Agricultural Chemicals and the Environment

Issues and Potential Solutions

2nd Edition

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EDITORS: R.E. HESTER AND R.M. HARRISON

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OF CHEMISTRY

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Preface

Agricultural production is in a period of rapid transformation involving an increase in the use of biotechnology, synthetic chemistry, biological chemicals and biopesticides. These disciplines are integrated with improvements in application technology, digital farming and the use of big data. Whilst offering unique opportunities to reduce potential environmental impacts, these advances also raise new environmental concerns.

This book provides an overview of the changes occurring in the agricultural industry, highlighting opportunities to address impacts and indicating potential barriers to adoption of new technology. This edition has been updated to include the very latest in agricultural developments, including organic farming and genetically modified crops. It will be of value to students and academics in agricultural colleges, as well as farmers and landowners and those working on agricultural legislation.

In the first chapter, Laura McConnell and her colleagues from Bayer CropScience have reviewed the ways in which agricultural technologies can be integrated in order to minimise their environmental impacts. Against a background of increasing world population, growing numbers of undernourished people, changes in climate that impact on agricultural productivity, including changes in rainfall patterns, and the urgent need for increased yields in food production, the role of the agrochemical industry and growth in the area of agricultural biologicals is discussed. Precision agriculture, enhanced by digital farming technologies, is of increasing importance in raising productivity levels and improving the sustainability of crop production. Improved synthetic pesticides lessen the risks to humans and wildlife and emerging technologies such as genetic engineering are of growing significance. Land management and regulatory controls also are addressed here.

Agricultural productivity is heavily dependent on the application of fertiliser nutrients to land, but inefficient use can cause environmental damage. Chapter 2, by Richard McDowell and his colleagues from New Zealand and Wales, outlines our current understanding of vital N and P

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use efficiencies by crops and the range and cost-effectiveness of strategies to mitigate fertiliser losses that result in contamination of freshwater. Equally important to agricultural productivity is the use of pesticides, including fungicides, insecticides, molluscicides and plant-growth regulators, herbicides. In addition to their treatment in Chapter 1, these are given special attention in Chapter 3 by Steven Bailey and colleagues from Natural England and Harper Adams University. Their wide-ranging treatment addresses in detail three current issues of concern: impacts on terrestrial wildlife and biodiversity, the development of resistance, and contamination of water by pesticides.

Chapter 4 is concerned with agroecology and organic farming as approaches to reducing the environmental impacts of agricultural chemicals. Nic Lampkin and his colleagues from the Organic Research Centre in Newbury, UK, describe how these approaches can be advantageous for biodiversity, resource use and emissions, but with potential trade-offs against productivity and profitability. These, however, can be mitigated through the use of specialist markets for organic products and through agri-environmental support or payment for ecosystem services. The chapter includes international comparisons and details the measures needed for financial viability. At the other end of the spectrum of agricultural practices, Chapter 5 deals with the subject of crop biotechnology for weed and insect control. Written by Huw Jones of Aberystwyth University, this describes the rapid uptake and widespread use of GM crop varieties with tolerance to herbicides and resistance to insect pests. However, this remains a highly controversial area, particularly for food crops such as soybean, maize and sugar beet. GM insect-resistant (Bt) cotton, on the other hand, has been widely adopted throughout the world, not only showing resistance to the traditional bollworm and budworm pests but also being associated with increases in beneficial arthropod predators, such as ladybirds and spiders, and a decrease in aphid pests. There are many regulatory hurdles to overcome for future growth of GM crop cultivation but the pressure for increased agricultural output and efficiency together with the development of new, highly specific gene-editing techniques are powerful drivers.

The final two chapters in the book are focused on the particular areas of aquaculture and horticulture. In Chapter 6, Colin Moffat, head of science at Marine Scotland, describes both the benefits and hazards of aquaculture for food production. Seafood is well known for being highly nutritious; seaweed is widely used in food around the world, but particularly in China and Japan; freshwater fish species such as trout and carp have been popular throughout history; shellfish similarly have been found to be a part of the human diet at least as far back as the Bronze Age. Aquaculture, the managed production of marine or freshwater animals and plants, is the world's fastest-growing system for food production, currently producing more than 70 million tonnes annually, the bulk of this in Asia. The chapter reviews the use of chemicals and pharmaceuticals in aquaculture for the control of pests, disease and parasites, and the environmental hazard that these present.

