantages, wide-scale implementation of these technologies has a number of challenges, including gaps in digital capacities between developed and developing countries, data governance, standardization of the traceability process, which will require restructuring within organizations, and the high costs of implementation (Chang, Iakovou and Shi, 2019).

© Yein Jeon/Shutterstock.com

Vertical farming.

Top: World Food Safety Day (7th June) at FAO headquarters, 2019; bottom: Codex Alimentarius Commission session at FAO headquarters.

CHAPTER 4

THE WAY FORWARD

Climate change has complex associations with a number of food safety hazards, potentially leading to increased risks of foodborne illnesses and affecting access to safe and nutritious food for millions of people around the globe. The food contamination issues also threaten the achievement of the Sustainable Development Goals (SDGs) namely SDG 2 (zero hunger), SDG 3 (good health and well-being), SDG 6 (clean water and sanitation), SDG 8 (decent work and economic growth), SDG 10 (reduced inequalities), SDG 12 (responsible consumption and production) and SDG 13 (climate change). The international and multidisciplinary nature of food safety risks imply that a "siloed" response to the growing challenges will simply not do. Instead, there is need for a holistic, integrated cross-sectoral approach based on timely collaboration among local, national and global efforts – in other words, a "One Health" approach to food safety issues, especially in the face of climate change. Although the concept of One Health is not new, it has re-emerged as an important idea in helping to tackle some of the contemporary challenges that the world is currently facing, such as the issue of antimicrobial resistance (AMR). Engagement of administrations with scientific communities, the private sector, health care providers, farmers/producers and non-governmental organizations is vital to bringing about a synergistic approach to addressing issues that have transdisciplinary impacts. Stronger collaboration among disciplines will help to focus expertise and resources on specific issues, avoid the duplication of efforts and provide holistic solution to challenges. This kind of approach is much needed in countries where domestic entities face resource shortfalls. The consolidation of strengths among sectors will lead to harmonized response to issues and maximize cost-efficiency. However, successful integration of expertise from different disciplines brings its own challenges and it is important to address these challenges, which include the barriers that continue to divide human and veterinary medicine from agronomy, ecological and evolutionary fields.

Under conditions of climate change, growing food security issues and lengthening food chains, improving food safety is a public health concern that must be addressed. Management of food contamination risks requires the engagement of all relevant actors in the food chain – government bodies, public health and veterinary authorities, plant pathologists, ecologists, national laboratories, private industries, food producers and non-governmental organizations. The adoption of good practice guidelines and the establishment of effective food safety systems are vital for ensuring the safety of national food supplies as well as food products that are meant for export. An essential part of this work is the adoption and enforcement of food safety standards and the harmonization of regulatory frameworks for food for domestic consumption and trade – at the regional and international levels. Rigorous risk assessments are needed in order to establish appropriate food safety standards, which must be periodically revised in line with evolving science and the data collected from monitoring and surveillance. Relevant surveillance data from different stages of the food production chain and on human diseases must be collected in tandem, analysed to evaluate trends, and shared with all relevant national and international partners. This form of data integration will contribute significantly to the prediction and prevention of foodborne disease outbreaks. International networks such as the FAO/WHO International Food Safety Authorities Network (INFOSAN) provide a platform for the sharing of information about foodborne disease outbreaks globally. However, effective monitoring and surveillance are contingent on the availability of the right resources. The disparities between developed and developing countries in terms of these requisites make global implementation of emerging technologies for outbreak surveillance challenging. For instance, advocacy for the widespread adoption of whole genome sequencing to improve the detection of foodborne disease outbreaks and facilitate effective response. While whole genome sequencing is routinely used in developed nations, such technologies are not easy to implement on a large scale in developing nations (Apruzzese *et al.,* 2019). The dissemination of knowledge to policy-makers in order to raise awareness of the benefits of new technologies and the need for investments in capacity building in terms of facilities and personnel training are among the many considerations required to foster effective implementation of emerging technologies in resource-poor countries.

The globalization of food supply chains compounds the challenges related to forecasting, detecting and providing timely response to foodborne disease outbreaks. In order to foster better preparedness for emerging issues, especially under climate change conditions, there is a growing need to shift the philosophy of food safety systems from reactive to more anticipatory approaches. Early warning systems form an important element of risk reduction approaches. Greater investments are needed to set up widespread early warning systems in climate-vulnerable countries. The establishment of such systems requires participation of the different sectors that are involved in ensuring public health. For instance, early warning systems for detecting phycotoxins off coastal areas must include relevant civic and public health authorities, coastal managers, weather forecasters, aquaculture farmers, local coastal communities and the scientists who design prediction models. Alongside such collaboration, the success of these systems also depends on information dissemination *via* effective networks that engage in transparent data sharing in order to foster appropriate preparedness. Novel mitigation systems must also be an integration part of initiatives in multiple sectors to provide well-rounded responses to epidemics.

The influence of consumers on food safety cannot be overlooked. Food safety authorities must be acutely mindful of the fact that consumer choices and dietary patterns are changing, driven by urbanization, globalization, keen sense of sustainability in food production and changes in food market systems. The onus for empowering consumers to make healthy choices in the context of sustainable food systems falls on government bodies, consumer associations, media outlets and the scientific community. This shared responsibility also extends to private enterprises involved in the agrifood industry. As FAO cultivates and strengthens its relationships with private partners, it calls on them to actively engage in corporate social responsibility, ensure sustainability and traceability throughout their supply chains and commit to aligning their production systems to science-based targets for helping to avert climate crises. Major transnational corporations in agriculture, forestry and fisheries have a great influence on the ways in which natural resources and food systems are managed today (Folke *et al.,* 2019). To foster transformative changes concerning sustainability in the agrifood arena, it is vital for corporations, the scientific community and policy-makers to collaborate on the establishment of biosphere stewardship initiatives. Such measures will also amplify the effects of global agreements such as the 2030 Agenda for Sustainable Development and its Sustainable Development Goals.

Scientific research is pivotal in deepening our understanding of climate change and finding novel approaches that solve challenges. Numerous gaps remain in the global understanding of how climate change affects food safety and there is need to encourage more studies that investigate these effects and the exposure risks that they pose – individually and in combinations of multiple hazards. Incorporating forward-looking approaches such as foresight with scientific innovations will not only aid in anticipating future challenges but also help to build resilient systems that can be continually updated as information is gathered. Stronger collaboration within the global scientific community is needed to support scientists from developing nations with tools and knowledge required to develop the competencies that are needed to solve contemporary and emerging issues in their respective countries. In order to create new and updated science-based policies, greater communications between academia and governmental agencies must be encouraged. The importance of investing in raising public awareness of climate change impacts is paramount. Today, humanity has reached a point where it is no longer possible to simply ignore the impacts of climate change and bear the costs of climate inaction. As science advances, it is clear that the pace of and risks associated with irreversible changes due to climate change have been underestimated. National authorities, scientists and the research community have the responsibility of engaging in effective communication with the public in order to foster an environment where people make more climate-sensitive decisions based on the best available knowledge about climate change.

©FAO/Pierre Albouy

International Forum on Food Safety and Trade at Geneva, 2019.

REFERENCES

Chapter 1: Introduction

Ahima, R. 2020. Global warming threatens human thermoregulation and survival. *The Journal of Clinical Investigation*, 130(2): 559 – 561.

Aragon, N.U., Stuhlmacher, M., Smith, J.P., Clinton, N. & Georgescu, M. 2019. Urban agriculture's bounty: contributions to Phoenix's sustainability goals. *Environmental Research Letters*, 14(10): 105001.

Atkinson, A., Hill, S.L., Pakhomov, E.A., Siegel, V., Reiss, C.S., Loeb, V.J., Steinberg, D.K., Schmidt, K., Tarling, G.A., Gerrish, L. & Sailley, S.F. 2019. Krill (*Euphausia superba*) distribution contracts southward during rapid regional warming. *Nature Climate Change*, 9(2): 142–147.

Bastin, J.F., Clark, E., Elliott, T., Hart, S., van den Hoogen, J., Hordijk, I., Ma, H., Majumder, S., Manoli, G., Maschler, J., Mo, L., Routh, D., Yu, K., Zohner, C.M. & Crowther, T.W. 2019. Understanding climate change from a global analysis of city analogues. *PLoS One*, 14(7): e0217592.

Bond-Lamberty, B., Bolton, H., Fansler, S., Heredia-Langner, A., Liu, C., McCue, L.A., Smith, J. & Bailey, V. 2016. Soil respiration and bacterial structure and function after 17 years of a reciprocal soil transplant experiment. *PLoS One*, 11(3): e0150599 [online]. [Cited 16 June 2019]. https://doi.org/10.1371/journal.pone.0150599

Breitburg, D., Levin, L.A., Oschlies, A., Gregoire, M., Chavez, F.P., Conley, D.J., Garçon, V., Gilbert, D., Gutiérrez, D., Isensee, K., Jacinto, G.S., Limburg, K.E., Montes, I., Naqvi, S.W.A., Pitcher, G.C., Rabalais, N.N., Roman, M.R., Rose, K.A., Seibel, B.A., Telszewski, M., Yasuhara, M. & Zhang, J. 2018. Declining oxygen in the global ocean and coastal waters. *Science*, 359(6371): eaam7240.

Brigham-Grette, J., Melles, M., Minyuk, P., Andreev, A., Tarasov, P., DeConto, R., Koenig, S., Nowaczyk, N., Wennrich, V., Rosen, P., Haltia, E., Cook, T., Gebhardt, C., Meyer-Jacob, C., Snyder, J. & Herzschuh, U. 2013. Pliocene warmth, polar amplification, and stepped Pleistocene cooling recorded in NE Arctic Russia. *Science*, 340(6139): 1421–1427.

Caldeira, K. & Wickett, M.E. 2003. Oceanography: anthropogenic carbon and ocean pH. *Nature*, 425(6956): 365.

Cavicchioli, R., Ripple, W.J., Timmis, K.N., Azam, F., Bakken, L.R., Baylis, M., Behrenfeld, M.J., Boetius, A., Boyd, P.W., Classen, A.T., Crowther, T.W., Danovaro, R., Foreman, C.M., Huisman, J., Hutchins, D.A., Jansson, J.K., Karl, D.M., Koskella, B., Mark Welch, D.B., Martiny, J.B.H., Moran, M.A., Orphan, V.J., Reay, D.S., Remais, J.V., Rich, V.I., Singh, B.K., Stein, L.Y., Stewart, F.J., Sullivan, M.B., van Oppen, M.J.H., Weaver, S.C., Webb, E.A. & Webster, N.S. 2019. Scientists' warning to humanity: microorganisms and climate change. *Nature Reviews Microbiology*, 17(9): 569–586.

Chaplin-Kramer, R., Sharp, R.P., Weil, C., Bennett, E.M., Pascual, U., Arkema, K.K., Brauman, K.A., Bryant, B.P., Guerry, A.D., Haddad, N.M., Hamann, M., Hamel, P., Johnson, J.A., Mandle, L., Pereira, H.M., Polasky, S., Ruckelshaus, M., Shaw, M.R., Silver, J.M., Vogl, A.L. & Daily, G.C. 2019. Global modeling of nature's contributions to people. *Science*, 366(6462): 255–258.

Colombo, S.M., Rodgers, T.F.M., Diamond, M.L., Bazinet, R.P. & Arts, M.T. 2019. Projected declines in global DHA availability for human consumption as a result of global warming. *Ambio*, 1–16. https://doi.org/10.1007/s13280-019-01234-6

Comeau, S., Cornwall, C.E., DeCarlo, T.M., Doo, S.S., Carpenter, R.C. & McCulloch, M.T. 2019. Resistance to ocean acidification in coral reef taxa is not gained by acclimatization. *Nature Climate Change*, 9(6): 477–483.

Cook, J., Oreskes, N., Doran, P.T., Anderegg, W.R.L., Verheggen, B., Maibach, E.W., Carlton, J.S., Lewandowsky, S., Skuce, A.G., Green, S.A., Nuccitelli, D., Jacobs, P., Richardson, M., Winkler, B., Painting, R. & Rice, K. 2016. Consensus on consensus: a synthesis of consensus estimates on human-caused global warming. *Environmental Research Letters*, 11(4): 048002.

Cornwal, W. 2019. Ocean heat waves like the Pacific's deadly "Blob" could become the new normal. *Science,* 31 January 2019. https://www.sciencemag.org/news/2019/01/ocean-heat-waves-pacific-s-deadly-blob-could-become-new-normal?utm_campaign=news_daily_2019-01-31&et_rid=348568894&et_cid=2630811

Davenport, F.V., Herrera-Estrada, J.E., Burke, M. & Diffenbaugh, N.S. 2019. Flood size increases non-linearly across Western United States in response to lower snow-precipitation ratios. *Water Resources Research*, 56(1): e2019WR025571. doi: 10.1029/2019WR025571

Denyer, S. 2018. Mongolia's nomadic way of life threatened by climate change, neglect, modernity. *The Washington Post*, 8 July 2018. (also available at https://www.washingtonpost.com/world/asia_pacific/mongolias-nomadic-way-of-life-threatened-by-climate-change-neglect-modernity/2018/07/06/4a22490e-68cb-11e8-a335-c4503d041eaf_story.html).

Dhaliwal, D.S. & Williams, M.M. II. 2019. Optimum plant density for crowding stress tolerant processing sweet corn. *PLoS One*, 14(9): e0223107 [online]. [Cited 25 November 2019]. https://doi.org/10.1371/journal.pone.0223107

Dickey, R.W. & Steven, M.P. 2010. Ciguatera: A public health perspective. *Toxicon*, 56(2): 123 – 136.

Diffenbaugh, N.S. & Burke, M. 2019. Global warming has increased global economic inequality. *Proceedings of the National Academy of Sciences of the USA,* 116(20): 9808–9813.

Dunne, D. 2018. Rising CO_2 levels could push "hundreds of millions" into malnutrition by 2050. *CarbonBrief,* 27 August 2018. https://www.carbonbrief.org/rising-co2-levels-could-push-hundreds-of-millions-into-malnutrition-by-2050.

Ebi, K.L. & Loladze, I. 2019. Elevated atmospheric CO_2 concentrations and climate change will affect our food's quality and quantity. *The Lancet Planetary Health*, 3(7): e283–e284 [online]. [Cited 9 September 2019]. doi: 10.1016/S2542-5196(19)30108-1

Fàbregas, N., Lozano-Elena, F., Blasco-Escámez, D., Tohge, T., Martínez-Andujar, C., Albacete, A., Osorio, S., Bustamante, M., Riechmann, J.L., Nomura, T., Yokota, T., Conesa, A., Alfocea, F.P., Fernie, A.R. & Caññо-Delgado, A.I. 2018. Overexpression of the vascular brassinosteroid receptor BRL3 confers drought resistance without penalizing plant growth. *Nature Communications*, 9(1): 4680.

FAO. 2008. *Climate change: Implications for food safety.* Jaykus, L.A., Woolridge, M., Frank, J.M., Miraglia, M., McQuatters-Gollop, A., Tirado C., Clarke R. and Friel, M. (contributors). Rome, FAO. 49 pp. (also available at http://www.fao.org/3/i0195e/i0195e00.pdf).

FAO. 2015. *The impact of natural hazards and disasters on agriculture and food security and nutrition. A call for action to build resilient livelihoods*. Rome, FAO. 15 pp. (update). (also available at http://www.fao.org/3/a-i4434e.pdf).

FAO. 2016. *The State of Food and Agriculture 2016: Climate change, agriculture and food security*. Rome, FAO. 194 pp. (also available at http://www.fao.org/3/a-i6030e.pdf).

FAO. 2017. *FAO Strategy on Climate Change*. Rome, FAO. 46 pp. (also available at http://www.fao.org/3/a-i7175e.pdf).

FAO. 2018. *The State of Food Security and Nutrition in the World 2018: Building climate resilience for food security and nutrition.* Rome, FAO. 206 pp. (also available at http://www.fao.org/3/I9553EN/i9553en.pdf).

FAO. 2019a. *The future of food safety.* Rome, FAO. 27 pp. (also available at http://www.fao.org/3/ca4289en/CA4289EN.pdf).

FAO. 2019b. *The State of Food and Agriculture 2019. Moving forward on food loss and waste reduction*. Rome, FAO. 182 pp. (also available at http://www.fao.org/3/ca6030en/ca6030en.pdf).

FAO & WHO. 2016. *Evaluation of certain contaminants in food.* Eighty-third report of the Joint FAO/WHO Expert Committee on Food Additives. Rome, FAO and WHO. 182 pp. (also available at https://apps.who.int/iris/bitstream/handle/10665/254893/9789241210027-eng.pdf?sequence=1#page=25%22%3E).

Gray, E. 2018. Unexpected future boost of methane from Arctic permafrost. *NASA's Earth Science News*, 20 August 2018. https://climate.nasa.gov/news/2785/unexpected-future-boost-of-methane-possible-from-arctic-permafrost/

Howe, L.C., MacInnis, B., Krosnick, J.A., Markowitz, E.M. & Socolow, R. 2019. Acknowledging uncertainty impacts public acceptance of climate scientists' predictions. *Nature Climate Change*, 9(11): 863–867.

Hughes, T.P., Kerry, J.T., Baird, A.H., Connolly, S.R., Chase, T.J., Dietzel, A., Hill, T., Hoey, A.S., Hoogenboom, M.O., Jacobson, M., Kerswell, A., Madin, J.S., Mieog, A., Paley, A.S., Pratchett, M.S., Torda, G. & Woods, R.M. 2019. Global warming impairs stock-recruitment dynamics of corals. *Nature*, 568(7752): 387–390.

Hummel, M.A., Berry, M.S. & Stacey, M.T. 2018. Sea level rise impacts on wastewater treatment systems along the US coasts. *Earth's Future*, 6(4): 622–633.

IDMC. 2019. Internal displacement from January to June 2019. Mid-year figures. 12 September 2019. Internal Displacement Monitoring Centre (IDMC). https://www.internal-displacement.org/sites/default/files/inline-files/2019-mid-year-figures_for%20website%20upload.pdf

IPCC. 2018. *Global Warming of 1.5 °C. An IPCC special report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development and efforts to eradicate poverty.* Masson-Delmotte, V., Zhai, P., Pörtner, H. O., Roberts, D., Skea, J., Shukla, P. R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Matthews, J. B. R., Chen, Y., Zhou, Y., Gomis, M. I., Lonnoy, E., Maycock, T., Tignor, M. and Waterfield, T. ed. Geneva, IPCC. 629 pp. (also available at https://www.ipcc.ch/site/assets/uploads/sites/2/2019/06/SR15_Full_Report_High_Res.pdf).

IPCC. 2019. *Climate change and land. Summary for policymakers.* Geneva, IPCC. 43 pp. (also available at https://www.ipcc.ch/site/assets/uploads/2019/08/4.-SPM_Approved_Microsite_FINAL.pdf).

Kersting, D.K. & Linares, C. 2019. Living evidence of a fossil survival strategy raises hope for warming-affected corals. *Science Advances*, 5(10): eaax2950 [online]. [Cited 19 October 2019]. doi: 10.1126/sciadv.aax2950

Kulp, S.A. & Strauss, B.H. 2019. New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding. *Nature Communications*, 10(1): 4844.

Lee, W., Kim, S.-H., Chu, P.S., Moon, I.-J. & Soloviev, A.V. 2019. An index to better estimate tropical cyclone intensity change in the Western North Pacific. *Geophysical Research Letters*, 46(15): 8960–8968.

Lenton, T.M., Rockström, J., Gaffney, O., Rahmstorf, S., Richardson, K., Steffen, W. & Schellnhuber, H.J. 2019. Climate tipping points - too risky to bet against. Nature, 575(7784): 592-595.

Le Quéré, C., Andrew, R.M., Canadell, J.G., Sitch, S., Korsbakken, J.I., Peters, G.P., Manning, A.C., Boden, T.A., Tans, P.P., Houghton, R.A., Keeling, R.F., Alin, S., Andrews, O.D., Anthoni, P., Barbero, L., Bopp, L., Chevallier, F., Chini, L.P., Ciais, P., Currie, K., Delire, C., Doney, S.C., Friedlingstein, P., Gkritzalis, T., Harris, I., Hauck, J., Haverd, V., Hoppema, M., Klein Goldewijk, K., Jain, A.K., Kato, E., Körtzinger, A., Landschützer, P., Lefèvre, N., Lenton, A., Lienert, S., Lombardozzi, D., Melton, J.R., Metzl, N., Millero, F., Monteiro, P.M.S., Munro, D.R., Nabel, J.E.M.S., Nakaoka, S., O'Brien, K., Olsen, A., Omar, A.M., Ono, T., Pierrot, D., Poulter, B., Rödenbeck, C., Salisbury, J., Schuster, U., Schwinger, J., Séférian, R., Skjelvan, I., Stocker, B.D., Sutton, A.J., Takahashi, T., Tian, H., Tilbrook, B., van der Laan-Luijkx, I.T., van der Werf, G.R., Viovy, N., Walker, A.P., Wiltshire, A.J. & Zaehle, S. 2016. Global carbon budget 2016. *Earth System Science Data*, 8(2): 605–649.

Li, L., Switzer, A.D., Wang, Y., Chan, C.-H., Qiu, Q. & Weiss, R. 2018. A modest 0.5-m rise in sea level will double the tsunami hazard in Macau. *Science Advances*, 4(8): eaat1180 [online]. [Cited 13 July 2019]. doi: 10.1126/sciadv.aat1180

Luhn, A. 2019. Russian scientists find 'most powerful' ever methane seep in Arctic Ocean. *The Telegraph*, 8 October 2019. (also available at https://www.telegraph.co.uk/news/2019/10/08/russian-scientists-find-powerful-ever-methane-seep-arctic-ocean/).

Masih, A. 2018. An enhanced seismic activity observed due to climate change: Preliminary results from Alaska. *IOP Conference Series: Earth and Environmental Science*, 167(1): 012018.

McHenry, J., Welch, H., Lester, S.E. & Saba, V. 2019. Projecting marine species range shifts from only temperature can mask climate vulnerability. *Global Change Biology*, 25(12): 4208–4221.

Mooney, C. 2016. Super-warm seas wiped out an entire underwater forest, scientists report. *The Washington Post*. 7 July 2016. (also available at https://www.washingtonpost.com/news/energy-environment/wp/2016/07/07/super-warm-waters-wiped-out-an-entire-underwater-forest-in-australia-scientists-report/).

Muehe, E.M., Wang, T., Kerl, C.F., Planer-Friedrich, B. & Fendorf, S. 2019. Rice production threatened by coupled stresses of climate and soil arsenic. *Nature Communications,* 10(1): 4985.

Natali, S.M., Watts, J.D., Rogers, B.M., Potter, S., Ludwig, S.M., Selbmann, A.-K., Sullivan, P.F., Abbott, B.W., Arndt, K.A., Birch, L., Björkman, M.P., Bloom, A.A., Celis, G., Christensen, T.R., Christiansen, C.T., Commane, R., Cooper, E.J., Crill, P., Czimczik, C., Davydov, S., Du, J., Egan, J.E., Elberling, B., Euskirchen, E.S., Friborg, T., Genet, H., Göckede, M., Goodrich, J.P., Grogan, P., Helbig, M., Jafarov, E.E., Jastrow, J.D., Kalhori, A.A.M., Kim, Y., Kimball, J.S., Kutzbach, L., Lara, M.J., Larsen, K.S., Lee, B.-Y., Liu, Z., Loranty, M.M., Lund, M., Lupascu, M., Madani, N., Malhotra, A., Matamala, R., McFarland, J., McGuire, A.D., Michelsen, A., Minions, C., Oechel, W.C., Olefeldt, D., Parmentier, F.-J.W., Pirk, N., Poulter, B., Quinton, W., Rezanezhad, F., Risk, D., Sachs, T., Schaefer, K., Schmidt, N.M., Schuur, E.A.G., Semenchuk, P.R., Shaver, G., Sonnentag, O., Starr, G., Treat, C.C., Waldrop, M.P., Wang, Y., Welker, J., Wille, C., Xu, X., Zhang, Z., Zhuang, Q. & Zona, D. 2019. Large loss of CO_2 in winter observed across the northern permafrost region. *Nature Climate Change*, 9(11): 852–857.

Nauels, A., Gütschow, J., Mengel, M., Meinshausen, M., Clark, P.U. & Schleussner, C.-F. 2019. Attributing long-term sea-level rise to Paris Agreement emission pledges. *Proceedings of the National Academy of Sciences of the USA*, 116(47): 23487–23492.

Nelson, G., Bogard, J., Lividini, K., Arsenault, J., Riley, M., Sulser, T.B., Mason-D'Croz, D., Power, B., Gustafson, D., Herrero, M., Wiebe, K., Cooper, K., Remans, R. Rosegrant, M. 2018. Income growth and climate change effects on global nutrition security to mid-century. *Nature Sustainability,* 1(12): 773–781.

Neukom, R., Barboza, L.A., Erb, M.P., Shi, F., Emile-Geay, J., Evans, M.N., Franke, J., Kaufman, D.S., Lücke, L., Rehfeld, K., Schurer, A., Zhu, F., Brönnimann, S., Hakim, G.J., Henley, B.J., Ljungqvist, F.C., McKay, N., Valler, V. & von Gunten, L. 2019a. Consistent multi-decadal variability in global temperature reconstructions and simulations over the Common Era. *Nature Geoscience,* 12(8): 643–649.

Neukom, R., Steiger, N., Gómez-Navarro, J.J., Wang, J. & Werner, J.P. 2019b. No evidence for globally coherent warm and cold periods over the preindustrial Common Era. *Nature*, 571(7766): 550–554.

Nkurunziza, L., Chirinda, N., Lana, M., Sommer, R., Karanja, S., Rao, I., Romero Sanchez, M.A., Quintero, M., Kuyah, S., Lewu, F., Joel, A., Nyamadzawo, G. & Smucker, A. 2019. The potential benefits and trade-offs of using sub-surface water retention technology on coarse-textured soils: Impacts of water and nutrient saving on maize production and soil carbon sequestration. *Frontiers in Sustainable Food Systems*, 3. https://doi.org/10.3389/fsufs.2019.00071

Nurse, L.A., McLean, R.F., Agard, J., Briguglio, L.P., Duvat-Magnan, V., Pelesikoti, N., Tompkins, E. & Webb, A. 2014. Small islands: In: *Climate change 2014: Impacts, adaptation and vulnerability. Part B: Regional aspects.* Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. pp. 1613–1654. Barros, V.R., Field, C.B., Dokken, D.J., Mastrandrea, M.D., Mach, K.J., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R. & White, L.L. eds.. Cambridge University Press. Cambridge, United Kingdom of Great Britain and Northern Ireland and New York. (also available at https://www.ipcc.ch/site/assets/uploads/2018/02/WGIIAR5-Chap29_FINAL.pdf).

Obbard, R.W., Sadri, S., Wong, Y.Q., Khitun, A.A., Baker, I. & Thompson, R.C. 2014. Global warming releases microplastic legacy frozen in Arctic Sea ice. *Earth's Future,* 2(6): 315–320.

Oliva, R., Ji, C., Atienza-Grande, G., Huguet-Tapia, J.C., Perez-Quintero, A., Li, T., Eom, J.-S., Li, C., Nguyen, H., Liu, B., Auguy, F., Sciallano, C., Luu, V.T., Dossa, G.S., Cunnac, S., Schmidt, S.M., Slamet-Loedin, I.H., Vera Cruz, C., Szurek, B., Frommer, W.B., White, F.F. & Yang, B. 2019. Broad-spectrum resistance to bacterial blight in rice using genome editing. *Nature Biotechnology*, 37(11): 1344–1350.

Paddock, R. C. & Suhartoo, M. 2019. Indonesia's capital is sinking, polluted and crowded. Its leader wants to build a new one. *The New York Times*, 26 August 2019. (also available at https://www.nytimes.com/2019/08/26/world/asia/indonesia-capital-jakarta-borneo.html).

Park, W. 2019. The country disappearing under rising tides. BBC Future, 2 September 2019. (also available at https://www.bbc.com/future/article/20190829-bangladesh-the-country-disappearing-under-rising-tides).

Park, J.Y., Stock, C.A., Dunne, J.P., Yang, X. & Rosati, A. 2019. Seasonal to multiannual marine ecosystem prediction with a global Earth system model. *Science,* 365(6450): 284–288.

Petersen, A.M., Vincent, E.M. & Westerling, A.L. 2019. Discrepancy in scientific authority and media visibility of climate change scientists and contrarians. *Nature Communications,* 10(1): 3502.

Reed, K. A., Stansfield, A. M., Wehner, M. F. & Zarzycki, C. M. 2020. Forecasted attribution of the human influence on hurricane Florence. *Science Advances*, 6(1): eaaw9253 [online]. doi: 10.1126/sciadv.aaw9253

Reynoso, M.A., Kajala, K., Bajic, M., West, D.A., Pauluzzi, G., Yao, A.I., Hatch, K., Zumstein, K., Woodhouse, M., Rodriguez-Medina, J., Sinha, N., Brady, S.M., Deal, R.B. & Bailey-Serres, J. 2019. Evolutionary flexibility in flooding response circuitry in angiosperms. *Science,* 365(6459): 1291–1295.

Ricke, K., Drouet, L., Caldeira, K. & Tavoni, M. 2018. Country-level social cost of carbon. *Nature Climate Change*, 8(10): 895–900.

Robel, A.A., Seroussi, H. & Roe, G.H. 2019. Marine ice sheet instability amplifies and skews uncertainty in projections of future sea-level rise. *Proceedings of the National Academy of Sciences of the USA*, 116(30): 14887–14892.

Schiermeier, Q. 2018. Droughts, heatwaves and floods: How to tell when climate change is to blame. *Nature,* 560(7716): 20–22.

Schmidhuber, J. & Tubiello, F.N. 2007. Global food security under climate change. *Proceedings of the National Academy of Sciences of the USA,* 104(50): 19703–19708.

Schmidtko, S., Stramma, L. & Visbeck, M. 2017. Decline in global oceanic oxygen content during the past five decades. *Nature,* 542(7641): 335–339.

Smedley, T. 2019. The poisons released by melting Arctic ice. *BBC Future*, 17 June 2019. (also available at https://www.bbc.com/future/article/20190612-the-poisons-released-by-melting-arctic-ice).

Smith, M.R. & Myers, S.S. 2018. Impact of anthropogenic CO_2 emissions on global human nutrition. *Nature Climate Change*, 8(9): 834–839.