Chapter 7, written by Rosemary Collier of the University of Warwick and her colleagues from NIAB at East Malling, is concerned with the wide range of plant families encompassed by the term horticulture. These include fruit, vegetables and ornamentals grown to provide cut flowers, pot, garden or landscaping plants; both outdoor and protected crops in glasshouses and polytunnels are also referenced. Although these crops occupy a relatively small footprint in comparison with arable crops and grassland supporting livestock, they often require more intensive use of fertilisers and pesticides in order to achieve the appearance and quality criteria that determine market value. The chapter summarises crop production methods, focusing on the use of agricultural chemicals and potential approaches to reducing their environmental impact; case studies on carrot production and integrated pest and disease management in apple orchards are included.

Ronald E. Hester
Roy M. Harrison

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Ronald E. Hester is now Emeritus Professor of Chemistry in the University of York. He was for short periods a research fellow in Cambridge and an assistant professor at Cornell before being appointed to a lectureship in chemistry in York in 1965. He was a full professor in York from 1983 to 2001. His more than 300 publications are mainly in the area of vibrational spectroscopy, latterly focusing on time-resolved studies of photoreaction intermediates and on biomolecular systems in solution. He is active in environmental chemistry and is a founder member and former chairman of the Environment Group of the Royal Society of Chemistry and editor of 'Industry and the Environment in Perspective' (RSC, 1983) and 'Understanding Our Environment' (RSC, 1986). As a member of the Council of the UK Science and Engineering Research Council and several of its sub-committees, panels and boards, he has been heavily involved in national science policy and administration. He was, from 1991 to 1993, a member of the UK Department of the Environment Advisory Committee on Hazardous Substances and from 1995 to 2000 was a member of the Publications and Information Board of the Royal Society of Chemistry.

Roy M. Harrison, BSc, PhD, DSc (Birmingham), FRSC, CChem, FRMetS, Hon MFPH, Hon FFOM, Hon MCIEH

Roy M. Harrison is Queen Elizabeth II Birmingham Centenary Professor of Environmental Health in the University of Birmingham. He was previously Lecturer in Environmental Sciences at the University of Lancaster and Reader and Director of the Institute of Aerosol Science at the University of Essex. His more than 400 publications are mainly in the field of environmental chemistry, although his current work includes studies of human health impacts of atmospheric pollutants as well as research into the chemistry of pollution phenomena. He is a past Chairman of the Environment Group of the Royal Society of Chemistry for whom he edited 'Pollution: Causes, Effects and Control' (RSC, 1983;

Fifth Edition 2014). He has also edited ‘‘An Introduction to Pollution Science’’, RSC, 2006 and ‘‘Principles of Environmental Chemistry’’, RSC, 2007. He has a close interest in scientific and policy aspects of air pollution, having been Chairman of the Department of Environment Quality of Urban Air Review Group and the DETR Atmospheric Particles Expert Group. He is currently a member of the DEFRA Air Quality Expert Group, the Department of Health Committee on the Medical Effects of Air Pollutants, and Committee on Toxicity.

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Integrating Technologies to Minimize Environmental Impacts

LAURA L. McCONNELL,* IAIN D. KELLY AND RUSSELL L. JONES

ABSTRACT

Historically, synthetic agrochemicals have had a central role in increasing yields in agricultural production. Assessment methods and approaches towards monitoring and addressing the environmental impact of the technology were relatively simple. Agricultural production, however, is in a period of rapid transformation. Research and Development companies are transforming their activities to provide a more holistic approach that provides producers with integrated solutions. These approaches encompass biotechnology, synthetic chemistry, biologicals and biopesticides, all disciplines that are integrated with improvements in application technology, digital farming and the use of big data. While these developments may raise new questions, they also provide unique opportunities to reduce potential environmental impacts. This chapter provides an overview of the changes occurring in the agricultural industry and highlights ways in which we might address their effects, while pointing out some of the barriers to adoption of new technologies.

1 Introduction

In 2015, the United Nations adopted the 2030 Agenda for Sustainable Development and 17 specific Sustainable Development Goals as a guide for

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global development designed to end poverty, protect the planet and ensure prosperity for all.[1] Sustainable Development Goal number 2 is to "end hunger, to achieve food security and improved nutrition, and promote sustainable agriculture" by 2030. At present, about 790 million people are undernourished;[2] therefore, achieving this ambitious goal will require significant and rapid technological innovations in agricultural production systems across the world. Other UN goals, related to sustainable management of water and addressing climate change and its impacts, will also require major advances in agricultural technology in order to increase food production in a sustainable manner, while keeping pace with the demands of an expanding population.