Smith, M.R. & Myers, S.S. 2019. Global health implications of nutrient changes in rice under high atmospheric carbon dioxide. *GeoHealth*, 3(7): 190–200).

Solly, M. 2019. One climate crisis disaster occurs every week, UN official warns. *Smithsonian Magazine*, 8 July 2019. https://www.smithsonianmag.com/smart-news/un-expert-warns-one-climate-crisis-disaster-occurs-every-week-180972573/

Sosdian, S.M., Greenop, R., Hain, M.P., Foster, G.L., Pearson, P.N. & Lear, C.H. 2018. Constraining the evolution of Neogene ocean carbonate chemistry using the boron isotope pH proxy. *Earth and Planetary Science Letters*, 498: 362–376.

Swindles, G.T., Watson, E.J., Savov, I.P., Lawson, I.T., Schmidt, A., Hooper, A., Cooper, C.L., Connor, C.B., Gloor, M. & Carrivick, J.L. 2017. Climatic control on Icelandic volcanic activity during the mid-Holocene. *Geology*, 46(1): 47–50.

Thompson, P.L. & Fronhofer, E.A. 2019. The conflict between adaptation and dispersal for maintaining biodiversity in changing environments. *Proceedings of the National Academy of Sciences of the USA,* 116(42): 21061–21067.

UNFCCC. 2018. *UN Climate Change Annual Report.* New York, UN. 58 pp. (also available at https://unfccc.int/sites/default/files/resource/UN-Climate-Change-Annual-Report-2018.pdf).

Velmurugan, G., Ramprasath, T., Gilles, M., Swaminathan, K. & Ramasamy, S. 2017. Gut microbiota, endocrine-disrupting chemicals, and the diabetes epidemic. *Trends in Endocrinology & Metabolism*, 28(8): 612–625. doi: 10.1016/j.tem.2017.05.001

Veng, T. & Andersen, O.B. 2020. Consolidating sea level acceleration estimates from satellite altimetry. *Advances in Space Research*, doi: 10.1016/j.asr.2020.01.016

Vermeulen, S.J., Campbell, B.M. & Ingram, J.S.I. 2012. Climate change and food systems. *Annual Review of Environment and Resources*, 37(1): 195–222.

Wang, B., Luo, X., Yang, Y.M., Sun, W., Cane, M.A., Cai, W., Yeh, S.W. & Liu, J. 2019. Historical change of El Niño properties sheds light on future changes of extreme El Niño. *Proceedings of the National Academy of Sciences of the USA,* 116(45): 22512–22517.

Watson, S., Chen, G., Sylla, A., Routledge, M.N. & Gong, Y.Y. 2016. Dietary exposure to aflatoxin and micronutrient status among young children from Guinea. *Molecular Nutrition and Food Research,* 60(3): 511–518.

Weyant, C., Brandeau, M.L., Burke, M., Lobell, D.B., Bendavid, E. & Basu, S. 2018. Anticipated burden and mitigation of carbon dioxide-induced nutritional deficiencies and related diseases: a simulation modelling study. *PLoS Medicine*, 15(7): e1002586 [online]. [Cited 30 January 2020]. doi: 10.1371/journal.pmed.1002586

Wu, J., Lawit, S.J., Weers, B., Sun, J., Mongar, N., Van Hemert, J., Melo, R., Meng, X., Rupe, M., Clapp, J., Haug Collet, K., Trecker, L., Roesler, K., Peddicord, L., Thomas, J., Hunt, J., Zhou, W., Hou, Z., Wimmer, M., Jantes, J., Mo, H., Liu, L., Wang, Y., Walker, C., Danilevskaya, O., Lafitte, R.H., Schussler, J.R., Shen, B. & Habben, J.E. 2019. Overexpression of *zmm28* increases maize grain yield in the field. *Proceedings of the National Academy of Sciences of the USA,* 116(47): 23850–23858.

Yeo, S. 2019. Where climate cash is flowing and why it's not enough. *Nature*, 573(7774): 328–331.

Zemp, M., Huss, M., Thibert, E., Eckert, N., McNabb, R., Huber, J., Barandun, M., Machguth, H., Nussbaumer, S.U., Gärtner-Roer, I., Thomson, L., Paul, F., Maussion, F., Kutuzov, S. & Cogley, J.G. 2019. Global glacier mass changes and their contributions to sea-level rise from 1961 to 2016. *Nature*, 568(7752): 382–386.

Zhou, W., Xu, Z., Ross, D., Dignan, J., Fan, Y., Huang, Y., Wang, G., Bagtzoglou, A.C., Lei, Y. & Li, B. 2019. Towards water-saving irrigation methodology: Field test of soil moisture profiling using flat thin mm-sized soil moisture sensors (MSMSs). *Sensors and Actuators B: Chemical,* 298: 126857.

Zhu, C., Kobayashi, K., Loladze, I., Zhu, J., Jiang, Q., Xu, X., Liu, G., Seneweera, S., Ebi, K.L., Drewnowski, A., Fukagawa, N.K. & Ziska, L.H. 2018. Carbon dioxide (CO_2) levels this century will alter the protein, micronutrients, and vitamin content of rice grains with potential health consequences for the poorest rice-dependent countries. *Science Advances,* 4(5): eaaq1012 [online]. [Cited 14 November 2019]. doi: 10.1126/sciadv.aaq1012

Chapter 2.A: Foodborne pathogens and parasites

Abanto, M., Gavilan, R.G., Baker-Austin, C., Gonzalez-Escalona, N. & Martinez-Urtaza, J. 2020. Global expansion of Pacific Northwest *Vibrio parahaemolyticus* sequence type 36. *Emerging Infectious Diseases*, 26(2): 323 – 326. https://dx.doi.org/10.3201/eid2602.190362

Adak, G.K., Long, S.M. & O'Brien, S.J. 2002. Trends in indigenous foodborne disease and deaths, England and Wales: 1992 to 2000. *Gut,* 51(6): 832–841.

Akil, L., Ahmad, H.A. & Reddy, R.S. 2014. Effects of climate change on *Salmonella* infections. *Foodborne Pathog. Dis.,* 11(12): 974–980.

Alarcón de Noya, B., Noya, O. & Robertson, L. J. 2015. Trypanosoma cruzi *as a foodborne pathogen.* Springer Briefs in Food, Health and Nutrition. New York, Springer.

Allard, R., Plante, C., Garnier, C. & Kosatsky, T. 2011. The reported incidence of campylobacteriosis modelled as a function of earlier temperatures and numbers of cases, Montreal, Canada, 1990–2006. *International Journal of Biometeorology,* 55(3): 353–560.

Allerberger, F. & Sessitsch, A. 2009. Incidence and microbiology of salad-borne disease. *CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources*, 4(019): doi: 10.1079/PAVSNNR20094019

Altizer, S., Ostfeld, R.S., Jognson, P.T., Kutz, S. & Harvell, C.D. 2013. Climate change and infectious diseases: from evidence to a predictive framework. *Science*, 341(6145): 514 – 519.

Alvarez-Moreno, C., Lavergne, R.A., Hagen, F., Morio, F., Meis, J.F. & Le Pape, P. 2019. Fungicide-driven alterations in azole-resistant *Aspergillus fumigatus* are related to vegetable crops in Colombia, South America. *Mycologia,* 111(2): 217–224.

Anyamba, A., Chretien, J.P., Britch, S.C., Soebiyanto, R.P., Small, J.L., Jepsen, R., Forshey, B.M., Sanchez, J.L., Smith, R.D., Harris, R., Tucker, C.J., Karesh, W.B. & Linthicum, K.J. 2019. Global disease outbreaks associated with the 2015–2016 El Niño event. *Scientific Reports,* 9(1): 1930. https://doi.org/10.1038/s41598-018-38034-z

Atchison, C.J., Tam, C.C., Hajat, S., van Pelt, W., Cowden, J.M. & Lopman, B.A. 2010. Temperature-dependent transmission of rotavirus in Great Britain and the Netherlands. *Proceedings of the Royal Society B: Biological Sciences,* 277(1683): 933–942. doi: 10.1098/rspb.2009.1755

Baker-Austin, C., Trinanes, J., Gonzalez-Escalona, N. & Martinez-Urtaza, J. 2017. Non-cholera Vibrios: The microbial barometer of climate change. *Trends in Microbiology,* 25(1): 76–84.

Baker-Austin, C., Trinanes, J.A., Taylor, N.G.H., Hartnell, R., Siitonen, A. & Martinez-Urtaza, J. 2012. Emerging Vibrio risk at high latitudes in response to ocean warming. *Nature Climate Change,* 3(1): 73–77.

Batz, M.B., Hoffmann, S. & Morris, J.G., Jr. 2012. Ranking the disease burden of 14 pathogens in food sources in the United States using attribution data from outbreak investigations and expert elicitation. *Journal of Food Protection,* 75(7): 1278–1291.

Bebber, D.P. 2015. Range-expanding pests and pathogens in a warming world. *Annual Review of Phytopathology,* 53: 335–356.

Bebber, D.P., Ramotowski, M.A.T. & Gurr, S.J. 2013. Crop pests and pathogens move polewards in a warming world. *Nature Climate Change,* 3(11): 985–988.

Begley, M. & Hill, C., 2015. Stress adaptation in foodborne pathogens. *Annual Review of Food Science & Technology*, 6: 191–210.

Berger, C.N., Sodha, S.V., Shaw, R.K., Griffin, P.M., Pink, D., Hand, P. & Frankel, G. 2010. Fresh fruit and vegetables as vehicles for the transmission of human pathogens. *Environmental Microbiology,* 12(9): 2385–2397.

Bernstein, N., Sela, S., Pinto, R. & Ioffe, M. 2007. Evidence for internalization of *Escherichia coli* into the aerial parts of maize *via* the root system. *Journal of Food Protection,* 70(2): 471–475.

Beyene, T., Endalamaw, D., Tolossa, Y. & Feyisa, A. 2015. Evaluation of rational use of veterinary drugs especially antimicrobials and anthelmintics in Bishoftu, Central Ethiopia. *BMC Research Notes*, 8: 482.

Brandl, M.T. 2006. Fitness of human enteric pathogens on plants and implications for food safety. *Annual Review of Phytopathology,* 44: 367–392.

Britton, E., Hales, S., Venugopal, K. & Baker, M.G. 2010. The impact of climate variability and change on cryptosporidiosis and giardiasis rates in New Zealand. *Journal of Water & Health*, 8(3): 561–571.

Broza, M., Gancz, H., Halpern, M. & Kashi, Y. 2005. Adult non-biting midges: possible windborne carriers of *Vibrio cholerae* non-O1 non-O139. *Environmental Microbiology*, 7(4): 576–585.

Brun, P., Stamieszkin, K., Visser, A.W., Licandro, P., Payne, M.R. & Kiorboe, T. 2019. Climate change has altered zooplankton-fuelled carbon export in the North Atlantic. *Nature Ecology & Evolution,* 3(3): 416–423.

Caballero-Ortega, H., Uribe-Salas, F.J., Conde-Glez, C.J., Cedillo-Pelaez, C., Vargas-Villavicencio, J.A., Luna-Pasten, H., Canedo-Solares, I., Ortiz-Alegria, L.B. & Correa, D. 2012. Seroprevalence and national distribution of human toxoplasmosis in Mexico: analysis of the 2000 and 2006 National Health Surveys. *Transactions of the Royal Society of Tropical Medicine and Hygiene,* 106(11): 653–659.

Cabello, F.C., Godfrey, H.P., Buschmann, A.H. & Dölz, H.J. 2016. Aquaculture as yet another environmental gateway to the development and globalisation of antimicrobial resistance. *The Lancet Infectious Diseases,* 16(7): e127–e133 [online]. [Cited 5 July 2019]. doi: 10.1016/S1473-3099(16)00100-6

Cai, W., Borlace, S., Lengaigne, M., van Rensch, P., Collins, M., Vecchi, G., Timmermann, A., Santoso, A., McPhaden, M.J., Wu, L., England, M.H., Wang, G., Guilyardi, E. & Jin, F.-F. 2014. Increasing frequency of extreme El Niño events due to greenhouse warming. *Nature Climate Change*, 4(2): 111–116.

Carlson, C.J., Burgio, K.R., Dougherty, E.R., Phillips, A.J., Bueno, V.M., Clements, C.F., Castaldo, G., Dallas, T.A., Cizauskas, C.A., Cumming, G.S., Dona, J., Harris, N.C., Jovani, R., Mironov, S., Muellerklein, O.C., Proctor, H.C. & Getz, W.M. 2017. Parasite biodiversity faces extinction and redistribution in a changing climate. *Science Advances,* 3(9): e1602422 [online]. [Cited 8 October 2019]. doi: 10.1126/sciadv.1602422

Carlton, E.J., Woster, A.P., DeWitt, P., Goldstein, R.S. & Levy, K. 2016. A systematic review and meta-analysis of ambient temperature and diarrhoeal diseases. *International Journal of Epidemiology*, 45(1): 117–130.

Casadevall, A., Kontoyiannis, D.P. & Robert, V. 2019. On the emergence of *Candida auris*: Climate change, azoles, swamps, and birds. *MBio,* 10(4): doi:10.1128/mBio.01397-19

Cash, B.A., Rodo, X., Emch, M., Yunus, M., Faruque, A.S. & Pascual, M. 2014. Cholera and shigellosis: different epidemiology but similar responses to climate variability. *PLoS One,* 9(9): e107223 [online]. [Cited 12 June 2019]. https://doi.org/10.1371/journal.pone.0107223

CDC. 2014. Outbreak of *Salmonella Heidelberg* infections linked to Tyson brand mechanically separated chicken at a correctional facility (final update). United States Centers for Disease Control and Prevention (CDC) [Cited 15 October 2019]. https://www.cdc.gov/salmonella/heidelberg-01-14/index.html

CDC. 2015. Antibiotic resistance in foodborne germs is an ongoing threat. [Cited 13 October 2019]. https://www.cdc.gov/media/releases/2015/a0609-antibiotic-resistance.html

CDC. 2016. Multistate outbreak of *Salmonella Poona* infections linked to imported cucumbers (final update). [Cited 15 October 2019]. https://www.cdc.gov/salmonella/poona-09-15/index.html

CDC. 2017. Multistate outbreak of *Salmonella Urbana* infections linked to imported maradol papayas (final update). [Cited 15 October 2019]. https://www.cdc.gov/salmonella/urbana-09-17/index.html

CDC. 2019. Outbreak of multidrug-resistant *Salmonella* infections linked to raw chicken products. [Cited 15 October 2019]. https://www.cdc.gov/salmonella/infantis-10-18/index.html

Chantziaras, I., Boyen, F., Callens, B. & Dewulf, J. 2014. Correlation between veterinary antimicrobial use and antimicrobial resistance in food-producing animals: a report on seven countries. *Journal of Antimicrobial Chemotherapy,* 69(3): 827–834.

Chersich, M.F., Scorgie, F., Rees, H. & Wright, C.Y. 2018. How climate change can fuel listeriosis outbreaks in South Africa. *South African Medical Journal,* 108(6): 453–454.

Cockburn, T.A. & Cassanos, J.G. 1960. Epidemiology of endemic cholera. *Public Health Reports (1896-1970),* 75(9): 791.

Colwell, R.R. 1996. Global climate and infectious disease: the cholera paradigm. *Science,* 274(5295): 2025–2031.

Cousins, M., Sargeant, J.M., Fisman, D. & Greer, A.L. 2019. Modelling the transmission dynamics of Campylobacter in Ontario, Canada, assuming house flies, *Musca domestica*, are a mechanical vector of disease transmission. *Royal Society Open Science,* 6(2): 181394.

D'Costa, V.M., King, C.E., Kalan, L., Morar, M., Sung, W.W., Schwarz, C., Froese, D., Zazula, G., Calmels, F., Debruyne, R., Golding, G.B., Poinar, H.N. & Wright, G.D. 2011. Antibiotic resistance is ancient. *Nature,* 477(7365): 457–461.

D'Souza, R.M., Becker, N.G., Hall, G. & Moodie, K.B. 2004. Does ambient temperature affect foodborne disease? *Epidemiology,* 15(1): 86–92.

Dai, A. 2012. Increasing drought under global warming in observations and models. *Nature Climate Change,* 3(1): 52–58.

Dengo-Baloi, L.C., Sema-Baltazar, C.A., Manhique, L.V., Chitio, J.E., Inguane, D.L. & Langa, J.P. 2017. Antibiotics resistance in El Tor *Vibrio cholerae* 01 isolated during cholera outbreaks in Mozambique from 2012 to 2015. *PLoS One,* 12(8): e0181496 [online]. [Cited 15 November 2019]. https://doi.org/10.1371/journal.pone.0181496

ECDC. 2012. *Assessing the potential impacts of limate change on food- and waterborne diseases in Europe.* Stockholm, European Centre for Disease Prevention and Control (ECDC). 24 pp. (also available at https://www.ecdc.europa.eu/en/publications-data/assessing-potential-impacts-climate-change-food-and-waterborne-diseases-europe).

ECDC. 2013. *Risk assessment on the impact of environmental usage of triazoles on the development and spread of resistance to medical triazoles in Aspergillus species.* Stockholm, ECDC. 22 pp. (also available at https://www.ecdc.europa.eu/sites/portal/files/media/en/publications/Publications/risk-assessment-impact-environmental-usage-of-triazoles-on-Aspergillus-spp-resistance-to-medical-triazoles.pdf).

ECDC. 2016. *Salmonellosis – Annual epidemiological report 2016 (2014 data).* Annual Epidemiological Report on Communicable Diseases in Europe. Stockholm, ECDC. (also available at https://www.ecdc.europa.eu/sites/portal/files/documents/Salmonellosis-aer-2014.pdf).

Ekdahl, K., Normann, B. & Andersson, Y. 2005. Could flies explain the elusive epidemiology of campylobacteriosis? *BMC Infectious Diseases,* 5: 11.

Elmali, M. & Can, H.Y. 2017. Occurrence and antimicrobial resistance of Arcobacter species in food and slaughterhouse samples. *Food Science and Technology,* 37(2): 280–285.

Engelthaler, D.M. & Casadevall, A. 2019. On the emergence of *Cryptococcus gattii* in the Pacific Northwest: Ballast tanks, tsunamis, and black swans. *MBio,* 10(5): doi:10.1128/mBio.02193-19.

Epstein, P.R. 1993. Algal blooms in the spread and persistence of cholera. *Biosystems,* 31(2–3): 209–221.

Estrada-Flores, S. & Platt, G. 2007. Electricity usage in the Australian cold chain. *Food Australia,* 59(8): 382–390.

European Commission. 2018. *RASFF: The Rapid Alert System for Food and Feed. 2018 annual report.* Luxembourg, Publications Office of the European Union. 53 pp. (also available at https://ec.europa.eu/food/sites/food/files/safety/docs/rasff_annual_report_2018.pdf).

FAO. 1996. Rome declaration on World Food Security and World Food Summit Plan of Action. World Food Summit 13-17 November 1996. Rome, FAO. (also available at http://www.fao.org/3/w3548e/w3548e00.htm).

FAO. 2008. *Climate change: Implications for food safety.* Rome, FAO. 49 pp. (also available at http://www.fao.org/3/i0195e/i0195e00.pdf).

FAO. 2018. *Antimicrobial resistance and foods of plant origin. Summary report of an FAO meeting of experts. FAO Antimicrobial Resistance Working Group.* 4 pp. Rome, FAO. (also available at http://www.fao.org/3/BU657en/bu657en.pdf).

FAO & WHO. 2014. *Multicriteria-based ranking for risk management of food-borne parasites.* Microbiological Risk Assessment Series No. 23. Rome, FAO. 302 pp. (also available at https://www.who.int/foodsafety/publications/mra_23/en/).

FAO & WHO. 2018a. *Evaluation of certain veterinary residues in food. Eighty-fifth report of the Joint FAO/WHO Expert Committee on Food Additives.* 164 pp. Malta, FAO. (also available at https://apps.who.int/iris/handle/10665/259895).

FAO & WHO. 2018b. *INFOSAN activity report 2016/2017*. Geneva, Switzerland, FAO and WHO. 60 pp. (also available at https://apps.who.int/iris/handle/10665/279581).

Fleury, M., Charron, D.F., Holt, J.D., Allen, O.B. & Maarouf, A.R. 2006. A time series analysis of the relationship of ambient temperature and common bacterial enteric infections in two Canadian provinces. *International Journal of Biometeorology,* 50(6): 385–391.

Fisher, M.C., Hawkins, N.J., Sanglard, D. & Gurr, S.J. 2018. Worldwide emergence of resistance to antifungal drugs challenges human health and food security. *Science*, 360: 739 – 742.

Flynn, K.J., Clark, D.R., Mitra, A., Fabian, H., Hansen, P.J., Glibert, P.M., Wheeler, G.L., Stoecker, D.K., Blackford, J.C. & Brownlee, C. 2015. Ocean acidification with (de) eutrophication will alter future phytoplankton growth and succession. *Proceedings of the Royal Society B: Biological Sciences,* 282(1804): 20142604.

Fox, N.J., White, P.C., McClean, C.J., Marion, G., Evans, A. and Hutchings, M.R. 2011. Predicting impacts of climate change on *Fasciola hepatica* risk. *PLoS One,* 6(1): e16126 [online]. [Cited 6 August 2019]. https://doi.org/10.1371/journal.pone.0016126

Garcia-Solache, M.A. & Casadevall, A. 2010. Global warming will bring new fungal diseases for mammals. *MBio,* 1(1): doi:10.1128/mBio.00061-10.

Ge, C., Lee, C. & Lee, J. 2012. The impact of extreme weather events on *Salmonella* internalization in lettuce and green onion. *Food Research International,* 45(2): 1118–1122.

Gfeller, K.Y., Roth, M., Meile, L. & Teuber, M. 2003. Sequence and genetic organization of the 19.3-kb erythromycin- and dalfopristin-resistance plasmid pLME300 from Lactobacillus fermentum ROT1. *Plasmid,* 50(3): 190–201.

Ghaly, T.M., Chow, L., Asher, A.J., Waldron, L.S. & Gillings, M.R. 2017. Evolution of class 1 integrons: Mobilization and dispersal *via* food-borne bacteria. *PLoS One,* 12(6): e0179169 [online]. [Cited 24 August 2019]. doi: 10.1371/journal.pone.0179169

Gkogka, E., Reij, M.W., Havelaar, A.H., Zwietering, M.H. & Gorris, L.G. 2011. Risk-based estimate of effect of foodborne diseases on public health, Greece. *Emerging Infectious Diseases,* 17(9): 1581–1590.

Goulson, D., Derwent, L.C., Hanley, M.E., Dunn, D.W. & Abolins, S.R. 2005. Predicting calyptrate fly populations from the weather, and probable consequences of climate change. *Journal of Applied Ecology,* 42(5): 795–804.

Greenfield, D.I., Gooch Moore, J., Stewart, J.R., Hilborn, E.D., George, B.J., Li, Q., Dickerson, J., Keppler, C.K. & Sandifer, P.A. 2017. Temporal and environmental factors driving *Vibrio vulnificus* and *V. parahaemolyticus* populations and their associations with harmful algal blooms in South Carolina detention ponds and receiving tidal creeks. *GeoHealth,* 1(9): 306–317.

Guarino, B. 2016. Anthrax sickens 13 in western Siberia, and a thawed-out reindeer corpse may be to blame. *The Washington Post.* 28 July 2016. (also available at https://www.washingtonpost.com/news/morning-mix/wp/2016/07/28/anthrax-sickens-13-in-western-siberia-and-a-thawed-out-reindeer-corpse-may-be-to-blame/).

Gueimonde, M., Sanchez, B., C, G.d.L.R.-G. & Margolles, A. 2013. Antibiotic resistance in probiotic bacteria. *Front. Microbiol.,* 4: 202: doi:10.3389/fmicb.2013.00202.

Hall, G., Kirk, M.D., Becker, N., Gregory, J.E., Unicomb, L., Millard, G., Stafford, R., Lalor, K. & OzFoodNet Working, G. 2005. Estimating foodborne gastroenteritis, Australia. *Emerging Infectious Diseases*, 11(8): 1257–1264.

Halpern, M. & Izhaki, I. 2017. Fish as hosts of *Vibrio cholerae*. *Frontiers in Microbiology,* 8: 282: doi:10.3389/fmicb.2017.00282.

Harb, M., Wang, P., Zarei-Baygi, A., Plumlee, M.H. & Smith, A.L. 2019. Background Antibiotic Resistance and Microbial Communities Dominate Effects of Advanced Purified Water Recharge to an Urban Aquifer. *Environmental Science and Technology Letters*, 6(10): 578–584.

Harris-Lovett, S & Sedlak, D. 2019. From toilet to tap: What cities need to overcome to make that happen. *The Wall Street Journal.* 17 May 2019. (also available at https://www.wsj.com/articles/from-toilet-to-tap-what-cities-need-to-do-to-make-it-happen-11558105505).

Harvell, C.D., Kim, K., Burkholder, J.M., Colwell, R.R., Epstein, P.R., Grimes, D.J., Hofmann, E.E., Lipp, E.K., Osterhaus, A.D., Overstreet, R.M., Porter, J.W., Smith, G.W. & Vasta, G.R. 1999. Emerging marine diseases – climate links and anthropogenic factors. *Science,* 285(5433): 1505–1510.

Harvell, C.D., Mitchell, C.E., Ward, J.R., Altizer, S., Dobson, A.P., Ostfeld, R.S. & Samuel, M.D. 2002. Climate warming and disease risks for terrestrial and marine biota. *Science,* 296(5576): 2158–2162.

Hashizume, M., Armstrong, B., Wagatsuma, Y., Faruque, A.S., Hayashi, T. & Sack, D.A. 2008. Rotavirus infections and climate variability in Dhaka, Bangladesh: a time-series analysis. *Epidemiology & Infection,* 136(9): 1281–1289.

Havelaar, A.H., Haagsma, J.A., Mangen, M.J., Kemmeren, J.M., Verhoef, L.P., Vijgen, S.M., Wilson, M., Friesema, I.H., Kortbeek, L.M., van Duynhoven, Y.T. & van Pelt, W. 2012. Disease burden of foodborne pathogens in the Netherlands, 2009. *International Journal of Food Microbiology,* 156(3): 231–238.

Heaney, A.K., Shaman, J. & Alexander, K.A. 2019. El Niño-Southern oscillation and under-5 diarrhea in Botswana. *Nature Communications*, 10: 5798.

Henderson, J.C., Herrera, C.M. & Trent, M.S. 2017. AlmG, responsible for polymyxin resistance in pandemic *Vibrio cholerae*, is a glycyltransferase distantly related to lipid A late acyltransferases. *Journal of Biological Chemistry,* 292(51): 21205–21215.

Heredia, N. & Garcia, S. 2018. Animals as sources of food-borne pathogens: A review. *Animal Nutrition,* 4(3): 250–255.

Herman, K.M., Hall, A.J. & Gould, L.H. 2015. Outbreaks attributed to fresh leafy vegetables, United States, 1973–2012. *Epidemiology & Infection,* 143(14): 3011–3021.

Hirneisen, K.A., Sharma, M. & Kniel, K.E. 2012. Human enteric pathogen internalization by root uptake into food crops. *Foodborne Pathogens & Diseases,* 9(5): 396–405.

Hofste, R.W., Reig, P. & Schiefer, L. 2019. 17 countries , home to one-quarter of the world's population, face extremely high water stress. World Resources Institute, 6 August 2019. https://www.wri.org/blog/2019/08/17-countries-home-one-quarter-world-population-face-extremely-high-water-stress

Horn, N. & Bhunia, A.K. 2018. Food-associated stress primes foodborne pathogens for the gastrointestinal phase of infection. *Frontiers in Microbiology,* 9: 1962: https://doi.org/10.3389/fmicb.2018.01962

Hummel, M.A., Berry, M.S. & Stacey, M.T. 2018. Sea level rise impacts on wastewater treatment systems along the US coasts. *Earth's Future,* 6(4): 622–633.

Hussain, M.A. & Dawson, C.O. 2013. Economic impact of food safety outbreaks on food businesses. *Foods,* 2(4): 585–589.

IACG. 2019. *No time to wait: Securing the future from drug-resistant infections.* Report to the Secretary-General of the United Nations. 28 pp. Interagency Coordination Group on Antimicrobial Resistance (IACG). https://www.who.int/docs/default-source/documents/no-time-to-wait-securing-the-future-from-drug-resistant-infections-en.pdf?sfvrsn=5b424d7_6

IPCC. 2007. *Climate change 2007: Impacts, adaptation and vulnerability.* Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J. and Hanson, C.E. eds. Cambridge, United Kingdom of Great Britain and Northern Ireland and New York, Cambridge University Press. 976 pp. (also available at https://www.ipcc.ch/report/ar4/wg2/).

Iqbal, A., Measures, L., Lair, S. & Dixon, B. 2018. *Toxoplasma gondii* infection in stranded St. Lawrence Estuary beluga *Delphinapterus leucas* in Quebec, Canada. *Diseases of Aquatic Organisms,* 130(3): 165–175.

Jagai, J.S., Castronovo, D.A., Monchak, J. & Naumova, E.N. 2009. Seasonality of cryptosporidiosis: A meta-analysis approach. *Environmental Research,* 109(4): 465–478.

James, S.J. & James, C. 2010. The food cold-chain and climate change. *Food Research International,* 43(7): 1944–1956.

Jensen, S.K., Aars, J., Lydersen, C., Kovacs, K.M. & Åsbakk, K. 2009. The prevalence of *Toxoplasma gondii* in polar bears and their marine mammal prey: evidence for a marine transmission pathway? *Polar Biology,* 33(5): 599–606.

Jiang, C., Shaw, K.S., Upperman, C.R., Blythe, D., Mitchell, C., Murtugudde, R., Sapkota, A.R. & Sapkota, A. 2015. Climate change, extreme events and increased risk of salmonellosis in Maryland, USA: Evidence for coastal vulnerability. *Environmental International,* 83: 58–62.

Johnsen, A.R. & Kroer, N. 2007. Effects of stress and other environmental factors on horizontal plasmid transfer assessed by direct quantification of discrete transfer events. *FEMS Microbiology Ecology,* 59(3): 718–728.

Johnson, C.N., Bowers, J.C., Griffitt, K.J., Molina, V., Clostio, R.W., Pei, S., Laws, E., Paranjpye, R.N., Strom, M.S., Chen, A., Hasan, N.A., Huq, A., Noriea, N.F., 3rd, Grimes, D.J. & Colwell, R.R. 2012. Ecology of *Vibrio parahaemolyticus* and *Vibrio vulnificus* in the coastal and estuarine waters of Louisiana, Maryland, Mississippi, and Washington (United States). *Applied Environmental Microbiology,* 78(20): 7249–7257.

Kastner, S., Perreten, V., Bleuler, H., Hugenschmidt, G., Lacroix, C. & Meile, L. 2006. Antibiotic susceptibility patterns and resistance genes of starter cultures and probiotic bacteria used in food. *Systematic & Applied Microbiology,* 29(2): 145–155.

Khaitsa, M. L., Bauer, M. L., Lardy, G. P., Doetkott, D. K., Kegode, R. B., & Gibbs, P. S. 2006. Fecal shedding of *Escherichia coli* O157:H7 in North Dakota feedlot cattle in the fall and spring. *Journal of Food Protection,* 69(5): 1154–1158.

Kim, Y.S., Park, K.H., Chun, H.S., Choi, C. & Bahk, G.J. 2015. Correlations between climatic conditions and foodborne disease. *Food Research International,* 68: 24–30.

Kirchhelle, C. 2018. Pharming animals: a global history of antibiotics in food production (1935–2017). *Palgrave Communications,* 4(1): 96.

Kirstein, I.V., Kirmizi, S., Wichels, A., Garin-Fernandez, A., Erler, R., Loder, M. & Gerdts, G. 2016. Dangerous hitchhikers? Evidence for potentially pathogenic *Vibrio spp.* on microplastic particles. *Marine Environmental Research,* 120: 1–8.

Konkel, M.E. & Tilly, K. 2000. Temperature-regulated expression of bacterial virulence genes. *Microbes and Infection,* 2(2): 157–166.

Kovats, R.S., Edwards, S.J., Charron, D., Cowden, J., D'Souza, R.M., Ebi, K.L., Gauci, C., Gerner-Smidt, P., Hajat, S., Hales, S., Hernandez Pezzi, G., Kriz, B., Kutsar, K., McKeown, P., Mellou, K., Menne, B., O'Brien, S., van Pelt, W. & Schmid, H. 2005. Climate variability and campylobacter infection: an international study. *International Journal of Biometeorology,* 49(4): 207–214.

Kovats, R.S., Edwards, S.J., Hajat, S., Armstrong, B.G., Ebi, K.L. & Menne, B. 2004. The effect of temperature on food poisoning: a time-series analysis of salmonellosis in ten European countries. *Epidemiology & Infection,* 132(3): 443–453.

Kwan, L.C., Cheung, D.K. & Kam, K.M. 2003. Peak occurrences of ciguatera fish poisoning precede cholera outbreaks in Hong Kong. *Epidemiology & Infection,* 131(1): 621–626.

Lake, R.J., Cressey, P.J., Campbell, D.M. & Oakley, E. 2010. Risk ranking for foodborne microbial hazards in New Zealand: burden of disease estimates. *Risk Analysis,* 30(5): 743–752.

Leão, J.M., Lozano-Leon, A., Giráldez, J., Vilariño, Ó. & Gago-Martinez, A. 2018. Preliminary results on the evaluation of the occurrence of tetrodotoxin associated to marine *Vibrio* spp. in bivalves from the Galician Rias (Northwest of Spain). *Marine Drugs*, 16: 81. doi: 10.3390/md16030081

Legendre, M., Bartoli, J., Shmakova, L., Jeudy, S., Labadie, K., Adrait, A., Lescot, M., Poirot, O., Bertaux, L., Bruley, C., Coute, Y., Rivkina, E., Abergel, C. & Claverie, J.M. 2014. Thirty-thousand-year-old distant relative of giant icosahedral DNA viruses with a pandoravirus morphology. *Proceedings of the National Academy of Sciences of the USA,* 111(11): 4274-4279.

Levy, K., Hubbard, A.E. & Eisenberg, J.N. 2009. Seasonality of rotavirus disease in the tropics: a systematic review and meta-analysis. *International Journal of Epidemiology,* 38(6): 1487–1496.

Li, L., Switzer, A.D., Wang, Y., Chan, C.H., Qiu, Q. & Weiss, R. 2018. A modest 0.5-m rise in sea level will double the tsunami hazard in Macau. *Science Advances,* 4(8): eaat1180 [online]. [Cited 11 September 2019]. doi: 10.1126/sciadv.aat1180

Lopez-Velasco, G., Sbodio, A., Tomas-Callejas, A., Wei, P., Tan, K.H. & Suslow, T.V. 2012. Assessment of root uptake and systemic vine-transport of *Salmonella enterica* sv. Typhimurium by melon (*Cucumis melo*) during field production. *International Journal of Food Microbiology,* 158(1): 65–72.

Lutz, C., Erken, M., Noorian, P., Sun, S. & McDougald, D. 2013. Environmental reservoirs and mechanisms of persistence of *Vibrio cholerae. Frontiers in Microbiology,* 4: 375.

Lynch, M.F., Tauxe, R.V. & Hedberg, C.W. 2009. The growing burden of foodborne outbreaks due to contaminated fresh produce: risks and opportunities. *Epidemiology & Infection,* 137(3): 307–315.

MacFadden, D.R., McGough, S.F., Fisman, D., Santillana, M. & Brownstein, J.S. 2018. Antibiotic resistance increases with local temperature. *Nature Climate Change,* 8(6): 510–514.

Martinez, P.P., King, A.A., Yunus, M., Faruque, A.S. & Pascual, M. 2016. Differential and enhanced response to climate forcing in diarrheal disease due to rotavirus across a megacity of the developing world. *Proceedings of the National Academy of Sciences of the USA,* 113(15): 4092–4097.

Martinez-Urtaza, J., Bowers, J.C., Trinanes, J. & DePaola, A. 2010. Climate anomalies and the increasing risk of *Vibrio parahaemolyticus* and *Vibrio vulnificus* illnesses. *Food Research International*, 43(7): 1780–1790.

Marx, M.A., Rodriguez, C.V., Greenko, J., Das, D., Heffernan, R., Karpati, A.M., Mostashari, F., Balter, S., Layton, M. & Weiss, D. 2006. Diarrheal illness detected through syndromic surveillance after a massive power outage: New York City, August 2003. *American Journal of Public Health,* 96(3): 547–553.

Mathur, S. & Singh, R. 2005. Antibiotic resistance in food lactic acid bacteria – a review. *International Journal of Food Microbiology,* 105(3): 281–295.

McCreesh, N., Nikulin, G. & Booth, M. 2015. Predicting the effects of climate change on *Schistosoma mansoni* transmission in eastern Africa. *Parasites & Vectors,* 8: 4.

McGough, S.F., MacFadden, D.R., Hattab, M.W., Mølbak, K. & Santillana, M. 2018. Rates of increase of antibiotic resistance and ambient temperature in Europe: a cross-national analysis of 28 countries between 2000–2016. *bioRxiv*: doi.org/10.1101/414920.

McIntyre, K.M., Setzkorn, C., Hepworth, P.J., Morand, S., Morse, A.P. & Baylis, M. 2017. Systematic assessment of the climate sensitivity of important human and domestic animals pathogens in Europe. *Scientific Reports,* 7(1): 7134. https://doi.org/10.1038/s41598-017-06948-9

McKenna, M. 2019. Antibiotics set to flood Florida's troubled orange orchards. *Nature,* 567(7748): 302–303.

McLaughlin, J.B., DePaola, A., Bopp, C.A., Martinek, K.A., Napolilli, N.P., Allison, C.G., Murray, S.L., Thompson, E.C., Bird, M.M. & Middaugh, J.P. 2005. Outbreak of *Vibrio parahaemolyticus* gastroenteritis associated with Alaskan oysters. *New England Journal of Medicine,* 353(14): 1463–1470.

McMichael, A., Woodruff, R., Whetton, P., Hennessy, K., Nicholls, N., Hales, S., Woodward, A. & Kjellstrom, T. 2003. Human health and climate change in Oceania: a risk assessment 2002. [online] http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.183.6422&rep=rep1&type=pdf

Meis, J.F., Chowdhary, A., Rhodes, J.L., Fisher, M.C. & Verweij, P.E. 2016. Clinical implications of globally emerging azole resistance in *Aspergillus fumigatus. Philosophical Transactions of the Royal Society B: Biological Sciences*, 371(1709). doi: 10.1098/rstb.2015.0460.

Middleton, N. 2019. Variability and trends in dust storm frequency on decadal timescales: Climatic drivers and human impacts. *Geosciences,* 9(6): 261.

Monks, K. 2015. From toilet to tap: Getting a taste for drinking recycled waste water. CNN. 17 November 2015. (also available at https://edition.cnn.com/2014/05/01/world/from-toilet-to-tap-water/index.html).

Moore, S.M., Azman, A.S., Zaitchik, B.F., Mintz, E.D., Brunkard, J., Legros, D., Hill, A., McKay, H., Luquero, F.J., Olson, D. & Lessler, J. 2017. El Niño and the shifting geography of cholera in Africa. *Proceedings of the National Academy of Sciences of the USA,* 114(17): 4436–4441.

Morley, J.W., Selden, R.L., Latour, R.J., Frolicher, T.L., Seagraves, R.J. & Pinsky, M.L. 2018. Projecting shifts in thermal habitat for 686 species on the North American continental shelf. *PLoS One,* 13(5): e0196127 [online]. [Cited 17 July 2019]. https://doi.org/10.1371/journal.pone.0196127

Mor-Mur, M. & Yuste, J. 2009. Emerging bacterial pathogens in meat and poultry: An overview. *Food and Bioprocess Technology,* 3(1): 24–35.

Mouriño-Pérez, R.R., Worden, A.A. & Azam, F. 2003. Growth of *Vibrio cholerae* O1 in red tide waters off California. *Applied and Environmental Microbiology,* 69(11): 6923–6931.

Naumova, E.N., Jagai, J.S., Matyas, B., DeMaria, A., Jr., MacNeill, I.B. & Griffiths, J.K. 2007. Seasonality in six enterically transmitted diseases and ambient temperature. *Epidemiology & Infection,* 135(2): 281–292.

Nichols, M., Butler, C.J., Lord, W.D. & Haynie, M.L., 2018. Projected expansion in climatic suitability for *Trypanosoma cruzi*, the etiological agent of Chagas Disease, and five widespread Triatoma species by 2070. *bioRxiv*, doi: 10.1101/490508.

Obradovich, N., Tingley, D. & Rahwan, I. 2018. Effects of environmental stressors on daily governance. *Proccedings of the National Academy of Sciences of the USA,* 115(35): 8710–8715.

Olaimat, A.N., Al-Holy, M.A., Shahbaz, H.M., Al-Nabulsi, A.A., Abu Ghoush, M.H., Osaili, T.M., Ayyash, M.M. & Holley, R.A. 2018. Emergence of antibiotic resistance in *Listeria monocytogenes* isolated from food products: A comprehensive review. *Comprehensive Reviews in Food Science and Food Safety,* 17(5): 1277–1292.

Pangloli, P., Dje, Y., Ahmed, O., Doane, C.A., Oliver, S.P. & Draughon, F.A. 2008. Seasonal incidence and molecular characterization of *Salmonella* from dairy cows, calves, and farm environment. *Foodborne Pathogens & Diseases,* 5(1): 87–96.

Park, M.S., Park, K.H. & Bahk, G.J. 2018. Interrelationships between multiple climatic factors and incidence of foodborne diseases. *International Journal of Environmental Research & Public Health,* 15(11): 2482.

Parkinson, A.J., Evengard, B., Semenza, J.C., Ogden, N., Borresen, M.L., Berner, J., Brubaker, M., Sjostedt, A., Evander, M., Hondula, D.M., Menne, B., Pshenichnaya, N., Gounder, P., Larose, T., Revich, B., Hueffer, K. &Albihn, A. 2014. Climate change and infectious diseases in the Arctic: establishment of a circumpolar working group. *International Journal of Circumpolar Health,* 73: 25163.

Pascual, M., Rodo, X., Ellner, S.P., Colwell, R. & Bouma, M.J. 2000. Cholera dynamics and El Niño-Southern Oscillation. *Science,* 289(5485): 1766–1769.

Paz, S. & Broza, M. 2007. Wind direction and its linkage with *Vibrio cholerae* dissemination. *Environmental Health Perspectives,* 115(2): 195–200.

Poirel, L., Madec, J.Y., Lupo, A., Schink, A.K., Kieffer, N., Nordmann, P. & Schwarz, S. 2018. Antimicrobial resistance in *Escherichia coli. Microbiology Spectrum,* 6(4): doi: 10.1128/microbiolspec.ARBA-0026-2017.

Restrepo-Mendez, M.C., Barros, A.J., Wong, K.L., Johnson, H.L., Pariyo, G., Franca, G.V., Wehrmeister, F.C. & Victora, C.G. 2016. Inequalities in full immunization coverage: trends in low- and middle-income countries. *Bulletin of the World Health Organization,* 94(11): 794–805B.

Robertson, L.J., Devleesschauwer, B., Alarcon de Noya, B., Noya Gonzalez, O. & Torgerson, P.R. 2016. *Trypanosoma cruzi:* Time for international recognition as a foodborne parasite. *PLoS Neglected Tropical Diseases.,* 10(6): e0004656 [online]. [Cited 4 October 2019]. https://doi.org/10.1371/journal.pntd.0004656

Rosenberg, A., Weinberger, M., Paz, S., Valinsky, L., Agmon, V. & Peretz, C. 2018. Ambient temperature and age-related notified Campylobacter infection in Israel: A 12-year time series study. *Environmental Research.,* 164: 539–545.

Scallan, E., Hoekstra, R.M., Angulo, F.J., Tauxe, R.V., Widdowson, M.A., Roy, S.L., Jones, J.L. & Griffin, P.M. 2011. Foodborne illness acquired in the United States – major pathogens. *Emerging Infectious Diseases.,* 17(1): 7–15.

Scallan, E., Hoekstra, R.M., Mahon, B.E., Jones, T.F. & Griffin, P.M. 2015. An assessment of the human health impact of seven leading foodborne pathogens in the United States using disability adjusted life years. *Epidemiology & Infection,* 143(13): 2795–2804.

Short, E.E., Caminade, C. & Thomas, B.N. 2017. Climate change contribution to the emergence or re-emergence of parasitic diseases. *Infectious Diseases: Research & Treatment,* doi: 10: 1178633617732296

Singh, R.B., Hales, S., de Wet, N., Raj, R., Hearnden, M. & Weinstein, P. 2001. The influence of climate variation and change on diarrheal disease in the Pacific Islands. *Environmental Health Perspectives,* 109(2): 155–159.

Smith, B.A. & Fazil, A. 2019. How will climate change impact microbial foodborne disease in Canada? *Canada Communicable Disease Report,* 45(4): 108–113.

Smith, R. & Coast, J. 2013. The true cost of antimicrobial resistance. *BMJ*, 346: f1493: https://doi.org/10.1136/bmj.f1493

Steele, M. & Odumeru, J. 2004. Irrigation water as source of foodborne pathogens on fruit and vegetables. *Journal of Food Protection,* 67(12): 2839–2849.

Stensgaard, A.S., Utzinger, J., Vounatsou, P., Hurlimann, E., Schur, N., Saarnak, C.F., Simoonga, C., Mubita, P., Kabatereine, N.B., Tchuem Tchuente, L.A., Rahbek, C. & Kristensen, T.K. 2013. Large-scale determinants of intestinal schistosomiasis and intermediate host snail distribution across Africa: does climate matter? *Acta Tropica,* 128(2): 378–390.

Suwannatrai, A., Pratumchart, K., Suwannatrai, K., Thinkhamrop, K., Chaiyos, J., Kim, C.S., Suwanweerakamtorn, R., Boonmars, T., Wongsaroj, T. & Sripa, B. 2017. Modeling impacts of climate change on the potential distribution of the carcinogenic liver fluke, *Opisthorchis viverrini*, in Thailand. *Parasitology Research,* 116(1): 243–250.

Tang, K.L., Caffrey, N.P., Nóbrega, D.B., Cork, S.C., Ronksley, P.E., Barkema, H.W., Polachek, A.J., Ganshorn, H., Sharma, N., Kellner, J.D. & Ghali, W.A. 2017. Restricting the use of antibiotics in food-producing animals and its associations with antibiotic resistance in food-producing animals and human beings: a systematic review and meta-analysis. *The Lancet Planetary Health,* 1(8): e316-e327.

Thanner, S., Drissner, D. & Walsh, F. 2016. Antimicrobial resistance in agriculture. *MBio,* 7(2): e02227-15 [online]. [Cited 19 September 2019]. doi: 10.1128/mBio.02227-15

Thomas, M.K., Murray, R., Flockhart, L., Pintar, K., Pollari, F., Fazil, A., Nesbitt, A. & Marshall, B. 2013. Estimates of the burden of foodborne illness in Canada for 30 specified pathogens and unspecified agents, circa 2006. *Foodborne Pathogens & Diseases,* 10(7): 639–648.

Thorpe, K.E., Joski, P. & Johnston, K.J. 2018. Antibiotic-resistant infection treatment costs have doubled since 2002, now exceeding $2 billion annually. *Health Aff. (Millwood),* 37(4): 662–669.

Tirado, M.C., Clarke, R., Jaykus, L.A., McQuatters-Gollop, A. & Frank, J.M. 2010. Climate change and food safety: A review. *Food Research International,* 43(7): 1745–1765.

Turner, J.W., Malayil, L., Guadagnoli, D., Cole, D. & Lipp, E.K. 2014. Detection of *Vibrio parahaemolyticus, Vibrio vulnificus* and *Vibrio cholerae* with respect to seasonal fluctuations in temperature and plankton abundance. *Environmental Microbiology,* 16(4): 1019–1028.

United States Department of Health and Human Services. 2019. Food safety by events and seasons. [Cited 10 September 2019]. https://www.foodsafety.gov/keep-food-safe/food-safety-by-events-and-seasons#summer.

Utaaker, K.S. & Robertson, L.J. 2015. Climate change and foodborne transmission of parasites: A consideration of possible interactions and impacts for selected parasites. *Food Research International,* 68: 16–23.

Uyttendaele, M., Jaykus, L.-A., Amoah, P., Chiodini, A., Cunliffe, D., Jacxsens, L., Holvoet, K., Korsten, L., Lau, M., McClure, P., Medema, G., Sampers, I. & Rao Jasti, P. 2015. Microbial hazards in irrigation water: Standards, norms, and testing to manage use of water in fresh produce primary production. *Comprehensive Reviews in Food Science and Food Safety,* 14(4): 336–356.

Vaillant, V., de Valk, H., Baron, E., Ancelle, T., Colin, P., Delmas, M.C., Dufour, B., Pouillot, R., Le Strat, Y., Weinbreck, P., Jougla, E. & Desenclos, J.C. 2005. Foodborne infections in France. *Foodborne Pathogens & Diseases,* 2(3): 221–232.

Van Boeckel, T.P., Brower, C., Gilbert, M., Grenfell, B.T., Levin, S.A., Robinson, T.P., Teillant, A. & Laxminarayan, R. 2015. Global trends in antimicrobial use in food animals. *Proceedings of the National Academy of Sciences of the USA,* 112(18): 5649–5654.

Van Boeckel, T.P., Pires, J., Silvester, R., Zhao, C., Song, J., Criscuolo, N.G., Gilbert, M., Bonhoeffer, S. & Laxminarayan, R. 2019. Global trends in antimicrobial resistance in animals in low- and middle-income countries. *Science*, 365(6459): doi: 10.1126/science.aaw1944

Van Paassen, J., Russcher, A., In't Veld-van Wingerden, A.W., Verweij, P.E. & Kuijper, E.J. 2016. Emerging aspergillosis by azole-resistant *Aspergillus fumigatus* at an intensive care unit in the Netherlands, 2010 to 2013. *Eurosurveillance,* 21(30) doi: 10.2807/1560-7917.ES.2016.21.30.30300.

Van Puyvelde, S., Pickard, D., Vandelannoote, K., Heinz, E., Barbe, B., de Block, T., Clare, S., Coomber, E.L., Harcourt, K., Sridhar, S., Lees, E.A., Wheeler, N.E., Klemm, E.J., Kuijpers, L., Mbuyi Kalonji, L., Phoba, M.F., Falay, D., Ngbonda, D., Lunguya, O., Jacobs, J., Dougan, G. & Deborggraeve, S. 2019. An African *Salmonella typhimurium* ST313 sublineage with extensive drug-resistance and signatures of host adaptation. *Nature Communications.,* 10(1): 4280.

Vasilev, V., Japheth, R., Yishai, R. & Andorn, N. 2004. Antimicrobial resistance of *Shigella flexneri* serotypes in Israel during a period of three years: 2000–2002. *Epidemiology & Infection,* 132(6): 1049–1054.

Venegas-Vargas, C., Henderson, S., Khare, A., Mosci, R.E., Lehnert, J.D., Singh, P., Ouellette, L.M., Norby, B., Funk, J.A., Rust, S., Bartlett, P.C., Grooms, D. & Manning, S.D. 2016. Factors associated with Shiga toxin-producing *Escherichia coli* shedding by dairy and beef cattle. *Applied & Environmental Microbiology,* 82(16): 5049–5056.

Verraes, C., Van Boxstael, S., Van Meervenne, E., Van Coillie, E., Butaye, P., Catry, B., de Schaetzen, M.A., Van Huffel, X., Imberechts, H., Dierick, K., Daube, G., Saegerman, C., De Block, J., Dewulf, J. & Herman, L. 2013. Antimicrobial resistance in the food chain: a review. International Journal of Environmental Research & *Public Health,* 10(7): 2643–2669.

Vezzulli, L., Grande, C., Reid, P.C., Helaouet, P., Edwards, M., Hofle, M.G., Brettar, I., Colwell, R.R. & Pruzzo, C. 2016. Climate influence on Vibrio and associated human diseases during the past half-century in the coastal North Atlantic. *Proceedings of the National Academy of Sciences of the USA,* 113(34): E5062–5071.

Vezzulli, L., Pruzzo, C., Huq, A. & Colwell, R.R. 2010. Environmental reservoirs of *Vibrio cholerae* and their role in cholera. *Environmental Microbiology Reports,* 2(1): 27–33.

Vieira, A.R., Collignon, P., Aarestrup, F.M., McEwen, S.A., Hendriksen, R.S., Hald, T. & Wegener, H.C. 2011. Association between antimicrobial resistance in *Escherichia coli* isolates from food animals and blood stream isolates from humans in Europe: an ecological study. *Foodborne Pathogens & Disease,* 8(12): 1295–1301.

Wang, J., Yan, M., Gao, H., Lu, X. & Kan, B. 2017. *Vibrio cholerae* colonization of soft-shelled turtles. *Applied Environmental Microbiology.,* 83(14): doi: 10.1128/AEM.00713-17.

Wang, X., Biswas, S., Paudyal, N., Pan, H., Li, X., Fang, W. & Yue, M. 2019. Antibiotic resistance in *Salmonella typhimurium* isolates recovered from the food chain through national antimicrobial resistance monitoring system between 1996 and 2016. *Frontiers in Microbiology,* 10: 985.

Wang, Z., Zhang, M., Deng, F., Shen, Z., Wu, C., Zhang, J., Zhang, Q. & Shen, J. 2014. Emergence of multidrug-resistant Campylobacter species isolates with a horizontally acquired rRNA methylase. *Antimicrobial Agents and Chemotherapy,* 58(9): 5405–5412.

Welden, N.A. & Lusher, A.L. 2017. Impacts of changing ocean circulation on the distribution of marine microplastic litter. *Integrated Environmental Assessment & Management,* 13(3): 483–487.

Westrich, J.R., Ebling, A.M., Landing, W.M., Joyner, J.L., Kemp, K.M., Griffin, D.W. & Lipp, E.K. 2016. Saharan dust nutrients promote Vibrio bloom formation in marine surface waters. *Proceedings of the National Academy of Sciences of the USA,* 113(21): 5964–5969.

WHO. 2015. *WHO estimates of the global burden of foodborne diseases. Foodborne disease burden epidemiology reference group 2007–2015.* Geneva, WHO. (also available at https://apps.who.int/iris/bitstream/handle/10665/199350/9789241565165_eng.pdf?sequence=1).

Woo, M. 2016. Why we all need to start drinking toilet water. *BBC Future*. 6 January 2016. (also available at https://www.bbc.com/future/article/20160105-why-we-will-all-one-day-drink-recycled-wastewater).

Yang, Y., Feye, K.M., Shi, Z., Pavlidis, H.O., Kogut, M., A, J.A. & Ricke, S.C. 2019. A historical review on antibiotic resistance of foodborne *Campylobacter*. *Frontiers in Microbiology,* 10: 1509.

Yoder, S. 2018. Assessment of the potential health impacts of climate change in Alaska. *State of Alaska Epidemiology Bulletin.* 69 pp. Anchorage, Alaska, USA, Alaska Department of Health and Social Services. (also available at http://www.epi.alaska.gov/bulletins/docs/rr2018_01.pdf).

Yun, J., Greiner, M., Holler, C., Messelhausser, U., Rampp, A. & Klein, G. 2016. Association between the ambient temperature and the occurrence of human *Salmonella* and *Campylobacter* infections. *Scientific Reports,* 6: 28442. https://doi.org/10.1038/srep28442

Zettler, E.R., Mincer, T.J. & Amaral-Zettler, L.A. 2013. Life in the "plastisphere": microbial communities on plastic marine debris. *Environmental Science & Technology,* 47(13): 7137–7146.

Zhang, Y., Bi, P. & Hiller, J.E. 2012. Projected burden of disease for *Salmonella* infection due to increased temperature in Australian temperate and subtropical regions. *Environment International,* 44: 26–30.

Zheng, J., Allard, S., Reynolds, S., Millner, P., Arce, G., Blodgett, R.J. & Brown, E.W. 2013. Colonization and internalization of *Salmonella enterica* in tomato plants. *Applied Environmental Microbiology*, 79(8): 2494–2502.

Chapter 2.B: Algal blooms

Altieri, A.H. & Gedan, K.B. 2015. Climate change and dead zones. *Glob. Chang Biol.,* 21(4): 1395–1406.

Anastopoulos, I. & Kyzas, G.Z. 2015. Progress in batch biosorption of heavy metals onto algae. *Journal of Molecular Liquids,* 209: 77–86.

Anderson, D. M. 2009. Approaches to monitoring, control and management of harmful algal blooms (HABs). *Ocean and Coastal Management*, 52(7): 342.

Anderson, D.M. 2012. HABs in a changing world: A perspective on harmful algal blooms, their impacts, and research and management in a dynamic era of climactic and environmental change. *Harmful Algae*, 2012: 3–17.

Anderson, C.R., Berdalet, E., Kudela, R.M., Cusack, C.K., Silke, J., O'Rourke, E., Dugan, D., McCammon, M., Newton, J.A., Moore, S.K., Paige, K., Ruberg, S., Morrison, J.R., Kirkpatrick, B., Hubbard, K. & Morell, J. 2019. Scaling up from regional case studies to a global harmful algal bloom observing system. *Frontiers in Marine Science,* 6. https://doi.org/10.3389/fmars.2019.00250

Anderson, D.M., Burkholder, J.M., Cochlan, W.P., Glibert, P.M., Gobler, C.J., Heil, C.A., Kudela, R., Parsons, M.L., Rensel, J.E., Townsend, D.W., Trainer, V.L. & Vargo, G.A. 2008. Harmful algal blooms and eutrophication: Examining linkages from selected coastal regions of the United States. *Harmful Algae,* 8(1): 39–53.

Anderson, D.M., Gilbert, P.M. & Burkholder, J.M. 2002. Harmful algal blooms and eutrophication: Nutrient sources, composition, and consequences. *Estuaries,* 25(4): 704–726.

Anderson, D.M., Richlen, M.L & Lefebvre, K.A. 2018. Harmful algal blooms in the Arctic. Arctic Report Card: Update for 2018. Arctic Program. [online]. https://www.arctic.noaa.gov/Report-Card/Report-Card-2018/ArtMID/7878/ArticleID/789/Harmful-Algal-Blooms-in-the-Arctic

Ardyna, M., Babin, M., Gosselin, M., Devred, E., Rainville, L. & Tremblay, J.-É. 2014. Recent Arctic Ocean sea ice loss triggers novel fall phytoplankton blooms. *Geophysical Research Letters,* 41(17): 6207–6212.

Backer, L. & Miller, M. 2016. Sentinel animals in a One Health approach to harmful cyanobacterial and algal blooms. *Veterinary Sciences*, 3(2): 8.

Baggesen, C., Moestrup, Ø., Daugbjerg, N., Krock, B., Cembella, A. & Madsen, S. 2012. Molecular phylogeny and toxin profiles of *Alexandrium tamarense* (Lebour) Balech (Dinophyceae) from the west coast of Greenland. *Harmful Algae*, 19: 108-116.

Bates, S.S., Hubbard, K.A., Lundholm, N., Montresor, M. & Leaw, C.P. 2018. *Pseudo-nitzschia, Nitzschia*, and domoic acid: New research since 2011. *Harmful Algae*, 79: 3–43.

Berdalet, E., Fleming, L.E., Gowen, R., Davidson, K., Hess, P., Backer, L.C., Moore, S.K., Hoagland, P. & Enevoldsen, H. 2015. Marine harmful algal blooms, human health and wellbeing: challenges and opportunities in the 21st century. *Journal of the Marine Biological Association of the UK*, 96(special issue 1): 61–91.

Bianchi, T.S., DiMarco, S.F., Cowan, J.H., Jr., Hetland, R.D., Chapman, P., Day, J.W. & Allison, M.A. 2010. The science of hypoxia in the Northern Gulf of Mexico: a review. *Science of the Total Environment,* 408(7): 1471–1484.

Biello, D. 2008. Oceanic dead zones continue to spread. *Scientific American.* 15 August 2008. https://www.scientificamerican.com/article/oceanic-dead-zones-spread/

Bilal, M., Rasheed, T., Sosa-Hernandez, J.E., Raza, A., Nabeel, F. & Iqbal, H.M.N. 2018. Biosorption: an interplay between marine algae and potentially toxic elements – A review. *Marine Drugs,* 16(2); doi: 10.3390/md16020065.