The goal of ending hunger and achieving food security becomes more challenging considering that the current world population of 7.3 billion is projected to reach 9.7 billion by 2050 and 11.2 billion by 2100.[3] In addition, global life expectancy is projected to increase from 70 to 77 years by 2045–2050. Developing countries are expected to have the greatest rate of population growth, and average food consumption in developing countries is projected to increase from 2005 levels of 2619 $\text{kcal person}^{-1}\text{ day}^{-1}$ to 3000 kcal by 2050.[4] With increasing consumption, there is an increase in demand for a more diverse and protein-rich diet including meat, milk, eggs and vegetable oils. Currently approximately 12% of the land surface of the globe is used for crop production. Recent estimates indicate that up to 34% of the world's land surface could be used for agriculture, although approximately 20% has been deemed marginal and unsuitable for rainfed agriculture. Therefore, careful management and protection of the most productive agricultural lands will be required, along with novel approaches to achieving increased production on marginal lands.

Climate change is expected to bring geographical changes in precipitation patterns and therefore will alter growing conditions and water availability in agricultural production regions both within the USA[5] and across the world.[6,7] Plant growth of both crops and weed species, will be affected by increases in carbon dioxide in the atmosphere.[8] While some agricultural regions may benefit from increased yields in a warming climate, northward expansion of insect pests and weed species is already being observed. Climate change will bring about additional challenges such as a general increase in extreme weather events which can damage crops and food distribution networks, a growing risk of food-borne illnesses and rising tropospheric ozone concentrations, resulting in damage to crop yields.[9,10]

With increasing population and a warming climate, additional factors will also influence the global availability of food, possibly leading to water scarcity and decreased water quality. Approximately 70% of global freshwater consumed is used in agriculture.[11] While domestic wastewater can be recycled, much of the water used in crop production is either incorporated into biomass or is transpired. As incomes in developing countries increase, greater demand for meat and dairy products will require more water for production compared with staple crops; it is estimated that agricultural production will need to grow by 60% by 2050 to keep up with this demand. Increased production on the same limited land resources will likely require a greater portion of cropland under irrigation, leading to increased water scarcity and the potential for decreased water quality. If increasing demand for food cannot be met with increasing yields, then more marginal lands will be pushed into food production, reducing habitats for native plants and animals along with other ecosystem services that these lands currently provide. This chapter seeks to summarize recent and emerging trends in the crop protection industry, to discuss the challenges facing the industry, the role of regulation in new technology development and recommendations on finding a way forward towards increased production and improved sustainability in agriculture.

2 Developments and Emerging Trends in the Crop Protection Industry

Over the last approximately 70 years, yield increases, particularly in the developed countries, have been significant. In the USA, for example, soybean yields have doubled and corn yields have increased by a factor of four, leading to increases in farm total factor productivity of 1.47% per year from 1948 to 2013.[12] Much of this improvement was achieved through the use of more efficient and automated machinery, improved seed varieties and agricultural chemicals, including fertilizers and pesticides and, most significantly, herbicides. Increased yields have lowered the cost of commodities and have resulted in a more abundant food supply, while publicly and privately funded agricultural research has contributed to innovations and new technologies.

The pesticide consumption index in the USA increased steadily from 1960 to the mid-1990s but has now leveled off and begun to decline, while the total farm output has continued to increase (Figure 1).[12] This leveling off of pesticide use coincided with the introduction of new genetic traits into the market, beginning around 1996 (Figure 2).[13] Herbicide-tolerant soybeans achieved more than 80% adoption in the marketplace by 2003; use of herbicide-tolerant cotton increased more slowly but exceeded 80% by 2012. Insecticide-tolerant cotton, or Bt cotton, contains the gene from a soil bacterium named *Bacillus thuringiensis,* and produces a protein that is toxic to certain insect pests. Bt cotton use has increased to 84% of all acres of cotton planted, as of 2014.