Bopp, L., Aumont, O., Cadule, P., Alvain, S. & Gehlen, M. 2005. Response of diatoms distribution to global warming and potential implications: A global model study. *Geophysical Research Letters*, 32(19). https://doi.org/10.1029/2005GL023653

Bouwman, L., Beusen, A., Glibert, P.M., Overbeek, C., Pawlowski, M., Herrera, J., Mulsow, S., Yu, R. & Zhou, M. 2013. Mariculture: significant and expanding cause of coastal nutrient enrichment. *Environmental Research Letters,* 8(4): 044026. doi: 10.1088/1748-9326/8/4/044026.

Braga, A.C., Camacho, C., Marques, A., Gago-Martinez, A., Pacheco, M. & Costa, P.R. 2018. Combined effects of warming and acidification on accumulation and elimination dynamics of paralytic shellfish toxins in mussels *Mytilus galloprovincialis*. *Environmental Research*, 164: 647–654.

Breitburg, D., Levin, L.A., Oschlies, A., Gregoire, M., Chavez, F.P., Conley, D.J., Garcon, V., Gilbert, D., Gutierrez, D., Isensee, K., Jacinto, G.S., Limburg, K.E., Montes, I., Naqvi, S.W.A., Pitcher, G.C., Rabalais, N.N., Roman, M.R., Rose, K.A., Seibel, B.A., Telszewski, M., Yasuhara, M. & Zhang, J. 2018. Declining oxygen in the global ocean and coastal waters. *Science,* 359(6371). doi: 10.1126/science.aam7240

Brown, E.G. 2016. Letter to the Secretary of the United States Department of Commerce from the Office of the Governor to the United States Department of Commerce. https://nrm.dfg.ca.gov/FileHandler.ashx?DocumentID=116284

Burkholder, J.M. 2002. Cyanobacteria. In Bitton, G., ed. *Encyclopedia of Environmental Microbiology* pp. 952–982. New York, Wiley Publishers.

Butler, J.N., Morris, B.F., Cadwallader, J. & Stoner, A.W. 1983. Studies of *Sargassum* and the *Sargassum* community. Special Publication No. 22. 311 pp. Bermuda Biological Station for Research.

Cai, W., Hu, X., Huang, W., Murrell, M.C., Lehrter, J.C., Lohrenz, S.E., Chou, W., Zhai, W., Hollibaugh, J.T., Wang, Y., Zhao, P., Guo, X., Gundersen, K., Dai M. & Gong, G. 2011. Acidification of subsurface coastal waters enhanced by eutrophication. *Nature Geoscience*, 4: 766–770.

Cavicchioli, R., Ripple, W.J., Timmis, K.N., Azam, F., Bakken, L.R., Baylis, M., Behrenfeld, M.J., Boetius, A., Boyd, P.W., Classen, A.T., Crowther, T.W., Danovaro, R., Foreman, C.M., Huisman, J., Hutchins, D.A., Jansson, J.K., Karl, D.M., Koskella, B., Mark Welch, D.B., Martiny, J.B.H., Moran, M.A., Orphan, V.J., Reay, D.S., Remais, J.V., Rich, V.I., Singh, B.K., Stein, L.Y., Stewart, F.J., Sullivan, M.B., van Oppen, M.J.H., Weaver, S.C., Webb, E.A. & Webster, N.S. 2019. Scientists' warning to humanity: microorganisms and climate change. *Nature Reviews Microbiology,* 17(9): 569–586.

CDC. 2019. One Health Harmful Algal Bloom System (OHHABS). United States Centers for Disease Control and Prevention. https://www.cdc.gov/habs/ohhabs.html

Chakraborty, S., Bhattacharya, T., Singh, G. & Maity, J.P. 2014. Benthic macroalgae as biological indicators of heavy metal pollution in the marine environments: a biomonitoring approach for pollution assessment. *Ecotoxicology & Environmental Safety,* 100: 61–68.

Chang, F. 2015. Cytotoxic effects of *Vicicitus globosus* (Class Dictyochophyceae) and *Chattonella marina* (Class Raphidophyceae) on rotifers and other microalgae. *Journal of Marine Science and Engineering,* 3(2): 401–411.

Chapra, S.C., Boehlert, B., Fant, C., Bierman, V.J., Jr., Henderson, J., Mills, D., Mas, D.M.L., Rennels, L., Jantarasami, L., Martinich, J., Strzepek, K.M. & Paerl, H.W., 2017. Climate change impacts on harmful algal blooms in US freshwaters: A screening-level assessment. *Environmental Science & Technology*, 51(16): 8933–8943.

Cheng, Y.S., Villareal, T.A., Zhou, Y., Gao, J., Pierce, R., Naar, J. & Baden, D.G. 2005. Characterization of red tide aerosol on the Texas coast. *Harmful Algae,* 4(1): 87–94.

Clancy, H. 2017. This edible packaging will make you reconsider seaweed. GreenBiz. 1 November 2017. https://www.greenbiz.com/article/edible-packaging-will-make-you-reconsider-seaweed

Cuellar-Martinez, T., Ruiz-Fernández, A.C., Alonso-Hernández, C., Amaya-Monterrosa, O., Quintanilla, R., Carrillo-Ovalle, H.L., Arbeláez M, N., Díaz-Asencio, L., Méndez, S.M., Vargas, M., Chow-Wong, N.F., Valerio-Gonzalez, L.R., Enevoldsen, H. & Dechraoui Bottein, M.-Y. 2018. Addressing the problem of harmful algal blooms in Latin America and the Caribbean: A regional network for early warning and response. *Frontiers in Marine Science*, 5. https://doi.org/10.3389/fmars.2018.00409

Davies, A. 2019. Australia launches emergency relocation of fish as largest river system faces collapse. *The Guardian*. 9 September 2019. https://www.theguardian.com/australia-news/2019/sep/09/plan-to-relocate-fish-as-australias-largest-river-system-faces-ecological-collapse

de Széchy, M.T.M., Guedes, P.M., Baeta-Neves, M.H. & Oliveira, E.N. 2012. Verification of *Sargassum natans* (Linnaeus) Gaillon (Heterokontophyta: Phaeophyceae) from the Sargasso Sea off the coast of Brazil, western Atlantic Ocean. *Check List,* 8(4): 638.

Diaz, R.J. & Rosenberg, R. 2008. Spreading dead zones and consequences for marine ecosystems. *Science,* 321(5891): 926–929.

do Rosario Gomes, H., Goes, J.I., Matondkar, S.G., Buskey, E.J., Basu, S., Parab, S. & Thoppil, P. 2014. Massive outbreaks of *Noctiluca scintillans* blooms in the Arabian Sea due to spread of hypoxia. *Nature Communications,* 5: 4862: doi: 10.1038/ncomms5862.

EASAC. 2013. *Trends in extreme weather events in Europe: Implications for national and European Union adaptation strategies*. European Academies Science Advisory Council (EASAC) Policy Report No. 22. Halle, Germany, German National Academy of Sciences 19 pp. (also available at https://easac.eu/fileadmin/PDF_s/reports_statements/Extreme_Weather/EASAC_report_Extreme_Weather_in_Europe_Nov13.pdf).

Edwards, M., Johns, D.G., Leterme, S.C., Svendsen, E. & Richardson, A.J. 2006. Regional climate change and harmful algal blooms in the northeast Atlantic. *Limnology and Oceanography*, 51(2): 820–829.

Edwards, M. & Richardson, A.J. 2004. Impact of climate change on marine pelagic phenology and trophic mismatch. *Nature,* 430(7002): 881–884.

EFSA. 2016. *Review and analysis of occurrence, exposure and toxicity of cyanobacteria toxins in food.* European Food Safety Authority (EFSA) Supporting Publication No. 2016: EN-998. 309 pp. https://www.efsa.europa.eu/en/supporting/pub/en-998

Eriksson, B.K. 2011. *Does overfishing promote algal blooms?* Directorate General for Internal Policies. Policy Department B: Structural and Cohesion Policies. Brussels, European Parliament. (also available at http://www.europarl.europa.eu/RegData/etudes/note/join/2011/474461/IPOL-PECH_NT(2011)474461_EN.pdf).

FAO. 2018. *The global status of seaweed production, trade and utilization.* FAO Globefish Research Programme Volume No. 124. Rome, FAO. 124 pp. (also available at http://www.fao.org/3/ca1121en/CA1121EN.pdf).

FAO & WHO. 2016. *Toxicity equivalence factors for marine biotoxins associated with bivalve molluscs*. Joint FAO/WHO Technical Report. Rome, FAO. 133 pp. (also available at http://www.fao.org/3/a-i5970e.pdf).

FAO & WHO. forthcoming. Expert Meeting on Ciguatera Poisoning, 19 – 23 November 2018. Rome.

Fasullo, J.T., Otto-Bliesner, B.L. & Stevenson, S. 2018. ENSO's changing influence on temperature, precipitation, and wildfire in a warming climate. *Geophysical Research Letters,* 45(17): 9216–9225.

Fleming, L.E., Kirkpatrick, B., Backer, L.C., Bean, J.A., Wanner, A., Reich, A., Zaias, J., Cheng, Y.S., Pierce, R., Naar, J., Abraham, W.M. & Baden, D.G. 2007. Aerosolized red-tide toxins (brevetoxins) and asthma. *Chest,* 131(1): 187–194.

Forster P., Ramaswamy V., Artaxo P., Berntsen T., Betts R., Fahey D.W., Haywood J., Lean J., Lowe D.C., Myhre G., Nganga J., Prinn R., Raga G., Schulz M. & Van Dorland R. 2007. Changes in atmospheric constituents and in radiative forcing. In: *AR4 Climate Change 2007: The physical science basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, pp. 131–234. [Solomon S., Qin D., Manning M., Chen Z., Marquis M., Averyt K.B., Tignor M. and Miller H.L. (eds)] Cambridge, United Kingdom and New York, Cambridge University Press. (also available at https://www.ipcc.ch/report/ar4/wg1/).

Fu, F.-X., Zhang, Y., Warner, M.E., Feng, Y., Sun, J. & Hutchins, D.A. 2008. A comparison of future increased CO_2 and temperature effects on sympatric *Heterosigma akashiwo* and *Prorocentrum minimum*. *Harmful Algae*, 7(1): 76–90.

Galloway, J.N., Townsend, A.R., Erisman, J.W., Bekunda, M., Cai, Z., Freney, J.R., Martinelli, L.A., Seitzinger, S.P. & Sutton, M.A. 2008. Transformation of the nitrogen cycle: recent trends, questions, and potential solutions. *Science,* 320(5878): 889–892.

Gillett, N.P., Kell, T.D. & Jones, P.D. 2006. Regional climate impacts of the Southern Annular Mode. *Geophysical Research Letters,* 33(23). https://doi.org/10.1029/2006GL027721

Gingold, D.B., Strickland, M.J. & Hess, J.J. 2014. Ciguatera fish poisoning and climate change: analysis of National Poison Center Data in the United States, 2001–2011. *Environmental Health Perspectives,* 122(6): 580–586.

Glibert, P.M., Allen, J.I., Bouwman, A.F., Brown, C.W., Flynn, K.J., Lewitus, A.J. & Madden, C.J. 2010. Modeling of HABs and eutrophication: Status, advances, challenges. *Journal of Marine Systems,* 83(3–4): 262–275.

Gobler, C.J., Berry, D.L., Dyhrman, S.T., Wilhelm, S.W., Salamov, A., Lobanov, A.V., Zhang, Y., Collier, J.L., Wurch, L.L., Kustka, A.B., Dill, B.D., Shah, M., VerBerkmoes, N.C., Kuo, A., Terry, A., Pangilinan, J., Lindquist, E.A., Lucas, S., Paulsen, I.T., Hattenrath-Lehmann, T.K., Talmage, S.C., Walker, E.A., Koch, F., Burson, A.M., Marcoval, M.A., Tang, Y.Z., Lecleir, G.R., Coyne, K.J., Berg, G.M., Bertrand, E.M., Saito, M.A., Gladyshev, V.N. & Grigoriev, I.V. 2011. Niche of harmful alga *Aureococcus anophagefferens* revealed through ecogenomics. *Proceedings of the National Academy of Sciences of the USA,* 108(11): 4352–4357.

Gobler, C.J., DePasquale, E.L., Griffith, A.W. & Baumann, H. 2014. Hypoxia and acidification have additive and synergistic negative effects on the growth, survival, and metamorphosis of early life stage bivalves. *PLoS One,* 9(1): e83648 [online. [Cited 17 July 2019]. https://doi.org/10.1371/journal.pone.0083648

Gobler, C.J., Doherty, O.M., Hattenrath-Lehmann, T.K., Griffith, A.W., Kang, Y. & Litaker, R.W. 2017. Ocean warming since 1982 has expanded the niche of toxic algal blooms in the North Atlantic and North Pacific oceans. *Proceedings of the National Academy of Sciences of the USA,* 114(19): 4975–4980.

Gobler, C.J., Lonsdale, D.J. & Boyer, G.L. 2005. A review of the causes, effects, and potential management of harmful brown tide blooms caused by *Aureococcus anophagefferens* (Hargraves et sieburth). *Estuaries,* 28(5): 726–749.

Goto-Azuma, K., Hirabayashi, M., Motoyama, H., Miyake, T., Kuramoto, T., Uemura, R., Igarashi, M., Iizuka, Y., Sakurai, T., Horikawa, S., Suzuki, K., Suzuki, T., Fujita, K., Kondo, Y., Hattori, S. & Fujii, Y. 2019. Reduced marine phytoplankton sulphur emissions in the Southern Ocean during the past seven glacials. *Nature Communications,* 10(1): 3247: https://doi.org/10.1038/s41467-019-11128-6

Gower, J.F.R. & King, S.A. 2011. Distribution of floating Sargassum in the Gulf of Mexico and the Atlantic Ocean mapped using MERIS. *International Journal of Remote Sensing,* 32(7): 1917–1929.

Gower, J., Young, E. & King, S. 2013. Satellite images suggest a new Sargassum source region in 2011. *Remote Sensing Letters,* 4(8): 764–773.

Grattan, L.M., Holobaugh, S. & Morris, J.G. 2016. Harmful algal blooms and public health. *Harmful Algae*, 57: 2–8.

Gumbo, R.J., Ross, G. & Cloete, E.T. 2008. Biological control of *Microcystis* dominated harmful algal blooms. *African Journal of Biotechnology,* 7(25): 4765–4773.

Guo, H., Ding, D. & Guan, C. 2013. The economic cost of harmful algal blooms in China from 2008–2012. Presentation at the North Pacific Marine Science Organization Annual Meeting. https://meetings.pices.int/publications/presentations/PICES-2013

Haberland, M.W. 2016. *Blue-green algae in waterways.* Cooperative Extension Fact Sheet No. FS1216. New Jersey, USA, Rutgers New Jersey Agricultural Experiment Station. 4 pp. https://njaes.rutgers.edu/fs1216/.

Hallegraeff, G.M. 2010. Ocean climate change, phytoplankton community responses, and harmful algal blooms: A formidable predictive challenge. *Journal of Phycology,* 46(2): 220–235.

Hammon, D. 2019. Designer creates algae sourced alternative for plastic packaging. *Inhabitat.* 27 February 2019. https://inhabitat.com/designer-creates-algae-sourced-alternative-for-plastic-packaging/.

Heisler, J., Glibert, P., Burkholder, J., Anderson, D., Cochlan, W., Dennison, W., Gobler, C., Dortch, Q., Heil, C., Humphries, E., Lewitus, A., Magnien, R., Marshall, H., Sellner, K., Stockwell, D., Stoecker, D. & Suddleson, M. 2008. Eutrophication and harmful algal blooms: A scientific consensus. *Harmful Algae,* 8(1): 3–13.

Hennon, G.M.M. & Dyhrman, S.T. 2019. Progress and promise of omics for predicting the impacts of climate change on harmful algal blooms. *Harmful Algae*, https://doi.org/10.1016/j.hal.2019.03.005.

Hinder, S.L., Hays, G.C., Edwards, M., Roberts, E.C., Walne, A.W. & Gravenor, M.B. 2012. Changes in marine dinoflagellate and diatom abundance under climate change. *Nature Climate Change,* 2(4): 271–275.

Hiroishi, S., Okada, H., Imai, I. & Yoshida, T. 2005. High toxicity of the novel bloom-forming species *Chattonella ovata* (Raphidophyceae) to cultured fish. *Harmful Algae,* 4(4): 783–787.

Hitti, N. 2019. Margarita Talep develops algae-based alternatives to single use plastic packaging. *Dezeen*. 18 January 2019. https://www.dezeen.com/2019/01/18/margarita-talep-algae-bioplastic-packaging-design/

Ho, J.C., Michalak, A.M. & Pahlevan, N. 2019. Widespread global increase in intense lake phytoplankton blooms since the 1980s. *Nature,* 574(7780): 667–670.

Hofste, R.W., Reig, P. & Schiefer, L. 2019. 17 countries, home to one-quarter of the world's population, face extremely high water stress. World Resources Institute blog. 6 August 2019. https://www.wri.org/blog/2019/08/17-countries-home-one-quarter-world-population-face-extremely-high-water-stress

Howarth, R.W. & Marino, R. 2006. Nitrogen as the limiting nutrient for eutrophication in coastal marine ecosystems: Evolving views over three decades. *Limnology and Oceanography,* 51(1 part 2): 364–376.

Howarth, R.W., Ramakrishna, K., Choi, E., Elmgren, R., Martinelli, L., Mendoza, A., Moomaw, W., Palm, C., Roy, R., Scholes, M & Zhu, Z.L. 2005. Nutrient management. In: *Ecosystems and human well-being, policy responses, volume 3*, pp. 295–311. Millennium Ecosystem Assessment. Washington, DC, Island Press. (also available at http://wedocs.unep.org/bitstream/handle/20.500.11822/7848/Ecosystems_human_wellbeing_policy_responses.pdf?sequence=3&isAllowed=y).

Huang, Y., Wu, S. & Kaplan, J.O. 2015. Sensitivity of global wildfire occurrences to various factors in the context of global change. *Atmospheric Environment,* 121: 86–92.

Hussey, M. 2014. Edible water bottle replaces plastic with algae. *Dezeen.* 1 April 2014. https://www.dezeen.com/2014/04/01/edible-water-bottle-uses-algae-to-create-biodegradable-alternative-to-plastic-containers/

Imai, I. & Itoh, K. 1987. Annual life cycle of *Chattonella* spp., causative flagellates of noxious red tides in the Inland Sea of Japan. *Marine Biology,* 94(2): 287–292.

IOC. 2016. *Exceptional summer conditions and HABs of* Pseudochattonella *in Southern Chile create record impacts on salmon farms*. Harmful Algae News No. 53. Intergovernmental Oceanographic Commission (IOC). 24 pp. https://unesdoc.unesco.org/ark:/48223/pf0000246503.

IPCC. 2019. Summary for policymakers. *In* Pörtner, H.O., Roberts, D.C., Masson-Delmotte, V., Zhai, P., Tignor, M., Poloczanska, E., Mintenbeck, K., Nicolai, M., Okem, A., Petzold, J., Rama, B. and Weyer, N. eds. *IPCC special report on the ocean and cryosphere in a changing climate*. (also available at https://www.ipcc.ch/srocc/download-report/).

Irwin, A.J., Finkel, Z.V., Muller-Karger, F.E. & Troccoli Ghinaglia, L. 2015. Phytoplankton adapt to changing ocean environments. *Proceedings of the National Academy of Sciences of the USA,* 112(18): 5762–5766.

Jeppesen, E., Brucet, S., Naselli-Flores, L., Papastergiadou, E., Stefanidis, K., Nõges, T., Nõges, P., Attayde, J.L., Zohary, T., Coppens, J., Bucak, T., Menezes, R.F., Freitas, F.R.S., Kernan, M., Søndergaard, M. & Beklioğlu, M. 2015. Ecological impacts of global warming and water abstraction on lakes and reservoirs due to changes in water level and related changes in salinity. *Hydrobiologia,* 750(1): 201–227.

Jiménez Cisneros, B.E., Oki, T., Arnell, N.W. Benito, G., Cogley, J.G., Döll, P., Jiang, T. & Mwakalila, S.S. 2014. Freshwater resources. In: *Climate change 2014: Impacts, adaptation and vulnerability. Part A: Global and sectoral aspects.* Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, pp 229–269. Field, C.B., Barros, V. R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, P.R., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R. and White, L.L. eds. Cambridge, United Kingdom of Great Britain and Northern Ireland and New York, Cambridge University Press.

Jöhnk, K.D., Huisman, J.E.F., Sharples, J., Sommeijer, B.E.N., Visser, P.M. & Stroom, J.M. 2008. Summer heatwaves promote blooms of harmful cyanobacteria. *Global Change Biology,* 14(3): 495–512.

Joshi, S., Kumari, R. & Upasani, V.N. 2018. Applications of algae in cosmetics: an overview. *International Journal of Innovative Research in Science, Engineering and Technology,* 7(2): 1269–1278.

Kadiri, M.O. & Isagba, S. 2018. Amnesic shellfish poisoning (ASP) and paralytic shellfish poisoning (PSP) in Nigerian Coast, Gulf of Guinea. *Frontiers in Marine Science,* 5: https://doi.org/10.3389/fmars.2018.00481

Kalabokidis, K.D. 2000. Effects of wildfire suppression chemicals on people and the environment –a review. *Global NEST Journal,* 2(2): 129–137.

Kamiyama, T., Nagai, S., Suzuki, T. & Miyamura, K. 2010. Effect of temperature on production of okadaic acid, dinophysistoxin-1, and pectenotoxin-2 by *Dinophysis acuminata* in culture experiments. *Aquatic Microbial Ecology,* 60(2): 193–202.

Karlberg, M. & Wulff, A. 2012. Impact of temperature and species interaction on filamentous cyanobacteria may be more important than salinity and increased pCO_2 levels. *Marine Biology,* 160(8): 2063–2072.

Khatiwala, S., Primeau, F. & Hall, T. 2009. Reconstruction of the history of anthropogenic CO_2 concentrations in the ocean. *Nature,* 462(7271): 346–349.

Kim, H., Spivack, A.J. & Menden-Deuer, S. 2013. pH alters the swimming behaviors of the raphidophyte *Heterosigma akashiwo*: Implications for bloom formation in an acidified ocean. *Harmful Algae,* 26: 1–11.

Kinley, R.D., de Nys, R., Vucko, M.J., Machado, L. & Tomkins, N.W. 2016. The red macroalgae *Asparagopsis taxiformis* is a potent natural antimethanogenic that reduces methane production during *in vitro* fermentation with rumen fluid. *Animal Production Science,* 56(3): 282: doi: 10.1071/AN15576.

Kirkpatrick, B., Pierce, R., Cheng, Y.S., Henry, M.S., Blum, P., Osborn, S., Nierenberg, K., Pederson, B.A., Fleming, L.E., Reich, A., Naar, J., Kirkpatrick, G., Backer, L.C. & Baden, D. 2010. Inland transport of aerosolized Florida red tide toxins. *Harmful Algae,* 9(2): 186–189.

Kite-Powell, J. 2018. See how algae could change our world. *Forbes.* 15 June, 2018. https://www.forbes.com/sites/jenniferhicks/2018/06/15/see-how-algae-could-change-our-world/#15c493703e46

Kremp, A., Godhe, A., Egardt, J., Dupont, S., Suikkanen, S., Casabianca, S. & Penna, A. 2012. Intraspecific variability in the response of bloom-forming marine microalgae to changed climate conditions. *Ecology & Evolution,* 2(6): 1195–1207.

Kudela, R. M., Berdalet, E., Bernard, S., Burford, M., Fernand, L., Lu, S., Roy, S., Tester, P., Usup, G., Magnien, R., Anderson, D. M., Cembella, A., Chinain, M., Hallegraeff, G., Reguera, B., Zingone, A., Enevoldsen, H. & Urban, E. 2015. Harmful algal blooms. A scientific summary for policy makers. IOC/UNESCO, Paris (IOC/INF – 1320). [online]. https://unesdoc.unesco.org/ark:/48223/pf0000233419

Langin, K. 2018. Mysterious masses of seaweed assault Caribbean islands. *Science.* 11 June 2018. https://www.sciencemag.org/news/2018/06/mysterious-masses-seaweed-assault-caribbean-islands.

Langley, E. 2019. Photo.Synth.Etica: The algae bio-curtains absorbing pollution from cities. *Evening Standard.* 12 August 2019. https://www.standard.co.uk/futurelondon/cleanair/algae-biocurtains-removing-co2-photosynthetica-a4211416.html.

Lassus, P., Chomérat, N., Hess, P. & Nézan, E. 2016. *Toxic and harmful microalgae of the world ocean.* IOC Manuals and Guides No. 68. 523 pp. Denmark, Intergovernmental Oceanographic Commission (IOC) and International Society for the Study of Harmful Algae (ISSHA).

Lee, J.J. 2014. Driven by climate change, algae blooms behind Ohio water scare are new normal. *National Geographic*. 6 August 2014. https://www.nationalgeographic.com/news/2014/8/140804-harmful-algal-bloom-lake-erie-climate-change-science/.

Lee, S. & Lee, D. 2018. Four major South Korea's rivers using deep learning models. *International Journal of Environmental Research &. Public Health*, 15(7): e1322[online]. [Cited 5 September 2019]. https://doi.org/10.3390/ijerph15071322

Lehman, P.W., Kurobe, T., Lesmeister, S., Baxa, D., Tung, A. & Teh, S.J. 2017. Impacts of the 2014 severe drought on the Microcystis bloom in San Francisco estuary. *Harmful Algae,* 63: 94–108.

Leon-Munoz, J., Urbina, M.A., Garreaud, R. & Iriarte, J.L. 2018. Hydroclimatic conditions trigger record harmful algal bloom in western Patagonia (summer 2016). *Scientific Reports,* 8(1): 1330: doi: 10.1038/s41598-018-19461-4.

Li, X., Norman, H.C., Kinley, R.D., Laurence, M., Wilmot, M., Bender, H., de Nys, R. & Tomkins, N. 2018. *Asparagopsis taxiformis* decreases enteric methane production from sheep. *Animal Production Science,* 58(4): 681: doi: 10.1071/AN15883.

Liu, Y., Cobb, K.M., Song, H., Li, Q., Li, C.Y., Nakatsuka, T., An, Z., Zhou, W., Cai, Q., Li, J., Leavitt, S.W., Sun, C., Mei, R., Shen, C.C., Chan, M.H., Sun, J., Yan, L., Lei, Y., Ma, Y., Li, X., Chen, D. & Linderholm, H.W. 2017. Recent enhancement of central Pacific El Niño variability relative to last eight centuries. *Nature Communications,* 8: 15386: https://doi.org/10.1038/ncomms15386.

Ma, Z., Lin, L., Wu, M., Yu, H., Shang, T., Zhang, T. & Zhao, M. 2018. Total and inorganic arsenic contents in seaweeds: Absorption, accumulation, transformation and toxicity. *Aquaculture,* 497: 49–55.

Madeira, M.S., Cardoso, C., Lopes, P.A., Coelho, D., Afonso, C., Bandarra, N.M. & Prates, J.A.M. 2017. Microalgae as feed ingredients for livestock production and meat quality: A review. *Livestock Science*, 205: 111–121.

Martinelli, L.A & Howarth, R.W. 2006. *Nitrogen cycling in the Americas: Natural and anthropogenic influences and controls*. 278 pp. Dordrecht, Netherlands, Springer and International Nitrogen Initiative.

Masó, M., Garcés, E., Pagès, F. & Camp, J. 2007. Drifting plastic debris as a potential vector for dispersing harmful algal bloom (HAB) species. *Scientia Marina*, 67(1): 107–111.

May, N.W., Olson, N.E., Panas, M., Axson, J.L., Tirella, P.S., Kirpes, R.M., Craig, R.L., Gunsch, M.J., China, S., Laskin, A., Ault, A.P. & Pratt, K.A. 2018. Aerosol emissions from Great Lakes harmful algal blooms. *Environmental Science & Technology,* 52(2): 397–405.

McCabe, R.M., Hickey, B.M., Kudela, R.M., Lefebvre, K.A., Adams, N.G., Bill, B.D., Gulland, F.M., Thomson, R.E., Cochlan, W.P. & Trainer, V.L. 2016. An unprecedented coastwide toxic algal bloom linked to anomalous ocean conditions. *Geophysical Research Letters,* 43(19): 10366–10376.

McDiarmid, J. 2012. Western Ghana's fisherfolk starve amid algae infestation. *Inter Press Service News Agency*. 18 April 2012. http://www.ipsnews.net/2012/04/western-ghanarsquos-fisherfolk-starve-amid-algae-infestation/

McKibben, S.M., Peterson, W., Wood, A.M., Trainer, V.L., Hunter, M. & White, A.E. 2017. Climatic regulation of the neurotoxin domoic acid. *Proceedings of the National Academy of Sciences of the USA,* 114(2): 239–244.

McLean, T.I. 2013. "Eco-omics": a review of the application of genomics, transcriptomics, and proteomics for the study of the ecology of harmful algae. *Microbial Ecology,* 65(4): 901–915.

Medeiros, I.D., Mathieson, A.C. & Rajakaruna, N. 2017. Heavy metals in seaweeds from a polluted estuary in coastal Maine. *Rhodora*, 119(979): 201–211.

Mekonnen, M. & Hoekstra, A.Y. 2017. Global anthropogenic phosphorus loads to freshwater and associated grey water footprints and water pollution levels: A high-resolution global study. *Water Resources Research,* 54(1): 345–358.

Miller, W.D., Harding, L.W. & Adolf, J.E. 2006. Hurricane Isabel generated an unusual fall bloom in Chesapeake Bay. *Geophysical Research Letters,* 33(6): doi: 10.1029/2005GL025658.

Moffitt, S.E., Hill, T.M., Roopnarine, P.D. & Kennett, J.P. 2015. Response of seafloor ecosystems to abrupt global climate change. *Proceedings of the National Academy of Sciences of the USA,* 112(15): 4684–4689.

Moestrup, Ø., Akselmann-Cardella, R., Fraga, S., Hoppenrath, M., Iwataki, M., Komárek, J., Larsen, J., Lundholm, N. & Zingone, A. (eds). 2009 onwards. *IOC-UNESCO taxonomic reference list of harmful micro algae.* http://www.marinespecies.org/hab (on 2019-12-20)

Møller, L.F. & Riisgård, H.U. 2007. Impact of jellyfish and mussels on algal blooms caused by seasonal oxygen depletion and nutrient release from the sediment in a Danish fjord. *Journal of Experimental Marine Biology and Ecology,* 351(1–2): 92–105.

Moore, S.K., Johnstone, J.A., Banas, N.S. & Salathe, E.P., Jr. 2015. Present-day and future climate pathways affecting Alexandrium blooms in Puget Sound, WA, USA. *Harmful Algae*, 48: 1–11.

Na, G., Choi, W. & Chun, Y. 1996. A study on red tide control with loess suspension. *Journal of Aquaculture*, 9(3):239–245.

Normile, D. 2019. Massive fish die-off sparks outcry in Australia. *Science,* 363(6425): 331.

Orr, J.C., Fabry, V.J., Aumont, O., Bopp, L., Doney, S.C., Feely, R.A., Gnanadesikan, A., Gruber, N., Ishida, A., Joos, F., Key, R.M., Lindsay, K., Maier-Reimer, E., Matear, R., Monfray, P., Mouchet, A., Najjar, R.G., Plattner, G.K., Rodgers, K.B., Sabine, C.L., Sarmiento, J.L., Schlitzer, R., Slater, R.D., Totterdell, I.J., Weirig, M.F., Yamanaka, Y. & Yool, A. 2005. Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. *Nature,* 437(7059): 681-686.

Ott, H.J. 2018. Climate change eroding women's status in Zanzibar. Pulitzer Center. 25 January 2018. https://pulitzercenter.org/reporting/climate-change-eroding-womens-status-zanzibar.

Paerl, H.W. & Huisman, J. 2008. Climate. Blooms like it hot. *Science,* 320(5872): 57–58.

Park, G.H., Lee, S.E., Kim, Y.I., Kim, D., Lee, K., Kang, J., Kim, Y.H., Kim, H., Park, S. & Kim, T.W. 2019. Atmospheric deposition of anthropogenic inorganic nitrogen in airborne particles and precipitation in the East Sea in the northwestern Pacific Ocean. *Science of the Total Environment,* 681: 400–412.

Park, T.G., Lim, W.A., Park, Y.T., Lee, C.K. & Jeong, H.J. 2013. Economic impact, management and mitigation of red tides in Korea. *Harmful Algae,* 30: S131–S143.

Pedrosa-Pàmies, R., Conte, M.H., Weber, J.C. & Johnson, R. 2019. Hurricanes enhance labile carbon export to the deep ocean. *Geophysical Research Letters,* 46(17–18): 10484–10494.

Petrou, K., Baker, K.G., Nielsen, D.A., Hancock, A.M., Schulz, K.G. & Davidson, A.T. 2019. Acidification diminishes diatom silica production in the Southern Ocean. *Nature Climate Change,* 9(10): 781–786.

Pickhardt, P.C., Folt, C.L., Chen, C.Y., Klaue, B. & Blum, J.D. 2002. Algal blooms reduce the uptake of toxic methylmercury in freshwater food webs. *Proceedings of the National Academy of Sciences of the USA,* 99(7): 4419–4423.

Pokrzywinski, K.L., Tilney, C.L., Warner, M.E. & Coyne, K.J. 2017. Cell cycle arrest and biochemical changes accompanying cell death in harmful dinoflagellates following exposure to bacterial algicide IRI-160AA. *Scientific Reports,* 7: 45102: https://doi.org/10.1038/srep45102

Rabalais, N.N., Turner, R.E. & Scavia, D. 2002. Beyond science into policy: Gulf of Mexico hypoxia and the Mississippi River. *BioScience,* 52(2): 129.

Ralston, E.P., Kite-Powell, H. & Beet, A. 2011. An estimate of the cost of acute health effects from food- and water-borne marine pathogens and toxins in the USA. *Journal of Water and Health*, 9(4): 680–694.

Reguera, B., Riobo, P., Rodriguez, F., Diaz, P.A., Pizarro, G., Paz, B., Franco, J.M. & Blanco, J. 2014. Dinophysis toxins: causative organisms, distribution and fate in shellfish. *Marine Drugs,* 12(1): 394–461.

Richardson, A.J., Walne, A.W., John, A.W.G., Jonas, T.D., Lindley, J.A., Sims, D.W., Stevens, D. & Witt, M. 2006. Using Continuous Plankton Recorder data. *Progress in Oceanography,* 68(1): 27–74.

Riebesell, U., Aberle-Malzahn, N., Achterberg, E.P., Algueró-Muñiz, M., Alvarez-Fernandez, S., Arístegui, J., Bach, L.T., Boersma, M., Boxhammer, T., Guan, W., Haunost, M., Horn, H.G., Löscher, C.R., Ludwig, A., Spisla, C., Sswat, M., Stange, P. & Taucher, J. 2018. Toxic algal bloom induced by ocean acidification disrupts the pelagic food web. *Nature Climate Change,* 8(12): 1082–1086.

Rhein, M., Rintoul, S.R., Aoki, S., Campos, E., Chambers, D., Feely, R.A., Gulev, S., Johnson, G.C., Josey, S.A., Kostianoy, A., Maruitzen, C., Roemmich, D., Talley, L.D. & Wang, F. 2013. Observations: Ocean. In [Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V. and Midgley, P.M. eds. *Climate Change 2013: The physical science basis: Contribution of Working Group I to the Fifth Assessment of the Intergovernmental Panel on Climate Change*, pp. 215–316. Cambridge, United Kingdom of

Great Britain and Northern Ireland and New York, Cambridge University Press. (also available at https://www.ipcc.ch/site/assets/uploads/2017/09/WG1AR5_Frontmatter_FINAL.pdf).

Röder, K., Hantzsche, F.M., Gebühr, C., Miene, C., Helbig, T., Krock, B., Hoppenrath, M., Luckas, B. & Gerdts, G. 2012. Effects of salinity, temperature and nutrients on growth, cellular characteristics and yessotoxin production of *Protoceratium reticulatum*. *Harmful Algae,* 15: 59–70.

Rongo, T. & van Woesik, R. 2011. Ciguatera poisoning in Rarotonga, southern Cook Islands. *Harmful Algae,* 10(4): 345–355.

Roque, B.M., Brooke, C.G., Ladau, J., Polley, T., Marsh, L.J., Najafi, N., Pandey, P., Singh, L., Kinley, R., Salwen, J.K., Eloe-Fadrosh, E., Kebreab, E. & Hess, M. 2019. Effect of the macroalgae *Asparagopsis taxiformis* on methane production and rumen microbiome assemblage. *Animal Microbiome,* 1(1): https://doi.org/10.1186/s42523-019-0004-4

Rousefell, G.A. & Evans, J.E. 1958. Large-scale experimental test of copper sulfate as a control for the Florida red tide. United States Fish and Wildlife Service. Special scientific report – Fisheries No. 270. Washington, DC, United States Department of the Interior. (also available at https://spo.nmfs.noaa.gov/sites/default/files/legacy-pdfs/SSRF270.pdf).

Ryckebosch, E., Bruneel, C., Termote-Verhalle, R., Goiris, K., Muylaert, K. & Foubert, I. 2014. Nutritional evaluation of microalgae oils rich in omega-3 long chain polyunsaturated fatty acids as an alternative for fish oil. *Food Chemistry,* 160: 393–400.

Sabine, C.L., Feely, R.A., Gruber, N., Key, R.M., Lee, K., Bullister, J.L., Wanninkhof, R., Wong, C.S., Wallace, D.W., Tilbrook, B., Millero, F.J., Peng, T.H., Kozyr, A., Ono, T. & Rios, A.F. 2004. The oceanic sink for anthropogenic CO_2. *Science,* 305(5682): 367–371.

Schindler, D.W. 1977. Evolution of phosphorus limitation in lakes. *Science,* 195(4275): 260–262.

Schmidtko, S., Stramma, L. & Visbeck, M. 2017. Decline in global oceanic oxygen content during the past five decades. *Nature,* 542(7641): 335–339.

Sengco, M.R. & Anderson, D.M. 2004. Controlling harmful algal blooms through clay flocculation. *Journal of Eukaryotic Microbiology,* 51(2): 169–172.

Sharma, P. & Sharma, N. 2017. Industrial and biotechnological applications of algae: A review. *Journal of Advances in Plant Biology,* 1(1): 1–25.

Sinha, E., Michalak, A.M. & Balaji, V. 2017. Eutrophication will increase during the 21st century as a result of precipitation changes. *Science*, 357(6349): 405–408.

Sison-Mangus, M.P., Jiang, S., Kudela, R.M. & Mehic, S. 2016. Phytoplankton-associated bacterial community composition and succession during toxic diatom bloom and non-bloom events. *Frontiers in Microbiology,* 7: 1433: doi: 10.3389/fmicb.2016.01433.

Smetacek, V. & Zingone, A. 2013. Green and golden seaweed tides on the rise. *Nature,* 504(7478): 84–88.

Sosdian, S.M., Greenop, R., Hain, M.P., Foster, G.L., Pearson, P.N. & Lear, C.H. 2018. Constraining the evolution of Neogene ocean carbonate chemistry using the boron isotope pH proxy. *Earth and Planetary Science Letters,* 498: 362–376.

Spilling, K., Olli, K., Lehtoranta, J., Kremp, A., Tedesco, L., Tamelander, T., Klais, R., Peltonen, H. & Tamminen, T. 2018. Shifting diatom – dinoflagellate dominance during spring bloom in the Baltic Sea and its potential effects on biogeochemical cycling. *Frontiers in Marine Science*, 5: https://doi.org/10.3389/fmars.2018.00327

Sun, J., Hutchins, D.A., Feng, Y., Seubert, E.L., Caron, D.A. & Fu, F.-X. 2011. Effects of changing pCO_2 and phosphate availability on domoic acid production and physiology of the marine harmful bloom diatom Pseudo-nitzschia multiseries. *Limnology and Oceanography,* 56(3): 829–840.

Sutton, M.A., Bleeker, A., Howard, C.M., Bekunda, M., Grizzetti, B., de Vries, W., van Grinsven, H.J., Abrol, Y.P., Adhya, T.K., Billen, G., Davidson, E.A., Datta, A., Diaz, R., Erisman, J.W., Liu, X.J., Oenema, O., Palm, C., Raghuram, N., Reis, S., Scholz, R.W., Sims, T., Westhoek, H & Zhang, F.S. 2013. *Our nutrient world: The challenge to produce more food and energy with less pollution*. Global overview of nutrient management. Edinburgh, United Kingdom of Great Britain and Northern Ireland, Centre for Ecology and Hydrology on behalf of the Global Partnership on Nutrient Management and the International Nitrogen Initiative. 127 pp. (also available at https://nora.nerc.ac.uk/id/eprint/500700/1/N500700BK.pdf).

Tatters, A.O., Flewelling, L.J., Fu, F., Granholm, A.A. & Hutchins, D.A. 2013. High CO_2 promotes the production of paralytic shellfish poisoning toxins by *Alexandrium catenella* from Southern California waters. *Harmful Algae,* 30: 37–43.

Tatters, A.O., Fu, F.X. & Hutchins, D.A. 2012. High CO_2 and silicate limitation synergistically increase the toxicity of *Pseudo-nitzschia fraudulenta*. *PLoS One*, 7(2): e32116 [online]. [Cited 18 June 2019]. https://doi.org/10.1371/journal.pone.0032116

Thirkell, T.J., Pastok, D. & Field, K.J., 2019. Carbon for nutrient exchange between arbuscular mycorrhizal fungi and wheat varies according to cultivar and changes in atmospheric carbon dioxide concentration. [published online ahead of print, 23 October 2019]. *Global Change Biology*, doi: 10.1111/gcb.14851

Trainer, V.L., Moore, S.K., Hallegraeff, G., Kudela, R.M., Clement, A., Mardones, J.I. & Cochlan, W.P. 2019. Pelagic harmful algal blooms and climate change: Lessons from nature's experiments with extremes. *Harmful Algae:* 101591: doi: 10.1016/j.hal.2019.03.009

Turner, R.E., Rabalais, N.N. & Justic, D. 2008. Gulf of Mexico hypoxia: alternate states and a legacy. *Environmental Science & Technology,* 42(7): 2323–2327.

Uysal, O., Uysal, F.O. & Ekinci, K. 2015. Evaluation of microalgae as microbial fertilizer. *European Journal of Sustainable Development,* 4(2): doi: 10.14207/ejsd.2015.v4n2p77.

Vachula, R.S., Russell, J.M. & Huang, Y. 2019. Climate exceeded human management as the dominant control of fire at the regional scale in California's Sierra Nevada. *Environmental Research Letters,* 14(10): 104011.

Van de Waal, D.B., Verspagen, J.M., Finke, J.F., Vournazou, V., Immers, A.K., Kardinaal, W.E., Tonk, L., Becker, S., Van Donk, E., Visser, P.M. & Huisman, J. 2011. Reversal in competitive dominance of a toxic versus non-toxic cyanobacterium in response to rising CO_2. *ISME J*ournal, 5(9): 1438–1450. https://doi.org/10.1038/ismej.2011.28

Van Dolah, F.M., Roelke, D. & Greene, R.M 2001. Health and ecological impacts of harmful algal blooms: Risk assessment needs. *Human and Ecological Risk Assessment,* 7(5): 1329–1345.

Villacorte, L.O., Tabatabai, S.A.A., Anderson, D.M., Amy, G.L., Schippers, J.C. & Kennedy, M.D. 2015. Seawater reverse osmosis desalination and (harmful) algal blooms. *Desalination,* 360: 61–80.

Wallace, R.B., Baumann, H., Grear, J.S., Aller, R.C. & Gobler, C.J. 2014. Coastal ocean acidification: The other eutrophication problem. *Estuarine, Coastal and Shelf Science,* 148: 1–13.

Wang, D. & Zhao, H. 2008. Estimation of phytoplankton responses to Hurricane Gonu over the Arabian Sea based on ocean color data. *Sensors*, 8: 4878 – 4893. doi: 10.3390/s8084878.

Wang, M. & Hu, C. 2016. Mapping and quantifying *Sargassum* distribution and coverage in the Central West Atlantic using MODIS observations. *Remote Sensing of Environment,* 183: 350–367.

Wang, M. & Hu, C. 2017. Predicting *Sargassum* blooms in the Caribbean Sea from MODIS observations. *Geophysical Research Letters,* 44(7): 3265–3273.

Wang, M., Hu, C., Barnes, B.B., Mitchum, G., Lapointe, B. & Montoya, J.P. 2019. The great Atlantic *Sargassum* belt. *Science*, 365(6448): 83–87.

Wells, M.L., Trainer, V.L., Smayda, T.J., Karlson, B.S., Trick, C.G., Kudela, R.M., Ishikawa, A., Bernard, S., Wulff, A., Anderson, D.M. & Cochlan, W.P. 2015. Harmful algal blooms and climate change: Learning from the past and present to forecast the future. *Harmful Algae*, 49: 68–93.

Wetz, M.S. & Paerl, H.W. 2008. Estuarine phytoplankton responses to hurricanes and tropical storms with different characteristics (trajectory, rainfall, winds). *Estuaries and Coasts*, 31(2): 419–429.

White, W. & Wilson, P. 2015. World seaweed utilization. In: *Seaweed sustainability: Food and non-food applications*. Tiwari, B.K. and Troy, D.J. eds. pp. 7–25. London, Academic Press.

WHO. 2015. *Human health and climate change in Pacific island countries*. Geneva, Switzerland. 172 pp. (also available at https://iris.wpro.who.int/bitstream/handle/10665.1/12399/9789290617303_eng.pdf).

Wisniewska, K., Lewandowska, A.U. & Sliwinska-Wilczewska, S. 2019. The importance of cyanobacteria and microalgae present in aerosols to human health and the environment – Review study. *Environment International*, 131: e104964 [online]. [Cited 29 November 2019]. https://doi.org/10.1016/j.envint.2019.104964

World Resources Institute. 2011. “Eutrophication & Hypoxia Map Data Set.” World Resources Institute. http://www.wri.org/resources/data-sets/eutrophication-hypoxia-map-data-set. Accessed through Resource Watch, (30 October 2019). www.resourcewatch.org.

Yokota, K., Waterfield, H., Hastings, C., Davidson, E., Kwietniewski, E. & Wells, B. 2017. Finding the missing piece of the aquatic plastic pollution puzzle: Interaction between primary producers and microplastics. *Limnology and Oceanography Letters*, 2(4): 91–104.

Zeraatkar, A.K., Ahmadzadeh, H., Talebi, A.F., Moheimani, N.R. & McHenry, M.P. 2016. Potential use of algae for heavy metal bioremediation, a critical review. *Journal of Environmental Management*, 181: 817–831.

Zettler, E.R., Mincer, T.J. & Amaral-Zettler, L.A. 2013. Life in the “plastisphere”: microbial communities on plastic marine debris. *Environmental Science & Technology*, 47(13): 7137–7146.

Zhang, X. 2017. A plan for efficient use of nitrogen fertilizers. *Nature*, 543(7645): 322–323.

Zhang, Q.-C., Qiu, L.-M., Yu, R.-C., Kong, F.-Z., Wang, Y.-F., Yan, T., Gobler, C.J. & Zhou, M.-J. 2012. Emergence of brown tides caused by *Aureococcus anophagefferens* Hargraves et Sieburth in China. *Harmful Algae*, 19: 117–124.

Zhang, C. & Zhang, J. 2015. Current techniques for detecting and monitoring algal toxins and causative harmful algal blooms. *Journal of Environmental Analytical Chemistry*, 02(01): doi: 10.4172/2380-2391.1000123.

Zingone, A. & Oksfeldt Enevoldsen, H. 2000. The diversity of harmful algal blooms: a challenge for science and management. *Ocean and Coastal Management*, 43(8–9): 725–748.

Chapter 2.C: Heavy metals

Ahmad, S.A., Khan, M.H. & Haque, M. 2018. Arsenic contamination in groundwater in Bangladesh: implications and challenges for healthcare policy. *Risk Management and Healthcare Policy*, 11: 251–261.

Ali, H., Khan, E. & Sajad, M.A. 2013. Phytoremediation of heavy metals--concepts and applications. *Chemosphere*, 91(7): 869–881.

Arao, T., Makino, T., Kawasaki, A., Akahane, I. & Kiho, N. 2018. Effect of air temperature after soil receiving heading of rice on the arsenic concentration of grain. *Soil Science and Plant Nutrition,* 64(3): 433–437.

Benotti, M.J., Stanford, B.D. & Snyder, S.A. 2010. Impact of drought on wastewater contaminants in an urban water supply. *J. Environ. Qual.,* 39(4): 1196–1200.

Canesi, L. & Corsi, I. 2016. Effects of nanomaterials on marine invertebrates. *Science of the Total Environment,* 565: 933–940.

Canli, M. & Atli, G. 2003. The relationships between heavy metal (Cd, Cr, Cu, Fe, Pb, Zn) levels and the size of six Mediterranean fish species. *Environmental Pollution,* 121(1): 129–136.

Carere, M., Miniero, R. & Cicero, M.R. 2011. Potential effects of climate change on the chemical quality of aquatic biota. *TrAC Trends in Analytical Chemistry,* 30(8): 1214–1221.

Carvalho, F.P. 2018. Radionuclide concentration processes in marine organisms: A comprehensive review. *Journal of Environmental Radioactivity,* 186: 124–130.

Chakraborti, D., Singh, S.K., Rahman, M.M., Dutta, R.N., Mukherjee, S.C., Pati, S. & Kar, P.B. 2018. Groundwater arsenic contamination in the Ganga River basin: A future health danger. *International Journal of Environmental Research &Public Health*, 15(2): doi: 10.3390/ijerph15020180.

Chen, C.Y., Stemberger, R.S., Klaue, B., Blum, J.D., Pickhardt, P.C. & Folt, C.L. 2000. Accumulation of heavy metals in food web components across a gradient of lakes. *Limnology and Oceanography,* 45(7): 1525–1536.

Clay, K., Portnykh, M. & Severnini, E. 2019. The legacy lead deposition in soils and its impact on cognitive function in preschool-aged children in the United States. *Economics & Human Biology,* 33: 181–192.

Conway, J.R., Hanna, S.K., Lenihan, H.S. & Keller, A.A. 2014. Effects and implications of trophic transfer and accumulation of CeO_2 nanoparticles in a marine mussel. *Environmental Science & Technology,* 48(3): 1517–1524.

De Gieter, M., Leermakers, M., Van Ryssen, R., Noyen, J., Goeyens, L. & Baeyens, W. 2002. Total and toxic arsenic levels in North Sea fish. *Archives of Environmental Contamination and Toxicology*, 43(4): 406-17.

Dennis, B., Mufson, S. & Eilperin, J. 2018. Dam breach sends toxic coal ash flowing into a major North Carolina river. *The Washington Post*. 22 September 2018. (also available at https://www.washingtonpost.com/energy-environment/2018/09/21/dam-breach-reported-former-nc-coal-plant-raising-fears-that-toxic-coal-ash-may-pollute-cape-fear-river/?arc404=true).

Downing, B.W. & Jacobs, J.A. 2014. Acid rock drainage as related to permafrost, glaciers, and climate change. *In* Jacobs, J.A., Lehr, J.H. and Testa, S.M. *Acid mine drainage, rock drainage, and acid sulfate soils: Causes, Assessment, prediction, prevention, and remediation,* chapter 15, pp. 185–189. Hoboken, New Jersey, United States, John Wiley and Sons.

Du, W., Gardea-Torresdey, J.L., Xie, Y., Yin, Y., Zhu, J., Zhang, X., Ji, R., Gu, K., Peralta-Videa, J.R. & Guo, H. 2017. Elevated CO_2 levels modify TiO_2 nanoparticle effects on rice and soil microbial communities. *Science of the Total Environment,* 578: 408–416.

Evans, S., Campbell, C. & Naidenko, O.V. 2019. Cumulative risk analysis of carcinogenic contaminants in United States drinking water. *Heliyon,* 5(9): e02314 [online]. [Cited 10 November 2019]. https://doi.org/10.1016/j.heliyon.2019.e02314

Fang, X.W., Luo, S.Q. & Lyu, S.H. 2019. Observed soil temperature trends associated with climate change in the Tibetan Plateau, 1960–2014. *Theoretical and Applied Climatology,* 135(1–2): 169–181

FAO. 2014. *The State of World Fisheries and Aquaculture.* Rome, FAO. 243 pp. (also available at http://www.fao.org/3/a-i3720e.pdf).

FAO & ITPS. 2015. *Status of the world's soil resources*. Rome, FAO. 650 pp. (also available at http://www.fao.org/3/a-i5199e.pdf).

FAO & WHO. 2007. *Evaluation of certain food additives and contaminants. Sixty-seventh report of the Joint FAO/WHO Expert Committee on Food Additives*. Rome, FAO. 104 pp. (also available at https://apps.who.int/iris/handle/10665/43592).

FAO & WHO. 2011a. *Evaluation of certain food additives and contaminants. Seventy-second report of the Joint FAO/WHO Expert Committee on Food Additives*. Rome, FAO. 115 pp. (also available at https://apps.who.int/iris/handle/10665/44514).

FAO & WHO. 2011b. *Evaluation of certain food additives and contaminants. Seventy-third report of the Joint FAO/WHO Expert Committee on Food Additives.* Rome, FAO. 237 pp. (also available at https://apps.who.int/iris/handle/10665/44515).

FAO & WHO. 2013. *Evaluation of certain food additives and contaminants. Seventy-seventh report of the Joint FAO/WHO Expert Committee on Food Additives.* Rome, FAO. 86 pp. (also available at https://apps.who.int/iris/handle/10665/98388).

Fergusson, J.E., ed. 1990. *The heavy elements: Chemistry, environmental impact and health effects*. Oxford, United Kingdom, Pergamon Press.

Greco, S.L., Belova, A., Haskell, J. & Backer, L. 2019. Estimated burden of disease from arsenic in drinking water supplied by domestic wells in the United States. *Journal of Water & Health,* 17(5): 801–812.

Guo, J.H., Liu, X.J., Zhang, Y., Shen, J.L., Han, W.X., Zhang, W.F., Christie, P., Goulding, K.W., Vitousek, P.M. & Zhang, F.S. 2010. Significant acidification in major Chinese croplands. *Science,* 327(5968): 1008–10010.

Mehta, N., Benzerara, K., Kocar, B. D. & Chapon, V. 2019. Sequestration of radionuclides Radium-226 and Strontium-90 by cyanobacteria forming intracellular calcium carbonates. *Environmental Science and Technology*, 53(21): 12639 – 12647.

IPCC. 2012. *Managing the risks of extreme events and disasters to advance climate change adaptation.* A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change, Field, C., Barros, V., Stocker, T., Qin, D., Dokken, D., Ebi, K., Mastrandrea, M., Mach, K., Plattner, G., Allen, S., Tignor, M. and Midgley, P. eds. Cambridge United Kingdom, and New York, Cambridge University Press.

Jarup, L. 2003. Hazards of heavy metal contamination. *British Medical Bulletin,* 68: 167–182.

Joris, I., Bronders, J., van der Grift, B. & Seuntjens, P. 2014. Model-based scenario analysis of the impact of remediation measures on metal leaching from soils contaminated by historic smelter emissions. *Journal of Environmental Quality*, 43(3): 859–868.

Khalid, S., Shahid, M., Niazi, N.K., Murtaza, B., Bibi, I. & Dumat, C. 2017. A comparison of technologies for remediation of heavy metal contaminated soils. *Journal of Geochemical Exploration,* 182: 247–268.

Knutson, T., Camargo, S.J., Chan, J.C.L., Emanuel, K., Ho, C.-H., Kossin, J., Mohapatra, M., Satoh, M., Sugi, M., Walsh, K. & Wu, L. 2019a. Tropical cyclones and climate change assessment: Part I: Detection and attribution. *Bulletin of the American Meteorological Society,* 100(10): 1987–2007.

Knutson, T., Camargo, S.J., Chan, J.C.L., Emanuel, K., Ho, C.-H., Kossin, J., Mohapatra, M., Satoh, M., Sugi, M., Walsh, K. & Wu, L. 2019b. Tropical cyclones and climate change assessment: Part II. Projected response to anthropogenic warming. *Bulletin of the American Meteorological Society,* doi: 10.1175/BAMS-D-18-0194.1.

Mahmood, A. & Malik, R.N. 2014. Human health risk assessment of heavy metals *via* consumption of contaminated vegetables collected from different irrigation sources in Lahore, Pakistan. *Arabian Journal of Chemistry,* 7(1): 91–99.

Masih, A. 2018. An enhanced seismic activity observed due to climate change: Preliminary results from Alaska. *IOP Conference Series: Earth and Environmental Science,* 167: 012018.

Mielke, H.W., Gonzales, C.R., Powell, E.T., Laidlaw, M.A.S., Berry, K.J., Mielke, P.W., Jr. & Egendorf, S.P. 2019. The concurrent decline of soil lead and children's blood lead in New Orleans. *Proceedings of the National Academy of Sciences of the USA,* 116(44): 22058–22064.

Muehe, E.M., Wang, T., Kerl, C.F., Planer-Friedrich, B. & Fendorf, S. 2019. Rice production threatened by coupled stresses of climate and soil arsenic. *Nature Communications,* 10(1): 4985. https://doi.org/10.1038/s41467-019-12946-4

Naseri, M., Vazirzadeh, A., Kazemi, R. & Zaheri, F. 2015. Concentration of some heavy metals in rice types available in Shiraz market and human health risk assessment. *Food Chemistry,* 175: 243–248.

Neumann, R.B., Seyfferth, A.L., Teshera-Levye, J. & Ellingson, J. 2017. Soil warming increases arsenic availability in the rice rhizosphere. *Agricultural & Environmental Letters,* 2(1): 170006. doi: 10.2134/ael2017.02.0006

OECD & FAO. 2018. *Agricultural outlook 2018–2027: Cereals.* 31 pp. Organisation for Economic Co-operation and Development (OECD) and FAO. http://www.agri-outlook.org/commodities/Agricultural-Outlook-2018-Cereals.pdf.

Qian, B., Gregorich, E.G., Gameda, S., Hopkins, D.W. & Wang, X.L. 2011. Observed soil temperature trends associated with climate change in Canada. *Journal of Geophysical Research,* 116(D2); D02106. https://doi.org/10.1029/2010JD015012

Ravenscroft, P., Brammer, H. & Richards, K. 2009. *Arsenic pollution; A global synthesis.* 618 pp. Royal Geographical Society, Wiley-Blackwell.

Salt, D.E., Blaylock, M., Kumar, N.P., Dushenkov, V., Ensley, B.D., Chet, I. & Raskin, I. 1995. Phytoremediation: a novel strategy for the removal of toxic metals from the environment using plants. *Biotechnology (NY),* 13(5): 468–474.

Seiler, C. & Berendonk, T.U. 2012. Heavy metal driven co-selection of antibiotic resistance in soil and water bodies impacted by agriculture and aquaculture. *Frontiers in Microbiology,* 3: 399. doi: 10.3389/fmicb.2012.00399. eCollection 2012.

Selvi, A., Rajasekar, A., Theerthagiri, J., Ananthaselvam, A., Sathishkumar, K., Madhavan, J. & Rahman, P.K.S.M. 2019. Integrated remediation processes toward heavy metal removal/recovery from various environments – A review. *Frontiers in Environmental Science,* 7. https://doi.org/10.3389/fenvs.2019.00066

Sezer, N., Kocaoglan, H.O., Kilic, O., Lacoue-Labarthe, T. & Belivermis, M. 2018. Acidified seawater increases accumulation of cobalt but not cesium in Manila clam *Ruditapes philippinarum*. *Journal of Environmental Radioactivity,* 184–185: 114–121.

Sharma, V.K. & Sohn, M. 2009. Aquatic arsenic: toxicity, speciation, transformations, and remediation. *Environment International,* 35(4): 743–759.

Shi, W., Han, Y., Guo, C., Su, W., Zhao, X., Zha, S., Wang, Y. & Liu, G. 2019. Ocean acidification increases the accumulation of titanium dioxide nanoparticles (nTiO2) in edible bivalve mollusks and poses a potential threat to seafood safety. *Scientific Reports,* 9(1): 3516. https://doi.org/10.1038/s41598-019-40047-1

Shi, W., Zhao, X., Han, Y., Che, Z., Chai, X. & Liu, G. 2016. Ocean acidification increases cadmium accumulation in marine bivalves: a potential threat to seafood safety. *Scientific Reports,* 6: 20197. https://doi.org/10.1038/srep20197

Tchounwou, P.B., Yedjou, C.G., Patlolla, A.K. & Sutton, D.J. 2012. Heavy metal toxicity and the environment. *Molecular, Clinical and Environmental Toxicology,* 101: 133–164. https://doi.org/10.1007/978-3-7643-8340-4_6

Thomas, A.N., Root, R.A., Lantz, R.C., Saez, A.E. & Chorover, J. 2018. Oxidative weathering decreases bioaccessibility of toxic metal(loid)s in PM10 emissions from sulfide mine tailings. *Geohealth,* 2(4): 118–138.

Tian, D. & Niu, S. 2015. A global analysis of soil acidification caused by nitrogen addition. *Environmental Research Letters,* 10(2): 024019.

Toth, G., Hermann, T., Da Silva, M.R. & Montanarella, L. 2016. Heavy metals in agricultural soils of the European Union with implications for food safety. *Environment International,* 88: 299–309.

Tracy, A.M., Weil, E. & Harvell, C.D. 2019. Warming and pollutants interact to modulate octocoral immunity and shape disease outcomes. [published online ahead of print 19 October 2019]. *Ecological Applications,* e02024 [online]. [Cited 5 November 2019]. doi:10.1002/eap.2024

Wang, Z., Yin, L., Zhao, J. & Xing, B. 2016. Trophic transfer and accumulation of TiO_2 nanoparticles from clamworm (*Perinereis aibuhitensis*) to juvenile turbot (*Scophthalmus maximus*) along a marine benthic food chain. *Water Research,* 95: 250–259.

Wijngaard, R.R., van der Perk, M., van der Grift, B., de Nijs, T.C.M. & Bierkens, M.F.P. 2017. The impact of climate change on metal transport in a lowland catchment. *Water Air, & Soil Pollution,* 228(3): 107.

Wilt, J. 2016. This is the looming climate change disaster in Canada's north that no one is talking about. *Vice Environment*. 12 January 2016. https://www.vice.com/en_ca/article/jma4ab/this-is-the-looming-climate-change-disaster-in-canadas-north-that-no-one-is-talking-about

Yeşilırmak, E. 2014. Soil temperature trends in Büyük Menderes Basin, Turkey. *Meteorological Applications*, 21(4): 859–866.

Ying, Y., Pourrahimi, A.M., Sofer, Z., Matejkova, S. & Pumera, M. 2019. Radioactive uranium preconcentration *via* self-propelled autonomous microrobots based on metal-organic frameworks. *ACS Nano,* 13(10): 11477–11487.

Yu, C., Sun, Y., Zhong, X., Yu, Z., Li, X., Yi, P., Jin, H. & Luo, D. 2019. Arsenic in permafrost-affected rivers and lakes of Tibetan Plateau, China. *Environmental Pollutants and Bioavailability,* 31(1): 226–232.

Zeng, F., Ali, S., Zhang, H., Ouyang, Y., Qiu, B., Wu, F. & Zhang, G. 2011. The influence of pH and organic matter content in paddy soil on heavy metal availability and their uptake by rice plants. *Environmental Pollution,* 159(1): 84–91.

Zeraatkar, A.K., Ahmadzadeh, H., Talebi, A.F., Moheimani, N.R. & McHenry, M.P. 2016. Potential use of algae for heavy metal bioremediation, a critical review. *Journal of Environmental Management,* 181: 817–831.

Zhang, X., Zhong, T., Liu, L. & Ouyang, X. 2015. Impact of soil heavy metal pollution on food safety in China. *PLoS One*, 10(8): e0135182 [online]. [Cited 8 October 2019]. https://doi.org/10.1371/journal.pone.0135182

Zheng, S.-a., Zheng, X. & Chen, C. 2012. Leaching behavior of heavy metals and transformation of their speciation in polluted simulated acid rain. *PLoS One,* 7(11): e49664 [online]. [Cited 7 September 2019]. https://doi.org/10.1371/journal.pone.0049664

Chapter 2.D: Methylmercury

Acha, D., Guedron, S., Amouroux, D., Point, D., Lazzaro, X., Fernandez, P. & Sarret, G. 2018. Algal bloom exacerbates hydrogen sulfide and methylmercury contamination in the emblematic high-altitude Lake Titicaca. *Geosciences*, 8(12): 438: doi: 10.3390/geosciences8120438

Afonso, C., Lourenço, H.M., Cardoso, C., Bandarra, N.M., Carvalho, M.L., Castro, M. & Nunes, M.L. 2013. From fish chemical characterisation to the benefit-risk assessment --part A. *Food Chemistry*, 137(1–4): 99–107.

Alava, J.J., Cisneros-Montemayor, A.M., Sumaila, U.R. & Cheung, W.W.L. 2018. Projected amplication of food web bioaccumulation of MeHg and PCBs under climate change in the Northeastern Pacific. *Scientific Reports*, 8: 13460. doi: 10.1038/s41598-018-31824-5

AMAP & UNEP. 2013. *Technical background report for the Global Mercury Assessment 2013.* Oslo, Arctic Monitoring and Assessment Program (AMAP) and Geneva, UNEP Chemicals Branch. 271 pp. (also available at https://www.amap.no/documents/doc/technical-background-report-for-the-global-mercury-assessment-2013/848).

AMAP & UNEP. 2015. *Global mercury modelling: Update of modelling results in the Global Mercury Assessment 2013.* Oslo, AMAP and Geneva, UNEP Chemicals Branch Geneva. 36 pp. (also available at https://www.amap.no/documents/doc/global-mercury-modelling-update-of-modelling-results-in-the-global-mercury-assessment-2013/1218).

Avramescu, M., Yumvihoze, E., Hintelmann, H., Ridal, J., Fortin, D. & Lean, D.R. 2011. Biogeochemical factors influencing net mercury methylation in contaminated freshwater sediments from the St. Lawrence River in Cornwall, Ontario, Canada. *Science of the Total Environment*, 409(5), 968–978.

Azevedo, L., Pestana, I., Rocha, A., Meneguelli-Souza, A., Lima, C., Almeida, M., Bastos, W. & Souza, C. 2018. Drought promotes increases in total mercury and methylmercury concentrations in fish from lower Paraíba do Sul river, south-eastern Brazil. *Chemosphere*, 202: 483–490.

Bakir, F., Damluji, S.F., Amin-Zaki, L., Murtadha, M., Khalidi, A., Al-Rawi, N.Y., Tikriti, S., Dhahir, H.I., Clarkson, T.W., Smith, J.C. & Doherty, R.A. 1973. Methylmercury poisoning in Iraq. *Science,* 181(4096): 230–241.

Bates, A.L., Orem, W.H., Harvey, J.W. & Spiker, E.C. 2002. Tracing sources of sulfur in the Florida everglades. *Journal of Environmental Quality*, 31(1): 287–299.

Bellanger, M., Pichery, C., Aerts, D., Berglund, M., Castaño, A.,Čejchanová, M., Crettaz, P., Davidson, F., Esteban, M. E., Fischer M., Gurzau, A.E., Halzlova K., Katsonouri, A., Knudsen, L.E., Kolossa-Gehring, M., Koppen, G., Ligocka, D., Miklavčič, A., Reis, M.F., Rudnai, P., Snoj, J.T., Weihe, P., Budtz-Jørgensen, E. & Grandjean, P. 2013. Economic benefits of methylmercury exposure control in Europe: Monetary value of neurotoxicity prevention. *Environmental Health: A Global Access Science Source*, 12(1): 1–10.

Black, F. J., Conaway, C. H. & Flegal, A. R. 2009. Stability of dimethyl mercury in seawater and its conversion to monomethyl mercury. *Environmental Science and Technology*, 43(11): 4056 – 4062.

Booth, S. & Zeller, D. 2005. Mercury, food webs, and marine mammals: implications of diet and climate change for human health. *Environmental Health Perspectives*, 113(5): 521–526.

Bowman, K.L., Hammerschmidt, C.R., Lamborg, C.H. & Swarr, G. 2015. Mercury in the North Atlantic Ocean: The U.S. GEOTRACES zonal and meridional sections. *Deep Sea Research II: Topical Studies in Oceanography,* 116: 251–261.

Bowman, K.L., Hammerschmidt, C.R., Lamborg, C.H., Swarr, G. & Agather, A.M. 2016. Distribution of mercury species across zonal section of the eastern tropical South Pacific Ocean (U.S. GEOTRACES GP16). *Marine Chemistry,* 186: 155–166.

Caldeira, K. & Wickett, M. 2005. Ocean model predictions of chemistry changes from carbon dioxide emissions to the atmosphere and ocean. *Journal of Geophysical Research: Oceans*, 110(9): 1–12.

Campbell, D., Gonzalez, M. & Sullivan, J.B. 1992. Mercury. *In,* Sullivan, J.B. and Krieger, G.R. *Hazardous materials toxicology – Clinical principles of environmental health*, pp 824–833. Maryland, Michigan, United States, Williams and Wilkins. 1 242 pp.

Chen, L., Liang, S., Liu, M., Yi, Y., Mi, Z., Zhang, Y., Li, Y., Qi, J., Meng, J., Tang, X., Zhang, H., Tong, Y., Zhang, W., Wang, X., Shu, J. & Yang, Z. 2019. Trans-provincial health impacts of atmospheric mercury emissions in China. *Nature Communications*, 10(1): 1–12.

Cheung, W.W., Lam, V.W., Sarmiento, J.L., Kearney, K., Watson, R.A. & Pauly, D. 2009. Projecting global marine biodiversity impacts under climate change scenarios. *Fish and Fisheries*, 10(3): 235–251.

Cossa, D., Averty, B. & Pirrone, N. 2009. The origin of methylmercury in open Mediterranean waters. *Limnology and Oceanography,* 54: 837–844.

Cui, W., Liu, G., Bezerra, M., Lagos, D.A., Li, Y. & Cai, Y. 2017. Occurrence of methylmercury in rice-based infant cereals and estimation of daily dietary intake of methylmercury for infants. *Journal of Agricultural and Food Chemistry*, 65(44): 9569–9578.

da Cunha, L.R., Costa, T.H. & Caldas, E.D. 2013. Mercury concentration in breast milk and infant exposure assessment during the first 90 days of lactation in a midwestern region of Brazil. *Biological Trace Element* Research, 151(1): 30–37.

Dietz, R., Riget, F., Cleeman, M., Aarkrog, A., Johansen, P. & Hansen, J.C. 2000. Comparison of contaminants from different trophic levels and ecosystems. *Science of the Total Environment,* 245: 221–231.

Dijkstra, J.A., Buckman, K.L., Ward, D., Evans, D.W., Dionne, M. & Chen, C.Y. 2013. Experimental and natural warming elevates mercury concentrations in estuarine fish. *Plos One*, 8(3): e58401 [online]. [Cited 17 August 2019]. https://doi.org/10.1371/journal.pone.0058401

Downs, S.G., Macleod, C.L. & Lester, J.N. 1998. Mercury in precipitation and its relation to bioaccumulation in fish: A literature review. *Water, Air, and Soil Pollution*, 108: 149–187.

EFSA. 2012. Scientific opinion on the risk for public health related to the presence of mercury and methylmercury in food. *EFSA Journal*, 10(12): 2985. https://www.efsa.europa.eu/en/efsajournal/pub/2985

EPA. 2004. Provisional peer reviewed toxicity values for dimethylmercury. Derivation of subchronic and chronic oral RfDs. https://cfpub.epa.gov/ncea/pprtv/documents/Dimethylmercury.pdf

EPA. 2018. *Mercury emissions: The global context*. United States. https://www.epa.gov/international-cooperation/mercury-emissions-global-context

European Environment Agency. 2017. Permafrost. https://www.eea.europa.eu/data-and-maps/indicators/mountain-permafrost-1/assessment-1

Fahnestock, M.F., Bryce, J.G., Mccalley, C.K., Montesdeoca, M., Bai, S., Li, Y., Driscoll, C.T., Crill, P.M., Rich, V.I. & Varner, R.K. 2019. Mercury reallocation in thawing subarctic peatlands. *Geochemical Perspectives Letters,* 11: 33–38.

FAO & WHO. 1972. *Evaluation of mercury, lead, cadmium and the food additives amaranth, diethylpyrocarbonate, and octyl gallate. Sixteenth report of the Joint FAO/WHO Expert Committee on Food Additives.* World Health Organization Technical Report Series No. 505. (also available at http://www.inchem.org/documents/jecfa/jecmono/v004je02.htm).

FAO & WHO. 2007. *Evaluation of certain food additives and contaminants. Sixty-seventh report of the Joint FAO/WHO Expert Committee on Food Additives*. Singapore, WHO. 104 pp. (also available at https://apps.who.int/iris/handle/10665/43592).

FAO & WHO. 2010. *Health risks associated with fish consumption. Focus on methylmercury, dioxins and dioxin-like PCBs. Joint FAO/WHO Expert Consultation on the risks and benefits of fish consumption*. 95 pp. Rome, FAO. (also available at http://www.fao.org/3/k7107e/k7107e.pdf).

Fasullo, J.T., Otto-Bliesner, B.L. & Stevenson, S. 2018. ENSO's changing influence on temperature, precipitation, and wildfire in a warming climate. *Geophysical Research Letters*, 45(17): 9216–9225.

Feng, X., Li, P., Qiu, G., Wang, S., Li, G., Shang, L., Meng, B., Jjiang, H., Bai, W., Li, Z. & Fu, X. 2008. Human exposure to methylmercury through rice intake in mercury mining areas, Guizhou Province, China. *Environmental Science & Technology,* 42: 326–332.

Friedli, H.R., Arellano, A F., Cinnirella, S. & Pirrone, N. 2009. Initial estimates of mercury emissions to the atmosphere from global biomass burning. *Environmental Science & Technology,* 43(10): 3507–3513.

Fujuki, M. 1980. The pollution of Minamata Bay by mercury and Minamata disease. *In Contaminants and sediments*, Baker R.A. (ed). 493 – 500. Ann Arbor, Michigan.

Giang, A. & Selin, N.E. 2016. Benefits of mercury controls for the United States. *Proceedings of the National Academy of Sciences of the USA*, 113(2): 286–291.

Gilmour, C.C., Bullock, A.L., McBurney, A., Podar, M. & Elias, D.A. 2018. Robust mercury methylation across diverse methanogenic Archaea. *mBio*, *9*(2): 1–13.

Gilmour, C. & Riedel, G.S. 2000. A survey of size-specific mercury concentrations in game fish from Maryland fresh and estuarine waters. *Archives of Environmental Contamination and Toxicology*, 39(1): 53–59.

Gionfriddo, C.M., Tate, M.T., Wick, R.R., Schultz, M.B., Zemla, A., Thelen, M.P., Schofield, R., Krabbenhoft, D.P., Holt, K.E. & Moreau, J.W. 2016. Microbial mercury methylation in Antarctic sea ice. *Nature Microbiology*, 1(10): 16127.

Gworek, B., Bemowska-Kałabun, O., Kijeńska, M. & Wrzosek-Jakubowska, J. 2016. Mercury in marine and oceanic waters – a review. *Water, Air, and Soil Pollution*, 227(10): 371. doi: 10.1007/s11270-016-3060-3.

Harada, M. 1968. Congenital Minamata disease: Intrauterine methylmercury poisoning. *Teratology,* 18(2): 285–288.

Harris, R.C., Rudd, J.W.M., Amyot, M., Babiarz, C.L., Beaty, K.G., Blanchfield, P.J., Bodaly, R.A., Branfireun, B.A., Gilmour, C.C., Graydon, J.A., Heyes, A., Hintelmann, H., Hurley, J.P., Kelly, C.A., Krabbenhoft, D.P., Lindberg, S.E., Mason, R.P., Paterson, M.J., Podemski, C.L., Robinson, A., Sandilands, K.A., Southworth, G.R., St. Louis, V.L. & Tate, M.T. 2007. Whole-ecosystem study shows rapid fish-mercury response to changes in mercury deposition. *Proceedings of the National Academy of Sciences of the USA*, 104(42): 16586–16591.

Heimbürger, L.E., Cossa, D., Marty, J.C., Migon, C., Averty, B., Dufour, A. & Ras, J. 2010. Methyl mercury distributions in relation to the presence of nano- and picophytoplankton in an oceanic water column (Ligurian Sea, north-western Mediterranean). *Geochimica et Cosmochimica Acta*, 74(19): 5549–5559.

Heimbürger, L.E., Sonke, J.E., Cossa, D., Point, D., Lagane, C., Laffont, L., Galfond, T., Nicolaus, M., Rabe, B. & van der Loeff, M.R. 2015. Shallow methylmercury production in the marginal sea ice zone of the central Arctic Ocean. *Scientific Reports,* 5: 10318. https://doi.org/10.1038/srep10318

Hu, H., Lin, H., Zheng, W., Tomanicek, S.J., Johs, A., Feng, X., Elias, D.A., Liang, L. & Gu, B. 2013. Oxidation and methylation of dissolved elemental mercury by anaerobic bacteria. *Nature Geoscience*, 6(9): 751–754.

Huang, Y., Wu, S. & Kaplan, J.O. 2015. Sensitivity of global wildfire occurrence to various factors in the context of global change. *Atmospheric Environment,* 121: 86–92.

IPCC. 2013. *Climate Change 2013. The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, United Kingdom of Great Britain and Northern Ireland and New York, Cambridge University Press. 1535 pp.

Jonsson, S., Andersson, A., Nilsson, M.B., Skyllberg, U., Lundberg, E., Schaefer, J.K., Åkerblom, S. & Björn, E. 2017. Terrestrial discharges mediate trophic shifts and enhance methylmercury accumulation in estuarine biota. *Science Advances*, *3*(1): e1601239 [online]. [Cited 11 August 2019]. doi: 10.1126/sciadv.1601239

Karagas, M.R., Choi, A.L., Oken, E., Horvat, M., Schoeny, R., Kamai, E., Cowell, W., Grandjean, P. & Korrick, S. 2012. Evidence on the human health effects of low-level methylmercury exposure. *Environmental Health Perspectives,* 120(6): 799–806.

Kelly, C.A., Rudd, J.W.M. & Holoka, M.H. 2003. Effect of pH on mercury uptake by an aquatic bacterium: Implications for Hg Cycling. *Environmental Science & Technology*, 37(13), 2941–2946.

Kim, H., Soerenson, A.L., Hur, J., Heimburger, L., Hahm, D., Rhee, T.S., Noh, S. & Han, S. 2017. Methylmerucry mass budgets and distribution characteristics in the Western Pacific Ocean. *Environmental Science & Technology,* 51(3): 1186–1194.

Krabbenhoft, D.P. & Sunderland, E.M. 2013. Global change and mercury. *Science*, 341(6153): 1457–1458.

Kumar, A., Wu, S., Huang, Y., & Kaplan, J.O. 2018. Mercury from wildfires: Global emission inventories and sensitivity to 2000–2050 global change. *Atmospheric Environment*, 173: 6–15.

Lamborg, C.H., Hammerschmidt, C.R., Bowman, K.L., Swarr, G.J., Munson, K.M., Ohnemus, D.C., Lam, P.J., Heimbürger, L.E., Rijkenberg, M.J.A. & Saito, M.A. 2014. A global ocean inventory of anthropogenic mercury based on water column measurements. *Nature,* 512: 65–68.

Le Faucheur, Ś., Tremblay, Y., Fortin, C. & Campbell, P.G.C. 2011. Acidification increases mercury uptake by a freshwater alga, *Chlamydomonas reinhardtii*. *Environmental Chemistry*, 8(6): 612–622.

Lepak, R.F., Hoffman, J.C., Janssen, S.E., Krabbenhoft, D.P., Ogorek, J.M., DeWild, J.F., Tate, M.T., Babiarz, C.L., Yin, R., Murphy, E.W., Engstrom, D.R. & Hurley, J.P. 2019. Mercury source changes and food web shifts alter contamination signatures of predatory fish from Lake Michigan. *Proceedings of the National Academy of Sciences of the USA,* 116(47): 23600–23608.

Liu, X., Ma, A., Zhuang, G. & Zhuang, X. 2017. Diversity of microbial communities potentially involved in mercury methylation in rice paddies surrounding typical mercury mining areas in China. *MicrobiologyOpen*, 7(4): e00577.

Lu, X., Gu, W., Zhao, L., Ul Haque, M.F., Di Spirito, A.A., Semrau, J.D. & Gu, B. 2017. Methylmercury uptake and degradation by methanotrophs. *Science Advances*, 3(5): e1700041 [online]. [Cited 16 October 2019]. doi: 10.1126/sciadv.1700041

Mason, R. P., Choi, A. L., Fitzgerald, W. F., Hammerschmidt, C. R., Lamborg, C. H., Soerensen, A. L. & Sunderland, E. M. 2012. Mercury biogeochemical cycling in the ocean and policy implications. *Environmental Research*, 119: 101 – 117.

Mason, R. & Fitzgerald, W. (1996) Sources, sinks and biogeochemical cycling of mercury in the ocean. *In Global and regional mercury cycles: sources, fluxes and mass balances.* Baeyens, W. Ebinghaus, R. & Vasiliev, O. eds. 249 – 272. The Netherlands.

Maulvault, A.M., Custódio, A., Anacleto, P., Repolho, T., Pousão, P., Nunes, M.L., Diniz, M., Rosa, R. & Marques, A. 2016. Bioaccumulation and elimination of mercury in juvenile seabass (*Dicentrarchus labrax*) in a warmer environment. *Environmental Research*, 149: 77 – 85.

Meng, M., Li, B., Shao, J.J., Wang, T., He, B., Shi, J.B., Ye, Z.H., & Jiang, G.B. 2014. Accumulation of total mercury and methylmercury in rice plants collected from different mining areas in China. *Environmental Pollution*, 184: 179–186.

Munson, K.M., Lamborg, C.H., Swarr, G. & Saito, M.A. 2015. Mercury species concentrations and fluxes in the Central Tropical Ocean. *Global Biogeochemical Cycles*, 29(5): 656–676.

Myrbo, A., Swain, E.B., Johnson, N.W., Engstrom, D.R., Pastor, J., Dewey, B., Monson, P., Brenner, J., Shore, M.D. & Peters, E.B. 2017. Increase in nutrients, mercury, and methylmercury as a consequence of elevated sulfate reduction to sulfide in experimental wetland mesocosms. *Journal of Geophysical Research: Biogeosciences*, 122(11): 2769–2785.

Nishimura, A., Shimoda, K., Tanaka, T., Toyama, T., Nishiyama, K., Shinkai, Y., Numaga-Tomita, T., Yamazaki, D., Kanda, Y., Akaike, T., Kumagai, Y. & Nishida, M. 2019. Depolysulfidation of Drp1 induced by low-dose methylmercury exposure increases cardiac vulnerability to hemodynamic overload. *Science Signaling*, 587(12): doi: 10.1126/scisignal.aaw1920

Obrist, D., Kirk, J.L., Zhang, L., Sunderland, E.M., Jiskra, M. & Selin. N.E. 2018. A review of global environmental mercury processes in response to human and natural perturbations: Changes of emissions, climate, and land use. *Ambio*, 47(2): 116–140.

Parks, J.M., Johs, A., Podar, M., Bridou, R., Hurt, R.A., Smith, S.D., Tomanicek, S.J., Quian, Y.D., Brown, S., Brandt, C.C., Palumbo, A.V., Smith, J.C., Wall J.D., Elias D.A. & Liang, L. 2013. The genetic basis for bacterial mercury methylation. *Science*, 339(6125): 1332–1335.

Pickhardt, P.C., Folt, C.L., Chen, C.Y., Klaue, B. & Blum, J.D. 2002. Algal blooms reduce the uptake of toxic methylmercury in freshwater food webs. *Proceedings of the National Academy of the Sciences of the USA*, 99(7): 4419–4423.

Podar, M., Gilmour, C.C., Brandt, C.C., Soren, A., Brown, S.D., Crable, B.R., Palumbo, A.V., Somenahally, A.C. & Elias, D.A. 2015. Global prevalence and distribution of genes and microorganisms involved in mercury methylation. *Science Advances*, 1(9): e1500675 [online]. [Cited 24 September 2019]. doi: 10.1126/sciadv.1500675

Razavi, N.R., Qu, M., Chen, D., Zhong, Y., Ren, W., Wang, Y. & Campbell, L.M. 2015. Effect of eutrophication on mercury (Hg) dynamics in subtropical reservoirs from a high Hg deposition ecoregion. *Limnology and Oceanography*, 60: 386–401.

Reist, J.D., Wrona, F.J., Prowse, T.D., Dempson, J.B., Power, M., Köck, G., Carmichael, T.J., Sawatzky, C.D., Lehtonen, H. & Tallman, R.F. 2006. Effects of climate change and UV radiation on fisheries for Arctic freshwater and anadromous species. *Ambio*, 35(7): 407–410.

Rodier, P.M. 1995. Developing brain as a target of toxicity. *Environmental Health Perspectives,* 103(suppl 6): S73–S76.

Roman, H.A., Walsh, T.L., Coull, B.A., Dewailly, E., Guallar, E., Hattis, D., Mariën, K., Schwartz, J., Stren, A.H., Virtanen, J.K. & Rice, G. 2011. Evaluation of the cardiovascular effects of methylmercury exposures: Current evidence supports development of a dose-response function for regulatory benefits analysis. *Environmental Health Perspectives,* 119(5): 607–614.

Schartup, A.T., Thackray, C.P., Qureshi, A., Dassuncao, C., Gillespie, K., Hanke, A. & Sunderland, E.M. 2019. Climate change and overfishing increase neurotoxicant in marine predators. *Nature*, 572(7771): 648–650.

Schuster, P.F., Schaefer, K.M., Aiken, G.R., Antweiler, R.C., Dewild, J.F., Gryziec, J.D., Gusmeroll, A., Hugelius, G., Jafarov, E., Krabbenhoft, D.P., Liu, L., Herman-Mercer, N., Mu, C., Roth, D.A., Schaefer, T., Striegl, R.G., Wickland, K. & Zhang, T. 2018. Permafrost stores a globally significant amount of mercury. *Geophysical Research Letters,* 45(3): 1463–1471.

Selin, N.E. 2011. Science and strategies to reduce mercury risks: A critical review. *Journal of Environmental Monitoring,* 13(9): 2389–2399.

Selin, H., Keane, S. E., Wang, S., Selin, N. E., Davis, K. & Bally, D. 2018. Linking science and policy to support the implementation of the Minamata Convention on mercury. *Ambio*, 47(2): 198 – 215.

Sheehan, M.C., Burke, T.A., Navas-Acien, A., Breysse, P.N., McGready, J. & Fox, M.A. 2014. Global methylmercury exposure from seafood consumption and risk of developmental neurotoxicity: a systematic review. *Bulletin of the World Health Organization*, 92(4): 254–269.

Sheu, G., Gay, D. A., Schmeltz, D., Olson, M., Chang, S., Lin, D. & Nguyen, L. S. P. 2019. A new monitoring effort for Asia: The Asia Pacific Mercury Monitoring Network (APMMN). *Atmosphere,* 10: 481. doi: 10.3390/atmos10090481

St. Pierre, K.A., Zolkos, S., Shakil, S., Tank, S.E., St. Louis, V.L. & Kokelj, S.V. 2018. Unprecedented increases in total and methyl mercury concentrations downstream of retrogressive thaw slumps in the Western Canadian Arctic. *Environmental Science & Technology,* 52(24): 14099–14109.

Stern, G.A., Macdonald, R.W., Outridge, P.M., Wilson, S., Chételat, J., Cole, A., Hintelmannh, H., Loseto, L.L., Steffeng, A., Wang, F. & Zdanowicz, C. 2011. How does climate change influence arctic mercury? *Science of the Total Environment*, 414: 22–42.

Storelli, M.M., Giacominelli-Stuffler, R., Storelli, A., D'Addabbo, R., Palermo, C. & Marcotrigiano, G.O. 2003b. Survey of total mercury and methylmercury levels in edible fish from the Adriatic Sea. *Food Additives and Contaminants*, 20(12): 1114–1119.

Storelli, M.M., Giacominelli-Stuffler, R., Storelli, A. & Marcotrigiano, G.O. 2003a. Total mercury and methylmercury content in edible fish from the Mediterranean Sea. *Journal of Food Protection, 12*(66): 300–303.

Storelli, M.M., Storelli, A., Giacominelli-Stuffler, R. & Marcotrigiano, G.O. 2005. Mercury speciation in the muscle of two commercially important fish, hake (*Merluccius merluccius*) and striped mullet (*Mullus barbatus*) from the Mediterranean Sea: Estimated weekly intake. *Food Chemistry*, 89(2): 295–300.

Streets, D.G., Zhang, Q. & Wu, Y. 2009. Projections of global mercury emissions in 2050. *Environmental Science and Technology*, 43(8): 2983–2988.

Sun, X., Wang, K., Kang, S., Guo, J., Zhang, G., Huang, J., Cong, Z., Sun, S. & Zhang, Q. 2017. The role of melting alpine glaciers in mercury export and transport: An intensive sampling campaign in the Qugaqie Basin, inland Tibetan Plateau. *Environmental Pollution*, 220: 936–945.

Sunderland, E.M. & Mason, R.P. 2007. Human impacts on open ocean mercury concentrations. *Global Biogeochemical Cycles*, 21(4): https://doi.org/10.1029/2006GB002876

Taylor, V.F., Buckman, K.L., Seelen, E.A., Mazrui, N.M., Balcom, P.H., Mason, R.P. & Chen, C.Y. 2019. Organic carbon content drives methylmercury levels in the water column and in estuarine food webs across latitudes in the Northeast United States. *Environmental Pollution*, 246: 639–649.

Trasande, L., DiGangi, J., Evers, D.C., Petrlik, J., Buck, D.G., Šamánek, J., Beeler, B., Turnquist, M.A. & Regan, K. 2016. Economic implications of mercury exposure in the context of the global mercury treaty: Hair mercury levels and estimated lost economic productivity in selected developing countries. *Journal of Environmental Management,* 183: 229–235.

Tsui, M.T., Liu, S., Brasso, R.L., Blum, J.D., Kwon, S.Y., Ulus, Y., Nollet, Y.H., Balogh, S.J., Eggert, S.L. & Finlay, J.C. 2019. Controls of methylmercury bioaccumulation in forest floor food webs. *Environmental Science and Technology*, 53(5): 2434–2440.

UNEP. 2016. *Global review of mercury monitoring networks* Geneva. 1–48 pp. (also available at http://wedocs.unep.org/bitstream/handle/20.500.11822/21059/UNEP%20-%20Global%20Review%20of%20Mercury%20Monitoring%20Networks_Final.pdf?sequence=1&isAllowed=y).

UNEP. 2019. Global mercury assessment 2018. Geneva, UNEP Chemicals and Health Branch. 59 pp. (also available at https://wedocs.unep.org/bitstream/handle/20.500.11822/27579/GMA2018.pdf?sequence=1&isAllowed=y).

Wang, M., Lee, J.S. & Li, Y. 2017. Global proteome profiling of a marine copepod and the mitigating effect of ocean acidification on mercury toxicity after multigenerational exposure. *Environmental Science & Technology*, 51(10): 5820–5831.

Webster, J. P., Kane, T. J., Obrist, D., Ryan, J. N. & Aiken, G. R. 2016. Estimating mercury emission resulting from wildfires in forests of the Western United States. *Science of the Total Environment*, 568: 578 – 586.

Yin, R., Zhang, W., Sun, G., Feng, Z., Hurley, J.P., Yang, L., Shang, L. & Feng, X. 2017. Mercury risk in poultry in the Wanshan mercury mine, China. *Environmental Pollution*, 230: 810–816.

Zhang, H., Feng, X., Larssen, T., Qiu, G. & Vogt, R.D. 2010. In inland China, rice, rather than fish, is the major pathway for methylmercury exposure. *Environmental Health Perspectives,* 188: 11883–11888.

Chapter 2.E: Pesticides

Bebber, D.P., Ramotowski, M.A.T. & Gurr, S.J. 2013. Crop pests and pathogens move polewards in a warming world. *Nature Climate Change,* 3(11): 985–988.

Beres, Z.T., Ernst, E.E., Ackley, B.A., Loux, M.M., Owen, M.D.K. & Snow, A.A. 2018. High levels of glyphosate resistance in *Conyza canadensis* from agricultural and non-agricultural sites in Ohio and Iowa. *Scientific Reports,* 8(1): 10483. https://doi.org/10.1038/s41598-018-28163-w

Blair, A., Ritz, B., Wesseling, C. & Freeman, L.B. 2015. Pesticides and human health. *Occupupational Environmental Medicine,* 72(2): 81–82.

Boxall, A.B., Hardy, A., Beulke, S., Boucard, T., Burgin, L., Falloon, P.D., Haygarth, P.M., Hutchinson, T., Kovats, R.S., Leonardi, G., Levy, L.S., Nichols, G., Parsons, S.A., Potts, L., Stone, D., Topp, E., Turley, D.B., Walsh, K., Wellington, E.M. & Williams, R.J. 2009. Impacts of climate change on indirect human exposure to pathogens and chemicals from agriculture. *Environmental Health Perspectives,* 117(4): 508–514.

Brander, S.M., Gabler, M.K., Fowler, N.L., Connon, R.E. & Schlenk, D. 2016. Pyrethroid pesticides as endocrine disruptors: Molecular mechanisms in vertebrates with a focus on fishes. *Environmental Science & Technology,* 50(17): 8977–8992.

Brodesser, J., Byron, D.H., Cannavan, A., Ferris, I.G., Gross-Helmert, K., Hendrichs, J., Maestroni, B.M., Unsworth, J., Vaagt, G. & Zapata, F. 2006. Pesticides in developing countries and the International Code of Conduct on the distribution and use of pesticides. [online]. [Cited 6 December 2019]. http://www-naweb.iaea.org/nafa/fep/News-AGES-CoC.pdf

Cabrerizo, A., Dachs, J., Barcelo, D. & Jones, K.C. 2013. Climatic and biogeochemical controls on the remobilization and reservoirs of persistent organic pollutants in Antarctica. *Environmental Science & Technology,* 47(9): 4299–4306.

Carson, R. 1962. *The silent spring.* 400 pp. New York, Houghton Miffin.

Carvalho, F.P. 2017. Pesticides, environment, and food safety. *Food and Energy Security,* 6(2): 48–60.

Casado, J., Brigden, K., Santillo, D. & Johnston, P. 2019. Screening of pesticides and veterinary drugs in small streams in the European Union by liquid chromatography high resolution mass spectrometry. *Science of the Total Environment,* 670: 1204–1225.

Ceballos, I., Ruiz, M., Fernandez, C., Pena, R., Rodriguez, A. & Sanders, I.R. 2013. The *in vitro* mass-produced model mycorrhizal fungus, *Rhizophagus irregularis*, significantly increases yields of the globally important food security crop cassava. *PLoS One,* 8(8): e70633 [online]. [Cited 28 November 2019]. https://doi.org/10.1371/journal.pone.0070633

Chakraborty, S., Tiedemann, A.V. & Teng, P.S. 2000. Climate change: potential impact on plant diseases. *Environmental Pollution,* 108(3): 317–326.

Cho, S.J. & McCarl, B.A. 2017. Climate change influences on crop mix shifts in the United States. *Scientific Reports,* 7: 40845. https://doi.org/10.1038/srep40845

Coakley, S.M., Scherm, H. & Chakraborty, S. 1999. Climate change and plant disease management. *Annual Review of Phytopathology,* 37: 399–426.

Cohen, J. 2019. To feed its 1.4 billion, China bets big on genome editing of crops. *Science*. 29 July 2019. doi:10.1126/science.aay8951

Corcellas, C., Feo, M.L., Torres, J.P., Malm, O., Ocampo-Duque, W., Eljarrat, E. & Barcelo, D. 2012. Pyrethroids in human breast milk: occurrence and nursing daily intake estimation. *Environment International,* 47: 17–22.

Damak, M., Mahmoudi, S.R., Hyder, M.N. & Varanasi, K.K. 2016. Enhancing droplet deposition through *in-situ* precipitation. *Nature Communications,* 7: 12560. doi: 10.1038/ncomms12560.

Delcour, I., Spanoghe, P. & Uyttendaele, M. 2015. Literature review: Impact of climate change on pesticide use. *Food Research International,* 68: 7–15.

Deutsch, C.A., Tewksbury, J.J., Tigchelaar, M., Battisti, D.S., Merrill, S.C., Huey, R.B. & Naylor, R.L. 2018. Increase in crop losses to insect pests in a warming climate. *Science,* 361(6405): 916–919.

Di Bartolomeis, M., Kegley, S., Mineau, P., Radford, R. & Klein, K. 2019. An assessment of acute insecticide toxicity loading (AITL) of chemical pesticides used on agricultural land in the United States. *PLoS One,* 14(8): e0220029 [online]. [Cited 10 October 2019]. https://doi.org/10.1371/journal.pone.0220029

Douglas, M. R., Sponsler, D. B., Lonsdorf, E. V & Grozinger, C. M. 2020. County-level analysis reveals a rapidly shifting landscape of insecticide hazard to honey bees (Apis mellifera) on US farmland. *Scientific Reports*, 10: 797. https://doi.org/10.1038/s41598-019-57225-w

Epstein, L. 2014. Fifty years since Silent Spring. *Annual Review of Phytopathology,* 52: 377–402.

Faheem, M., Saeed, S., Sajjad, A., Wang, S. & Ali, A. 2019. Spatio-temporal variations in wheat aphid populations and their natural enemies in four agro-ecological zones of Pakistan. *PLoS One*, 14(9): e0222635 [online]. [Cited 22 November 2019]. https://doi.org/10.1371/journal.pone.0222635

FAO. 2010. International Code of Conduct on the Distribution and Use of Pesticides. Regular monitoring report – 2008. Rome, FAO. 40 pp. (also available at http://www.fao.org/fileadmin/templates/agphome/documents/Pests_Pesticides/Code/CODE_2014Sep_ENG.pdf).

FAO. 2015. *Agroecology for food security and nutrition, Proceedings of the FAO International Symposium*. Rome. (also available at http://www.fao.org/3/a-i4729e.pdf).

FAO. 2019. FAOSTAT. Pesticides Use. [online]. [Cited 6 December 2019]. http://www.fao.org/faostat/en/#data/RP/visualize

FAO. 2020. FAO Locust Watch. Current upsurge (2019-2020). [online]. [Cited 11 February 2020]. http://www.fao.org/ag/locusts/en/info/2094/index.html

FAOSTAT. 2019. Pesticides Use. [online]. [Cited 6 December 2019]. http://www.fao.org/faostat/en/#data/RP/visualize

FAO & ITU. 2018. *E-agriculture in action: Drones for agriculture*. Bangkok, FAO and International Telecommunication Union (ITU). 126 pp. (also available at http://www.fao.org/3/I8494EN/i8494en.pdf).

FAO & WHO. 2014. The International Code of Conduct on Pesticide Management. Rome, FAO. 49 pp. (also available at http://www.fao.org/fileadmin/templates/agphome/documents/Pests_Pesticides/Code/CODE_2014Sep_ENG.pdf).

Feo, M.L., Eljarrat, E., Manaca, M.N., Dobano, C., Barcelo, D., Sunyer, J., Alonso, P.L., Menendez, C. & Grimalt, J.O. 2012. Pyrethroid use – malaria control and individual applications by households for other pests and home garden use. *Environment International,* 38(1): 67–72.

Furlong, M.J. & Zalucki, M.P. 2017. Climate change and biological control: the consequences of increasing temperatures on host-parasitoid interactions. *Current Opinion on Insect Science,* 20: 39–44.

Gallai, N., Salles, J.-M., Settele, J. & Vaissière, B.E. 2009. Economic valuation of the vulnerability of world agriculture confronted with pollinator decline. *Ecological Economics,* 68(3): 810–821.

Ge, L.-Q., Wu, J.-C., Sun, Y.-C., Ouyang, F. & Ge, F. 2013. Effects of triazophos on biochemical substances of transgenic Bt rice and its nontarget pest *Nilaparvata lugens* Stål under elevated CO_2. *Pesticide Biochemistry and Physiology,* 107(2): 188–199.

Gottlieb, D., Qvinn, E., Nega, M., Rapaport, A., Doron, J. & Kostyukovsky, M. 2018. Climate change and its implications on stored food grains. Proceedings of the 12th International Working Conference on Stored Product Protection (IWCSPP), in Berlin, Germany, October 7–11, 2018, pp. 85–89. [online] [Cited 6 December 2019]. https://ojs.openagrar.de/index.php/JKA/article/view/10627

Gould, F., Brown, Z.S. & Kuzma, J. 2018. Wicked evolution: Can we address the sociobiological dilemma of pesticide resistance? *Science,* 360(6390): 728–732.

Hatfield, J.L., Boote, K.J., Kimball, B.A., Ziska, L.H., Izaurralde, R.C., Ort, D., Thomson, A.M. & Wolfe, D. 2011. Climate impacts on agriculture: Implications for crop production. *Agronomy Journal,* 103(2): 351. doi: 10.2134/agronj2010.0303

Hawkins, N.J., Bass, C., Dixon, A. & Neve, P. 2018. The evolutionary origins of pesticide resistance. *Biological Reviews of the Cambridge Philosophical Society,* 94(1): 135–155.

Heap, I. & Duke, S.O. 2018. Overview of glyphosate-resistant weeds worldwide. *Pest Management Science,* 74(5): 1040–1049.

Humann-Guilleminot, S., Binkowski, Ł.J., Jenni, L., Hilke, G., Glauser, G., Helfenstein, F. & Rohr, J. 2019. A nation-wide survey of neonicotinoid insecticides in agricultural land with implications for agri-environment schemes. *Journal of Applied Ecology,* 56(7): 1502–1514.

Jørgensen, P.S., Aktipis, A., Brown, Z., Carrière, Y., Downes, S., Dunn, R.R., Epstein, G., Frisvold, G.B., Hawthorne, D., Gröhn, Y.T., Gujar, G.T., Jasovský, D., Klein, E.Y., Klein,

F., Lhermie, G., Mota-Sanchez, D., Omoto, C., Schlüter, M., Scott, H.M., Wernli, D. & Carroll, S.P. 2018. Antibiotic and pesticide susceptibility and the Anthropocene operating space. *Nature Sustainability*, 1(11): 632–641.

Kim, K.H., Kabir, E. & Jahan, S.A. 2017. Exposure to pesticides and the associated human health effects. *Science of the Total Environment,* 575: 525–535.

Kozak, G.M., Wadsworth, C.B., Kahne, S.C., Bogdanowicz, S.M., Harrison, R.G., Coates, B.S. & Dopman, E.B. 2019. Genomic basis of circannual rhythm in the European corn borer moth. *Current Biology,* 29(20): 3501–3509 e5.

Kumar, A.S., Lakshmanan, V., Caplan, J.L., Powell, D., Czymmek, K.J., Levia, D.F. & Bais, H.P. 2012. Rhizobacteria *Bacillus subtilis* restricts foliar pathogen entry through stomata. *The Plant Journal,* 72(4): 694–706.

Kurenbach, B., Hill, A.M., Godsoe, W., van Hamelsveld, S. & Heinemann, J.A. 2018. Agrichemicals and antibiotics in combination increase antibiotic resistance evolution. *PeerJ,* 6: e5801 [online]. [Cited 17 September 2019]. doi:10.7717/peerj.5801

Lehmann, P., Ammunét, T., Barton, M., Battisti, A., Eigenbrode, S.D., Jepsen, J.U., Kalinkat, G., Neuvonen, S., Niemelä, P., Økland, B., Terblanche, J.S. & Björkman, C. 2018. Complex responses of global insect pests to climate change. *bioRxiv,* doi: 10.1101/425488.

Li, J., Zhu, T., Wang, F., Qiu, X.H. & Lin, W.L. 2006. Observation of organochlorine pesticides in the air of the Mt. Everest region. *Ecotoxicology and Environmental Safety*, 63(1): 33–41.

Licht, T.R. & Bahl, M.I. 2019. Impact of the gut microbiota on chemical risk assessment. *Current Opinion in Toxicology,* 15: 109–113.

Loladze, I. 2014. Hidden shift of the ionome of plants exposed to elevated CO_2 depletes minerals at the base of human nutrition. *eLife,* 3: e02245 [online]. [Cited 10 December 2019]. doi: 10.7554/ELIFE.02245

Lopez, S.B.G., Guimaraes-Ribeiro, V., Rodriguez, J.V.G., Dorand, F., Salles, T.S., Sa-Guimaraes, T.E., Alvarenga, E.S.L., Melo, A.C.A., Almeida, R.V. & Moreira, M.F. 2019. RNAi-based bioinsecticide for Aedes mosquito control. *Scientific Reports*, 9(1): 4038. https://doi.org/10.1038/s41598-019-39666-5

Ma, J., Hung, H., Tian, C. & Kallenborn, R. 2011. Revolatilization of persistent organic pollutants in the Arctic induced by climate change. *Nature Climate Change,* 1(5): 255–260.

Macdonald, R.W., Harner, T. & Fyfe, J. 2005. Recent climate change in the Arctic and its impact on contaminant pathways and interpretation of temporal trend data. *Science of the Total Environment,* 342(1–3): 5–86.

Marasco, R., Rolli, E., Ettoumi, B., Vigani, G., Mapelli, F., Borin, S., Abou-Hadid, A.F., El-Behairy, U.A., Sorlini, C., Cherif, A., Zocchi, G. & Daffonchio, D. 2012. A drought resistance-promoting microbiome is selected by root system under desert farming. *PLoS One*, 7(10): e48479 [online]. [Cited 25 November 2019]. https://doi.org/10.1371/journal.pone.0048479

Matzrafi, M. 2019. Climate change exacerbates pest damage through reduced pesticide efficacy. *Pest Management Science,* 75(1): 9–13.

Miner, K.R., Campbell, S., Gerbi, C., Liljedahl, A., Anderson, T., Perkins, L.B., Bernsen, S., Gatesman, T. & Kreutz, K.J. 2018. Organochlorine pollutants within a polythermal glacier in the interior eastern Alaska range. *Water,* 10(9): 1157. doi: 10.3390/w10091157

Multigner, L., Kadhel, P., Rouget, F., Blanchet, P. & Cordier, S. 2016. Chlordecone exposure and adverse effects in French West Indies populations. *Environmental Science and Pollution Research International,* 23(1): 3–8.

Newman, J.A., Gibson, D.J., Parsons, A.J. & Thornley, J.H.M. 2003. How predictable are aphid population responses to elevated CO_2? *Journal of Animal Ecology,* 72(4): 556–566.

Noyes, P.D., McElwee, M.K., Miller, H.D., Clark, B.W., Van Tiem, L.A., Walcott, K.C., Erwin, K.N. & Levin, E.D. 2009. The toxicology of climate change: environmental contaminants in a warming world. *Environment International,* 35(6): 971–986.

Oerke, E.C. 2006. Crop losses to pests. *Journal of Agricultural Science,* 144(1): 31–43.

Pandi, G.G., Chander, S., Singh, M.P. & Pathak, H. 2018. Impact of elevated CO_2 and temperature on brown planthopper population in rice ecosystem. *Proceedings of the National Academy of Sciences, India Section B: Biological Sciences,* 88(1): 57–64.

Patterson D.T. 1995. Weeds in a changing climate. Weed Science, 43(4): 685–701.

Potapowicz, J., Szuminska, D., Szopinska, M. & Polkowska, Z. 2019. The influence of global climate change on the environmental fate of anthropogenic pollution released from the permafrost: Part I. Case study of Antarctica. *Science of the Total Environment,* 651(1): 1534–1548.

Pretty, J. & Bharucha, Z.P. 2015. Integrated pest management for sustainable intensification of agriculture in Asia and Africa. *Insects*, 6(1): 152–182.

Pugliese, M. & Gullino M.L. 2011. Effect of climate change on infection of grapevine by downy and powdery mildew under controlled environment. *Communications in Agricultural and Applied Biological Sciences,* 76(4): 579–582.

Ramesh, K., Matloob, A., Aslam, F., Florentine, S.K. & Chauhan, B.S. 2017. Weeds in a changing climate: Vulnerabilities, consequences, and implications for future weed management. *Frontiers in Plant Science,* 8: 95. (also available at https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5303747/).

Reboud, X., Eychenne, N., Délos, M. & Folcher, L. 2016. Withdrawal of maize protection by herbicides and insecticides increases mycotoxins contamination near maximum thresholds. *Agronomy for Sustainable Development,* 36(3). https://doi.org/10.1007/s13593-016-0376-8.

Rodenburg, J., Meinke, H. & Johnson, D.E. 2011. Challenges for weed management in African rice systems in a changing climate. *Journal of Agricultural Science*, 149(4): 427–435.

Rodríguez-Eugenio, N., McLaughlin, M. & Pennock, D. 2018. Soil pollution: a hidden reality. Rome, FAO. 142 pp. (also available at http://www.fao.org/3/I9183EN/i9183en.pdf).

Roos, J., Hopkins, R., Kvarnheden, A. & Dixelius, C. 2010. The impact of global warming on plant diseases and insect vectors in Sweden. *European Journal of Plant Pathology,* 129(1): 9–19.

Ruiz, I.B. 2019. Riesling wine, holding out between pesticides and climate change. *Deutsche Welle*, 27 May 2019. [online]. [Cited 6 December 2019]. https://www.dw.com/en/riesling-wine-holding-out-between-pesticides-and-climate-change/a-48748575.

Sabarwal, A., Kumar, K. & Singh, R.P. 2018. Hazardous effects of chemical pesticides on human health – cancer and other associated disorders. *Environmental Toxicology and Pharmacology,* 63: 103–114.

Sagiv, S.K., Bruno, J.L., Baker, J.M., Palzes, V., Kogut, K., Rauch, S., Gunier, R., Mora, A.M., Reiss, A.L. & Eskenazi, B. 2019. Prenatal exposure to organophosphate pesticides and functional neuroimaging in adolescents living in proximity to pesticide application. *Proceedings of the National Academy of Sciences of the USA*, 116(37): 18347–18356.

Saravanakumar, D., Muthumeena, K., Lavanya, N., Suresh, S., Rajendran, L., Raguchander, T. & Samiyappan, R. 2007. Pseudomonas-induced defence molecules in rice plants against leaffolder (*Cnaphalocrocis medinalis*) pest. *Pest Management Science,* 63(7): 714–721.

Schreinemachers, P. & Tipraqsa, P. 2012. Agricultural pesticides and land use intensification in high, middle and low income countries. *Food Policy,* 37(6): 616–626.

Sereda, B., Bouwman, H. & Kylin, H. 2009. Comparing water, bovine milk, and indoor residual spraying as possible sources of DDT and pyrethroid residues in breast milk. *Journal of Toxicology and Environmental Health, Part A*, 72(13): 842–851.

Shardlow, M. 2017. *Neonicotinoid insecticides in British freshwaters. 2016 Water Framework Directive Watch List Monitoring Results and Recommendations* [online]. [Cited 6 December 2019]. https://cdn.buglife.org.uk/2019/10/QA-Neonicotinoids-in-water-in-the-UK-final-2-NI.pdf.

Shew, A.M., Durand-Morat, A., Nalley, L.L., Zhou, X.G., Rojas, C. & Thoma, G. 2019. Warming increases bacterial panicle blight (*Burkholderia glumae*) occurrences and impacts on USA rice production. *PLoS One,* 14(7): e0219199 [online]. [Cited 5 August 2019]. https://doi.org/10.1371/journal.pone.0219199

Smith, M.R. & Myers, S.S. 2018. Impact of anthropogenic CO_2 emissions on global human nutrition. *Nature Climate Change*, 8(9): 834–839.

Stokstad, E. 2018. A new leaf. *Science*, 362(6411): 144–147.

Swevers, L. & Smagghe, G. 2012. Use of RNAi for control of insect crop pests, *In* Smagghe, G. and Diaz, I., eds. *Arthropod–plant interactions: Novel insights and approaches for applied IPM,* pp. 177–197. Dordrecht, Heidelberg, New York and London, Springer

Taylor, R., Herms, D., Cardina, J. & Moore, R. 2018. Climate change and pest management: Unanticipated consequences of trophic dislocation. Agronomy, 8(1): 7. doi: 10.3390/agronomy8010007.

Taylor, R.A., Ryan, S.J., Lippi, C.A., Hall, D.G., Narouei-Khandan, H.A., Rohr, J.R., Johnson, L.R. & Flory, L. 2019. Predicting the fundamental thermal niche of crop pests and diseases in a changing world: A case study on citrus greening. *Journal of Applied Ecology*, doi: 10.1111/1365-2664.13455.

Vogel, E., Santos, D., Mingels, L., Verdonckt, T.W. & Broeck, J.V. 2018. RNA interference in insects: Protecting beneficials and controlling pests. *Frontiers in Physiology,* 9: 1912. doi: 10.3389/fphys.2018.01912.

Walsh, M.J. & Powles, S.B. 2014. Management of herbicide resistance in wheat cropping systems: learning from the Australian experience. *Pest Management Science*, 70(9): 1324–1328.

Wang, C., Hawthorne, D., Qin, Y., Pan, X., Li, Z. & Zhu, S. 2017. Impact of climate and host availability on future distribution of Colorado potato beetle. *Scientific Reports,* 7(1): 4489. doi: 10.1038/s41598-017-04607-7.

Yamamuro, M., Komuro, T., Kamiya, H., Kato, T., Hasegawa, H. & Kameda, Y. 2019. Neonicotinoids disrupt aquatic food webs and decrease fishery yields. *Science*, 366(6465): 620–623.

Yuan, X., Pan, Z., Jin, C., Ni, Y., Fu, Z. & Jin, Y. 2019. Gut microbiota: An underestimated and unintended recipient for pesticide-induced toxicity. *Chemosphere,* 227: 425–434.

Zhang, Y.W., McCarl, B.A., Luan, Y. & Kleinwechter, U. 2017. Climate change effects on pesticide usage reduction efforts: a case study in China. *Mitigation and Adaptation Strategies for Global Change*, 23(5): 685–701.

Zhu, C., Kobayashi, K., Loladze, I., Zhu, J., Jiang, Q., Xu, X., Liu, G., Seneweera, S., Ebi, K.L., Drewnowski, A., Fukagawa, N.K. & Ziska, L.H. 2018. Carbon dioxide (CO_2) levels this century will alter the protein, micronutrients, and vitamin content of rice grains with potential health consequences for the poorest rice-dependent countries. *Science Advances*, 4(5): eaaq1012. doi:10.1126/sciadv.aaq1012

Chapter 2.F: Mycotoxins

Achaglinkame, M.A., Opoku, N. & Amagloh, F.K. 2017. Aflatoxin contamination in cereals and legumes to reconsider usage as complementary food ingredients for Ghanaian infants: A review. *Journal of Nutrition and Intermediary Metabolism,* 10: 1–7.

Alassane-Kpembi, I., Schatzmayr, G., Taranu, I., Marin, D., Puel, O. & Oswald, I.P. 2017. Mycotoxins co-contamination: Methodological aspects and biological relevance of combined toxicity studies. *Critical Reviews in Food Science and Nutrition,* 57(16): 3489-3507.

Alshannaq, A. & Yu, J.H. 2017. Occurrence, toxicity, and analysis of major mycotoxins in food. *International Journal of Environmental Research and Public Health,* 14(6). doi: 10.3390/ijerph14060632.

Assunção, R., Silva, M.J. & Alvito, P. 2016. Challenges in risk assessment of multiple mycotoxins in food. *World Mycotoxin Journal,* 9(5): 791–811.

Avantaggiato, G., Quaranta, F., Desiderio, E. & Visconti, A. 2003. Fumonisin contamination of maize hybrids visibly damaged by Sesamia. *Journal of the Science of Food and Agriculture,* 83(1): 13–18.

Balbus, J.M., Boxall, A.B., Fenske, R.A., McKone, T.E. & Zeise, L. 2013. Implications of global climate change for the assessment and management of human health risks of chemicals in the natural environment. *Environmental Toxicology and Chemistry,* 32(1): 62–78.

Battilani, P., Toscano, P., Van der Fels-Klerx, H.J., Moretti, A., Camardo Leggieri, M., Brera, C., Rortais, A., Goumperis, T. & Robinson, T. 2016. Aflatoxin B1 contamination in maize in Europe increases due to climate change. *Scientific Reports,* 6: 24328. https://doi.org/10.1038/srep24328

Bebber, D.P. 2015. Range-expanding pests and pathogens in a warming world. *Annual Review of Phytopatholy,* 53: 335–356.

Bencze, S., Puskas, K., Vida, G., Karsai, I., Balla, K., Komaromi, J. & Veisz, O. 2017. Rising atmospheric CO_2 concentration may imply higher risk of *Fusarium mycotoxin* contamination of wheat grains. *Mycotoxin Research,* 33(3): 229–236.

Bennett, J.W. & Klich, M. 2003. Mycotoxins. *Clinical Microbiology Reviews,* 16(3): 497–516.

Berthiller, F., Crews, C., Dall'Asta, C., Saeger, S.D., Haesaert, G., Karlovsky, P., Oswald, I.P., Seefelder, W., Speijers, G. & Stroka, J. 2013. Masked mycotoxins: a review. *Molecular Nutrition & Food Research,* 57(1): 165–186.

Bhatnagar-Mathur, P., Sunkara, S., Bhatnagar-Panwar, M., Waliyar, F. & Sharma, K.K. 2015. Biotechnological advances for combating *Aspergillus flavus* and aflatoxin contamination in crops. *Plant Science,* 234: 119–132.

Bullerman, L.B. & Bianchini, A. 2007. Stability of mycotoxins during food processing. *International Journal of Food Microbiology,* 119(1-2): 140–146.

Cappelle, K.M., Munkvold, G.P. & Wolt, J.D. 2019. Meta-effect of insect resistant maize on fumonisin B1 in grain estimated by variance-weighted and replication-weighted analyses. *World Mycotoxin Journal,* 12(2): 141–151.

Carbone, I., Jakobek, J.L., Ramirez-Prado, J.H. & Horn, B.W. 2007. Recombination, balancing selection and adaptive evolution in the aflatoxin gene cluster of *Aspergillus parasiticus. Molecular Ecology,* 16(20): 44014417.

CAST. 2003. *Mycotoxins: Risks in plant, animal, and human systems.* Report No. 139. Council for Agricultural Science and Technology, Ames, Iowa, United States of America. https://www.international-food-safety.com/pdf/Mycotoxins%20-%20Risks%20in%20Plant,%20Animals%20and%20Human%20Systems.pdf

Chauhan, Y., Tatnell, J., Krosch, S., Karanja, J., Gnonlonfin, B., Wanjuki, I., Wainaina, J. & Harvey, J. 2015. An improved simulation model to predict pre-harvest aflatoxin risk in maize. *Field Crops Research,* 178: 91–99.

Chen, C., Mitchell, N.J., Gratz, J., Houpt, E.R., Gong, Y., Egner, P.A., Groopman, J.D., Riley, R.T., Showker, J.L., Svensen, E., Mduma, E.R., Patil, C.L. & Wu F. 2018. Exposure to aflatoxin and fumonisin in children at risk for growth impairment in rural Tanzania. *Environment International,* 115: 29–37.

Chen, C., Riley, R.T. & Wu, F. 2018. Dietary fumonisin and growth impairment in children and animals: A review. *Comprehensive Reviews in Food Science and Food Safety,* 17(6): 1448–1464.

Chulze, S.N. 2010. Strategies to reduce mycotoxin levels in maize during storage: a review. *Food Additives & Contaminants: Part A: Chemistry, Analysis, Control, Exposure & Risk Assessment,* 27(5): 651–657.

Dall'Erta, A., Cirlini, M., Dall'Asta, M., Del Rio, D., Galaverna, G. & Dall'Asta, C. 2013. Masked mycotoxins are efficiently hydrolyzed by human colonic microbiota releasing their aglycones. *Chemical Research in Toxicology,* 26(3): 305–312.

Dobolyi, C., Sebők, F., Varga, J., Kocsubé, S., Szigeti, G., Baranyi, N., Szécsi, Á., Tóth, B., Varga, M., Kriszt, B., Szoboszlay, S., Krifaton, C. & Kukolya, J. 2013. Occurrence of aflatoxin producing *Aspergillus flavusisolates* in maize kernel in Hungary. *Acta Alimentaria,* 42(3): 451–459.

FAO. 2004. *Worldwide regulations for mycotoxins in food and feed in 2003.* FAO Food and Nutrition Paper No. 81. Rome, FAO. 165 pp. (also available at http://www.fao.org/3/y5499e/y5499e00.htm).

FAO & WHO. 2016. *Evaluation of certain contaminants in food. Eighty-third report of the Joint FAO/WHO Expert Committee on Food Additives*. Rome, FAO. 182 pp. (also available at https://apps.who.int/iris/handle/10665/254893).

FDA. 2018. *Guidance for industry: Evaluating the safety of flood-affected food crops for human consumption.* United States Food and Drug Administration (FDA). [online] https://www.fda.gov/regulatory-information/search-fda-guidance-documents/guidance-industry-evaluating-safety-flood-affected-food-crops-human-consumption

Freire, L. & Sant'Ana, A.S. 2018. Modified mycotoxins: An updated review on their formation, detection, occurrence, and toxic effects. *Food and Chemical Toxicology,* 111: 189–205.

Garcia, D., Ramos, A.J., Sanchis, V. & Marin, S. 2009. Predicting mycotoxins in foods: a review. *Food Microbiology,* 26(8): 757–769.

Giorni, P., Magan, N., Pietri, A., Bertuzzi, T. & Battilani, P. 2007. Studies on *Aspergillus* section Flavi isolated from maize in northern Italy. *International Journal of Food Microbiology,* 113(3): 330–338.

Gonçalves, R.A., Schatzmayr, D., Hofstetter, U. & Santos, G.A. 2017. Occurrence of mycotoxins in aquaculture: preliminary overview of Asian and European plant ingredients and finished feeds. *World Mycotoxin Journal,* 10(2): 183–194.

Gonzalez Pereyra, M.L., Martinez, M.P. & Cavaglieri, L.R. 2019. Presence of aiiA homologue genes encoding for N-Acyl homoserine lactone-degrading enzyme in aflatoxin B1-decontaminating *Bacillus* strains with potential use as feed additives. *Food and Chemical Toxicology,* 124: 316–323.

Gratz, S.W., Currie, V., Richardson, A.J., Duncan, G., Holtrop, G., Farquharson, F., Louis, P., Pinton, P. & Oswald, I.P. 2018. Porcine small and large intestinal microbiota rapidly hydrolyze the masked mycotoxin deoxynivalenol-3-glucoside and release deoxynivalenol in spiked batch cultures *in vitro. Applied and Environmental Microbiology,* 84(2). doi: 10.1128/AEM.02106-1.

Gratz, S.W., Duncan, G. & Richardson, A.J. 2013. The human fecal microbiota metabolizes deoxynivalenol and deoxynivalenol-3-glucoside and may be responsible for urinary deepoxy-deoxynivalenol. *Applied and Environmental Microbiology,* 79(6): 1821–1825.

Gruber-Dorninger, C., Jenkins, T. & Schatzmayr, G. 2019. Global mycotoxin occurrence in feed: A ten-year survey. *Toxins (Basel),* 11(7). doi: 10.3390/toxins11070375.

Hooker, D.C., Schaafsma, A.W. & Tamburic-Ilincic, L. 2002. Using weather variables pre- and post-heading to predict deoxynivalenol content in winter wheat. *Plant Disease,* 86(6): 611–619.

Humpf, H.U., Rychlik, M. & Cramer, B. 2019. Modified mycotoxins: A new challenge? *In* Melton, L., Feriedoon, S. and Vareli, P., eds. *Encylopedia of food chemistry*, volume 1, pp. 393-400. Amsterdam, Netherlands, Elsevier.

IARC. 2012a. *Chemical agents and related occupations. A review of human carcinogens.* IARC Monographs Volume 100 F. 628 pp. Lyon, France, International Agency for Research on Cancer (IARC). (also available at https://monographs.iarc.fr/wp-content/uploads/2018/06/mono100F.pdf).

IARC. 2012b. *Improving public health through mycotoxin control.* IARC Scientific Publication No. 158. Lyon, France, IARC. 168 pp. (also available at https://publications.iarc.fr/Book-And-Report-Series/Iarc-Scientific-Publications/Improving-Public-Health-Through-Mycotoxin-Control-2012).

IARC. 2015. *Mycotoxin control in low- and middle- income countries.* IARC Working Group Report No. 9. Lyon, France. 66 pp. (also available at https://publications.iarc.fr/Book-And-Report-Series/Iarc-Working-Group-Reports/Mycotoxin-Control-In-Low--And-Middle-income-Countries-2015).

Jajic, I., Dudas, T., Krstovic, S., Krska, R., Sulyok, M., Bagi, F., Savic, Z., Guljas, D. & Stankov, A. 2019. Emerging fusarium mycotoxins fusaproliferin, beauvericin, enniatins, and moniliformin in Serbian maize. *Toxins (Basel),* 11(6): 35. doi: 10.3390/toxins11060357.

Jestoi, M. 2008. Emerging fusarium-mycotoxins fusaproliferin, beauvericin, enniatins, and moniliformin: a review. *Critical Review in Food Science and Nutrition,* 48(1): 21–49.

Kebede, H., Abbas, H.K., Fisher, D.K. & Bellaloui, N. 2012. Relationship between aflatoxin contamination and physiological responses of corn plants under drought and heat stress. *Toxins (Basel),* 4(11): 1385–1403.

Khoury, C.K., Bjorkman, A.D., Dempewolf, H., Ramirez-Villegas, J., Guarino, L., Jarvis, A., Rieseberg, L.H. & Struik, P.C. 2014. Increasing homogeneity in global food supplies and the implications for food security. *Proceedings of the National Academy of Sciences of the USA,* 111(11): 4001–4006.

Kos, J., Janic Hajnal, E., Saric, B., Jovanov, P., Mandic, A., Duragic, O. & Kokic, B. 2018. Aflatoxins in maize harvested in the Republic of Serbia over the period 2012–2016. *Food Additives & Contaminants: Part B Surveillance,* 11(4): 246–255.

Kovalsky, P., Kos, G., Nahrer, K., Schwab, C., Jenkins, T., Schatzmayr, G., Sulyok, M. & Krska, R. 2016. Co-occurrence of regulated, masked and emerging mycotoxins and secondary metabolites in finished feed and maize – an extensive survey. *Toxins (Basel),* 8(12). doi: 10.3390/toxins8120363.

Lee, H.J. & Ryu, D. 2017. Worldwide occurrence of mycotoxins in cereals and cereal-derived food products: Public health perspectives of their co-occurrence. *Journal of Agricultural and Food Chemistry,* 65(33): 7034–7051.

Liu, Y. & Wu, F. 2010. Global burden of aflatoxin-induced hepatocellular carcinoma: a risk assessment. *Environmental Health Perspectives,* 118(6): 818–824.

Luo, S., Terciolo, C., Bracarense, A., Payros, D., Pinton, P. & Oswald, I.P. 2019. *In vitro* and *in vivo* effects of a mycotoxin, deoxynivalenol, and a trace metal, cadmium, alone or in a mixture on the intestinal barrier. *Environment International,* 132: 105082. doi: 10.1016/j.envint.2019.105082.

Medina, A., Akbar, A., Baazeem, A., Rodriguez, A. & Magan, N. 2017. Climate change, food security and mycotoxins: Do we know enough? *Fungal Biology Reviews,* 31(3): 143–154.

Miller, J.D. 1995. Fungi and mycotoxins in grain: Implications for stored product research. *Journal of Stored Products Research,* 31(1): 1–16.

Miller, J.D. 2016a. Changing patterns of fungal toxins in crops: Challenges for analysts. *Journal of AOAC International,* 99(4): 837–841.

Miller, J.D. 2016b. Mycotoxins in food and feed: A challenge for the twenty-first century. *In* Li, D.-W., ed. *Biology of microfungi,* pp. 469–493. Cham, Switzerland, Springer International.

Misihairabgwi, J.M., Ezekiel, C.N., Sulyok, M., Shephard, G.S. & Krska, R. 2019. Mycotoxin contamination of foods in Southern Africa: A 10-year review (2007–2016). *Critical Review of Food Science and Nutrition,* 59(1): 43–58.

Mitchell, N.J., Bowers, E., Hurburgh, C. & Wu, F. 2016. Potential economic losses to the USA corn industry from aflatoxin contamination. *Food Additives and Contaminants: Part A: Chemistry, Analysis, Control, Exposure & Risk Assessment,* 33(3): 540–550.

Moore, G.G. 2014. Sex and recombination in aflatoxigenic Aspergilli: global implications. *Frontiers in Microbiology,* 5: 32. https://doi.org/10.3389/fmicb.2014.00032

Moore, G.G., Singh, R., Horn, B.W. & Carbone, I. 2009. Recombination and lineage-specific gene loss in the aflatoxin gene cluster of *Aspergillus flavus*. Molecular Ecology, 18(23): 4870-4887.

Moretti, A., Pascale, M. & Logrieco, A.F. 2019. Mycotoxin risks under a climate change scenario in Europe. *Trends in Food Science and Technology,* 84: 38–40.

Pandey, M.K., Kumar, R., Pandey, A.K., Soni, P., Gangurde, S.S., Sudini, H.K., Fountain, J.C., Liao, B., Desmae, H., Okori, P., Chen, X., Jiang, H., Mendu, V., Falalou, H., Njoroge, S., Mwololo, J., Guo, B., Zhuang, W., Wang, X., Liang, X. & Varshney, R.K. 2019. Mitigating aflatoxin contamination in groundnut through a combination of genetic resistance and post-harvest management practices. *Toxins (Basel),* 11(6). doi: 10.3390/toxins11060315.

Paterson, R.R. & Lima, N. 2017. Thermophilic fungi to dominate aflatoxigenic/mycotoxigenic fungi on food under global warming. *International Journal of Environmental Reseach and Public Health*, 14(2). doi: 10.3390/ijerph14020199.

Patriarca, A. & Pinto, V.F. 2017. Prevalence of mycotoxins in foods and decontamination. *Current Opinion in Food Science,* 14: 50–60.

Pellegrino, E., Bedini, S., Nuti, M. & Ercoli, L. 2018. Impact of genetically engineered maize on agronomic, environmental and toxicological traits: a meta-analysis of 21 years of field data. *Sci. Rep.,* 8(1): 3113. (also available at https://www.nature.com/articles/s41598-018-21284-2.pdf).

Pitt, J.I. & Miller, J.D. 2017. A concise history of mycotoxin research. *Journal of Agricultural and Food Chemistry,* 65(33): 7021–7033.

Ramirez-Cabral, N.Y.Z., Kumar, L. & Shabani, F. 2017. Global alterations in areas of suitability for maize production from climate change and using a mechanistic species distribution model (CLIMEX). *Scientific Reports,* 7(1): 5910. doi: 10.1038/s41598-017-05804-0.

RASFF. 2018. *The Rapid Alert System for Food and Feed. 2018 annual report.* Luxembourg. 53 pp. (also available at https://ec.europa.eu/food/sites/food/files/safety/docs/rasff_annual_report_2018.pdf).

Reboud, X., Eychenne, N., Délos, M. & Folcher, L. 2016. Withdrawal of maize protection by herbicides and insecticides increases mycotoxins contamination near maximum thresholds. *Agronomy for Sustainable Development,* 36(3). doi: 10.1007/s13593-016-0376-8.

Rembold, F., Hodges, R., Bernard, M., Knipschild, H. & Olivier L. 2011. The African Postharvest Losses Information System (APHLIS). Luxembourg, Publications Office of the European Union. (also available at http://publications.jrc.ec.europa.eu/repository/handle/JRC62618).

Rembold, F., Meroni, M., Urbano, F., Csak, G., Kerdiles, H., Perez-Hoyos, A., Lemoine, G., Leo, O. & Negre, T. 2019. ASAP: A new global early warning system to detect anomaly hot spots of agricultural production for food security analysis. *Agricultural Systems,* 1 68: 247–257.

Rychlik, M., Humpf, H.U., Marko, D., Danicke, S., Mally, A., Berthiller, F., Klaffke, H. & Lorenz, N. 2014. Proposal of a comprehensive definition of modified and other forms of mycotoxins including "masked" mycotoxins. *Mycotoxin Research,* 30(4): 197–205.

Schatzmayr, G. & Streit, E. 2013. Global occurrence of mycotoxins in the food and feed chain: facts and figures. *World Mycotoxin Journal,* 6(3): 213–222.

Smith, M.C., Madec, S., Coton, E. & Hymery, N. 2016. Natural co-occurrence of mycotoxins in foods and feeds and their *in vitro* combined toxicological effects. *Toxins (Basel),* 8(4): 94. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4848621/.

Udomkun, P., Wiredu, A.N., Nagle, M., Muller, J., Vanlauwe, B. & Bandyopadhyay, R. 2017. Innovative technologies to manage aflatoxins in foods and feeds and the profitability of application – A review. *Food Control,* 76: 127–138.

UNEP. 2016. *UNEP frontiers 2016 report. Emerging issues of environmental concern.* Nairobi. 76 pp. (also available at https://wedocs.unep.org/bitstream/handle/20.500.11822/7664/Frontiers_2016.pdf?sequence=1&isAllowed=y).

van der Fels-Klerx, H.J., Olesen, J.E., Madsen, M.S. & Goedhart, P.W. 2012. Climate change increases deoxynivalenol contamination of wheat in north-western Europe. *Food Additives and Contaminants: Part A: Chemistry, Analysis, Control, Exposure & Risk Assessment*, 29(10): 1593–1604.

Vary, Z., Mullins, E., McElwain, J.C. & Doohan, F.M. 2015. The severity of wheat diseases increases when plants and pathogens are acclimatized to elevated carbon dioxide. *Global Change Biology,* 21(7): 2661–2669.

Vaughan, M.M., Huffaker, A., Schmelz, E.A., Dafoe, N.J., Christensen, S., Sims, J., Martins, V.F., Swerbilow, J., Romero, M., Alborn, H.T., Allen, L.H. & Teal, P.E. 2014. Effects of elevated CO_2 on maize defence against mycotoxigenic *Fusarium verticillioides. Plant, Cell & Environment*, 37(12): 2691–2706.

Vermeulen, S.J., Campbell, B.M. & Ingram, J.S.I. 2012. Climate change and food systems. *Annual Review of Environment and Resources,* 37(1): 195–222.

Vidal, A., Claeys, L., Mengelers, M., Vanhoorne, V., Vervaet, C., Huybrechts, B., De Saeger, S. & De Boevre, M. 2018. Humans significantly metabolize and excrete the mycotoxin deoxynivalenol and its modified form deoxynivalenol-3-glucoside within 24 hours. *Scientific Reports,* 8(1): 5255. https://doi.org/10.1038/s41598-018-23526-9

Watson, S., Chen, G., Sylla, A., Routledge, M.N. & Gong, Y.Y. 2016. Dietary exposure to aflatoxin and micronutrient status among young children from Guinea. *Molecular Nutrition & Food Research,* 60(3): 511518.

Watson, S., Moore, S.E., Darboe, M.K., Chen, G., Tu, Y.K., Huang, Y.T., Eriksen, K.G., Bernstein, R.M., Prentice, A.M., Wild, C.P., Xu, Y., Routledge, M.N. & Gong, Y.Y. 2018. Impaired growth in rural Gambian infants exposed to aflatoxin: a prospective cohort study. *BMC Public Health*, 18(1): 1247. https://doi.org/10.1186/s12889-018-6164-4

WHO. 2015. *WHO estimates of the global burden of foodborne diseases. Foodborne disease burden epidemiology reference group 2007–2015.* Geneva. 265 pp. (also available at https://apps.who.int/iris/bitstream/handle/10665/199350/9789241565165_eng.pdf;jsessionid=74E8A2A4D12B925ADDB489117F397B88?sequence=1).

Willis, K.J. (ed.). 2018. *State of the world's fungi 2018*. Report. London, Royal Botanic Gardens, Kew. 92 pp. (also available at https://stateoftheworldsfungi.org/).

Wilson, W., Dahl, B. & Nganje, W. 2018. Economic costs of fusarium head blight, scab and deoxynivalenol. *World Mycotoxin Journal,* 11(2): 291–302.

Wu, F. 2006. Mycotoxin reduction in Bt corn: potential economic, health, and regulatory impacts. *Transgenic Research,* 15(3): 277–289.

Wu, F. 2015. Global impacts of aflatoxin in maize: trade and human health. *World Mycotoxin Journal,* 8(2): 137–142.

Yang, X., Liu, W., Lin, H., Zeng, H., Zhang, R., Pu, C., Wang, L., Zheng, C., Tan, Y., Luo, Y., Feng, X., Tian, Y., Xiao, G., Wang, J., Huang, Y., Luo, J., Qiu, Z., Chen, J.A., Wu, L., He, L. & Shu, W. 2017. Interaction effects of AFB1 and MC-LR co-exposure with polymorphism of metabolic genes on liver damage: focusing on SLCO1B1 and GSTP1. *Scientific Reports,* 7(1): 16164. https://doi.org/10.1038/s41598-017-16432-z

Zhang, X. & Cai, X. 2011. Climate change impacts on global agricultural land availability. *Environmental Research Letters,* 6(1): 014014.

Chapter 3: Emerging issues and intelligence gathering

Al-Kodmany, K. 2018. The vertical farm: A review of developments and implications for the vertical city. *Buildings,* 8(2): 24. https://doi.org/10.3390/buildings8020024

Allen, S., Allen, D., Phoenix, V.R., Le Roux, G., Durántez Jiménez, P., Simonneau, A., Binet, S. & Galop, D. 2019. Atmospheric transport and deposition of microplastics in a remote mountain catchment. *Nature Geoscience*, 12(5): 339–344.

Ambrosini, R., Azzoni, R.S., Pittino, F., Diolaiuti, G., Franzetti, A. & Parolini, M. 2019. First evidence of microplastic contamination in the supraglacial debris of an alpine glacier. *Environmental Pollution,* 253: 297–301.

Arshad, M.S., Javed, M., Sohaib, M., Saeed, F., Imran, A., Amjad, Z. & Yildiz, F. 2017. Tissue engineering approaches to develop cultured meat from cells: A mini review. *Cogent Food and Agriculture,* 3(1). doi: 10.1080/23311932.2017.1320814.

Barboza, L. G., Vieira, L. R., Branco, V., Carvalho, C & Guilhermino, L. 2018. Microplastics increase mercury bioconcentration in gills and bioaccumulation in the liver, and cause oxidative stress and damage in *Dicentrarchus labrax* juveniles. *Scientific Reports*, 8: 15655. doi: 10.1038/s41598-018-34125-z

Cardoso, P., Barton, P.S., Birkhofer, K., Chichorro, F., Deacon, C., Fartmann, T., Fukushima, C.S., Gaigher, R., Habel, J.C.,Hallmann, C.A., Hill, M.J., Hochkirch, A., Kwak, M.L., Mammola, S., Noriega, J.A., Orfinger, A.B., Pedraza, F., Pryke, J.S., Roque, F.O., Settele, J., Simaike, J.P., Stork, N.E., Suhling, F., Vorster, C. & Samways, M.J. 2020. Scientists'warning to humanity on insect extinctions. *Biological Conservation*. 108426. doi: 10.1016/j.biocon.2020.108426

Carrington, D. 2019. Microplastic pollution revealed "absolutely everywhere" by new research. *The Guardian*. 7 March 2019. (also available at https://www.theguardian.com/environment/2019/mar/07/microplastic-pollution-revealed-absolutely-everywhere-by-new-research).

Chang, Y., Iakovou, E. & Shi, W. 2019. Blockchain in global supply chains and cross border trade: a critical synthesis of the state-of-the-art, challenges and opportunities. *International Journal of Production Research,* 1–18. doi: 10.1080/00207543.2019.1651946

Choy, C.A., Robison, B.H., Gagne, T.O., Erwin, B., Firl, E., Halden, R.U., Hamilton, J.A., Katija, K., Lisin, S.E., Rolsky, C. & K, S.V.H. 2019. The vertical distribution and biological transport of marine microplastics across the epipelagic and mesopelagic water column. *Scientific Reports,* 9(1): 7843. doi: 10.1038/s41598-019-44117-2

Costa, K.M., McManus, J.F., Anderson, R.F., Ren, H., Sigman, D.M., Winckler, G., Fleisher, M.Q., Marcantonio, F. & Ravelo, A.C. 2016. No iron fertilization in the equatorial Pacific Ocean during the last ice age. *Nature*, 529(7587): 519–522.

Dobermann, D., Swift, J.A. & Field, L.M. 2017. Opportunities and hurdles of edible insects for food and feed. *Nutrition Bulletin*, 42(4): 293–308.

EFSA. 2015. Risk profile related to production and consumption of insects as food and feed. *EFSA Journal* 13: 4257. doi: 10.2903/j.efsa.2015.4257

FAO. 2013. *Edible insects. Future prospects for food and feed security.* Rome, FAO. FAO Forestry Paper No. 171. 201 pp. (also available at http://www.fao.org/3/i3253e/i3253e.pdf).

FAO. 2015. *Enhancing early warning capabilities and capacities for food safety. Training handbook*, first edition. Rome. 105 pp. (also available at http://www.fao.org/3/a-i5168e.pdf).

FAO. 2017a. *The future of food and agriculture. Trends and challenges*. Rome. 180 pp. (also available at http://www.fao.org/3/a-i6583e.pdf).

FAO. 2017b. *Microplastics in fisheries and aquaculture*. Rome. 147 pp. (also available at http://www.fao.org/3/a-i7677e.pdf).

FAO. 2018. *The future of food and agriculture. Alternative pathways to 2050*. Rome. 228 pp. (also available at http://www.fao.org/3/I8429EN/i8429en.pdf).

França, F.M., Ferreira, J., Vaz-de-Mello, F.Z., Maia, L.F., Berenguer, E., Palmeira, A.F., Fadini, R., Louzada, J., Braga, R., Oliveira, V.H. & Barlow, J. 2020. El Niño impacts on human-modified tropical forests: consequences for dung beetle diversity and associated ecological process. *bioTropica*, doi: 10.1111/btp.12756

Geyer, R., Jambeck, J.R. & Law, K.L. 2017. Production, use, and fate of all plastics ever made. *Science Advances,* 3(7): e1700782 [online]. [Cited 4 October 2019]. doi: 10.1126/sciadv.1700782

Hallmann, C.A., Sorg, M., Jongejans, E., Siepel, H., Hofland, N., Schwan, H., Stenmans, W., Muller, A., Sumser, H., Horren, T., Goulson, D. & de Kroon, H. 2017. More than 75 percent decline over 27 years in total flying insect biomass in protected areas. *PLoS One,* 12(10): e0185809 [online]. [Cited 17 August 2019]. https://doi.org/10.1371/journal.pone.0185809

Henry, B., Laitala, K. & Klepp, I.G. 2019. Microfibres from apparel and home textiles: Prospects for including microplastics in environmental sustainability assessment. *Science of the Total Environment,* 652: 483–494.

Hodges, J.R. & Kimball, A.M. 2005. The global diet: trade and novel infections. *Global Health,* 1(1): 4.

Kamilaris, A., Fonts, A. & Prenafeta-Boldú, F.X. 2019. The rise of blockchain technology in agriculture and food supply chains. *Trends in Food Science and Technology,* 91: 640–652.

Kim, J.S., Lee, H.J., Kim, S.K. & Kim, H.J. 2018. Global pattern of microplastics (MPs) in commercial food-grade salts: Sea salt as an indicator of seawater MP pollution. *Environmental Science and Technology,* 52(21): 12819–12828.

Kirstein, I.V., Kirmizi, S., Wichels, A., Garin-Fernandez, A., Erler, R., Loder, M. & Gerdts, G. 2016. Dangerous hitchhikers? Evidence for potentially pathogenic *Vibrio* spp. on microplastic particles. *Marine Environmental Research,* 120: 1–8.

Lagana, P., Caruso, G., Corsi, I., Bergami, E., Venuti, V., Majolino, D., La Ferla, R., Azzaro, M. & Cappello, S. 2019. Do plastics serve as a possible vector for the spread of antibiotic resistance? First insights from bacteria associated to a polystyrene piece from King George Island (Antarctica). *International Journal of Hygiene and Environmental Health,* 222(1): 89–100.

Li, J., Zhang, K. & Zhang, H. 2018. Adsorption of antibiotics on microplastics. *Environmental Pollution,* 237: 460–467.

Lister, B.C. & Garcia, A. 2018. Climate-driven declines in arthropod abundance restructure a rainforest food web. *Proceedings of the National Academy of Sciences of the USA*, 115(44): E10397–E10406.

Lynch, J. & Pierrehumbert, R. 2019. Climate impacts of cultured meat and beef cattle. *Frontiers in Sustainable Food Systems*, 3. https://doi.org/10.3389/fsufs.2019.00005

Martin, J.H. & Fitzwater, S.E. 1988. Iron deficiency limits phytoplankton growth in the north-east Pacific subarctic. *Nature*, 331(6154): 341–343.

Masó, M., Garcés, E., Pagès, F. & Camp, J. 2007. Drifting plastic debris as a potential vector for dispersing harmful algal bloom (HAB) species. *Scientia Marina*, 67(1): 107–111.

Perez, B., Nykvist, H., Brogger, A.F., Larsen, M.B. & Falkeborg, M.F. 2019. Impact of macronutrients printability and 3D-printer parameters on 3D-food printing: A review. *Food Chemistry*, 287: 249–257.

Rivers, M.L., Gwinnett, C. & Woodall, L.C. 2019. Quantification is more than counting: Actions required to accurately quantify and report isolated marine microplastics. *Marine Pollution Bulletin,* 139: 100–104.

Rodrigues, A., Oliver, D.M., McCarron, A. & Quilliam, R.S. 2019. Colonisation of plastic pellets (nurdles) by *E. coli* at public bathing beaches. *Marine Pollution Bulletin,* 139: 376–380.

Rubio, N., Datar, I., Stachura, D., Kaplan, D. & Krueger, K. 2019. Cell-based fish: A novel approach to seafood production and an opportunity for cellular agriculture. *Frontiers in Sustainable Food Systems*, 3: 43. doi: 10.3389/fsufs.2019.00043

Smetana, S., Palanisamy, M., Mathys, A. & Heinz, V. 2016. Sustainability of insect use for feed and food: Life Cycle Assessment perspective. *Journal of Cleaner Production,* 137: 741–751.

Trick, C.G., Bill, B.D., Cochlan, W.P., Wells, M.L., Trainer, V.L. & Pickell, L.D. 2010. Iron enrichment stimulates toxic diatom production in high-nitrate, low-chlorophyll areas. *Proceedings of the National Academy of Sciences of the USA*, 107(13): 5887–5892.

van Sebille, E., Wilcox, C., Lebreton, L., Maximenko, N., Hardesty, B.D., van Franeker, J.A., Eriksen, M., Siegel, D., Galgani, F. & Law, K.L. 2015. A global inventory of small floating plastic debris. *Environmental Research Letters,* 10(12): 124006. https://iopscience.iop.org/article/10.1088/1748-9326/10/12/124006/pdf.

van Strien, A.J., van Swaay, C.A.M., van Strien-van Liempt, W.T.F.H., Poot, M.J.M. & WallisDeVries, M.F. 2019. Over a century of data reveal more than 80% decline in butterflies in the Netherlands. *Biological Conservation*, 234: 116–122.

Welden, N.A. & Lusher, A.L. 2017. Impacts of changing ocean circulation on the distribution of marine microplastic litter. *Integrated Environmental Assessment and Management,* 13(3): 483–487.

WHO. 2019. *Microplastics in drinking water.* Geneva. 124 pp. (also available at https://apps.who.int/iris/bitstream/handle/10665/326499/9789241516198-eng.pdf)

Wright, S.L. & Kelly, F.J. 2017. Plastic and human health: A micro issue? *Environmental Science & Technology*, 51(12): 6634–6647.

Zaraska, M. 2013. Lab-grown beef taste test: "Almost" like a burger. *The Washington Post*. 5 August 2013. (also available at https://www.washingtonpost.com/national/health-science/lab-grown-beef-taste-test-almost-like-a-burger/2013/08/05/921a5996-fdf4-11e2-96a8-d3b921c0924a_story.html).

Chapter 4: Conclusions

Apruzzese, I., Song, E., Bonah, E., Sanidad, V.S., Leekitcharoenphon, P., Medardus, J.J., Abdalla, N., Hosseini, H. and Takeuchi, M. 2019. Investing in food safety for developing countries: Opportunities and challenges in applying whole-genome sequencing for food safety management. *Foodborne Pathogens and Disease,* 16(7): 463–473.

Folke, C., Osterblom, H., Jouffray, J.B., Lambin, E.F., Adger, W.N., Scheffer, M., Crona, B.I., Nystrom, M., Levin, S.A., Carpenter, S.R., Anderies, J.M., Chapin, S., 3rd, Crepin, A.S., Dauriach, A., Galaz, V., Gordon, L.J., Kautsky, N., Walker, B.H., Watson, J.R., Wilen, J. and de Zeeuw, A. 2019. Transnational corporations and the challenge of biosphere stewardship. *Nature Ecology & Evolution*, 3(10): 1396–1403.

CLIMATE CHANGE:
UNPACKING THE BURDEN ON FOOD SAFETY

Climate change is causing unprecedented damage to our ecosystem. Increasing temperatures, ocean warming and acidification, severe droughts, wildfires, altered precipitation patterns, melting glaciers, rising sea levels and amplification of extreme weather events have direct implications for our food systems. While the impacts of such environmental factors on food security are well known, the effects on food safety receive less attention. The purpose of *Climate change: Unpacking the burden on food safety* is to identify and attempt to quantify some current and anticipated food safety issues that are associated with climate change. The food safety hazards considered in the publication are foodborne pathogens and parasites, harmful algal blooms, pesticides, mycotoxins and heavy metals with emphasis on methylmercury. There is also, a dedicated section on the benefits of forward-looking approaches such as horizon scanning and foresight, which will not only aid in anticipating future challenges in a shifting global food safety landscape, but also help build resilient food systems that can be continually updated as more knowledge is assimilated. By building a more widespread and better understanding of the consequences climate change has on food safety, it is hoped that this document will aid in fostering stronger international cooperation in making our food safer by reducing the global burden of these concerns.

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS (FAO)
AGRICULTURE AND CONSUMER PROTECTION DEPARTMENT
OFFICE FOR FOOD SAFETY
FOOD SAFETY AND QUALITY UNIT

WWW.FAO.ORG/FOOD-SAFETY

ISBN 978-92-5-132293-2 ISSN 2415-1173
9 789251 322932
CA8185EN/1/03.20