Public investments in agricultural research, however, have slowed in recent years while private sector research and development has grown rapidly.[14] Continued investments from both public and private sources will be required to achieve the increases in agricultural productivity required to meet global food demand. Within the private sector, the challenge of feeding an ever-increasing population in a period of changing environmental conditions will be accomplished by a much different industry, under the scrutiny of a civil society with near-universal access to smart phone

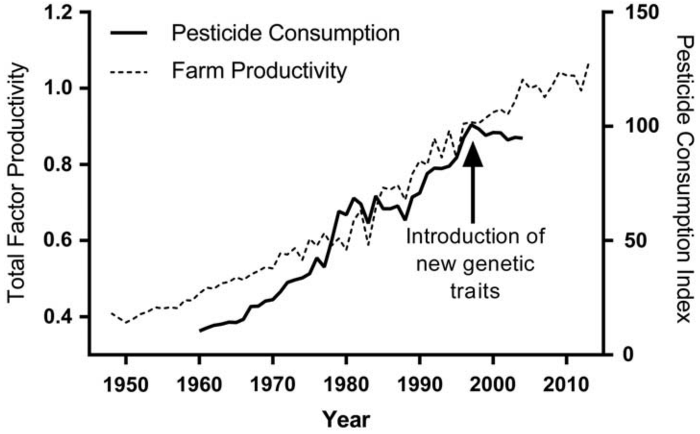

Figure 1 Comparison of trends in pesticide consumption index and total factor productivity of US farms from 1948 to 2013. Pesticide consumption indices are relative to use in Alabama in 1996 = 1. Values displayed are the sum of consumption index for 48 states.
Source data: Ref. 12.

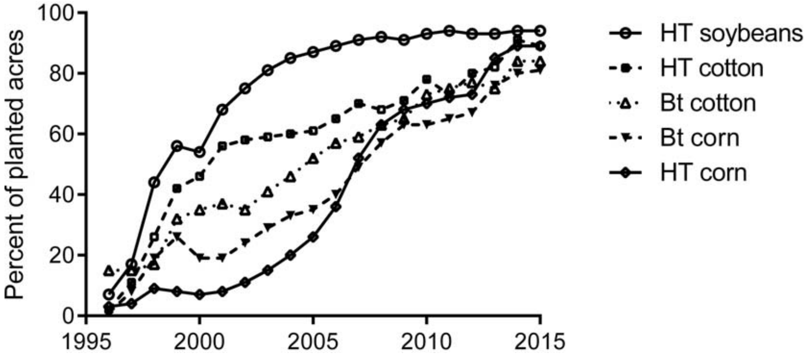

Figure 2 Adoption of genetically engineered crops in the United States, 1996 to 2015. HT = herbicide-tolerant crop, Bt = insect resistant crop containing the gene from *Bacillus thuringiensis*.
Source data and figure adapted from ref. 13.

technology, information and commentaries. Some have recently proposed that the global economy is entering a fourth industrial revolution, leading to extreme automation and connectivity.[15] At a recent World Economic Forum, a new report on the *Future of Jobs* was published, describing changes in the economy expected by 2020:

> "*We are today at the beginning of a Fourth Industrial Revolution. Developments in previously disjointed fields such as artificial intelligence and machine learning, robotics, nanotechnology, 3D printing and genetics and biotechnology are all building on and amplifying one another. Smart*

> *systems—homes, factories, farms, grids or entire cities—will help tackle problems ranging from supply chain management to climate change. Concurrent to this technological revolution are a set of broader socioeconomic, geopolitical and demographic developments, with nearly equivalent impact to the technological factors.*''[16]

The effects of these changes in economic forces are already evident in the structure of the agrochemical industry as it enters a period of faster consolidation and more diverse acquisition. In the period 1998–2002 the industry had a significant consolidation as the ten major research and development companies merged to create six (Monsanto, Syngenta, Bayer CropScience, Dupont, Dow AgroSciences and BASF),[17] each with total sales of over €5 million in 2014 (Figure 3). As the figure shows, within these six companies there was a clear differentiation in the size of the agrochemicals business compared to the seed business. Monsanto and DuPont have greater than 50% of their sales in seeds while in Syngenta, Dow AgroSciences and Bayer CropScience, agrochemicals predominate. BASF focused primarily on agrochemicals.

The last five years have seen considerable acquisitions and penetration by the major agrochemical companies into the area of agricultural biologicals. In 2012 alone, Bayer acquired AgraQuest, Inc., Monsanto announced its BioDirect™ technology platform, BASF acquired Becker Underwood, Inc., and Syngenta acquired Pasteuria Bioscience, Inc. as each of these companies strengthened their position in this promising new area of agricultural technology. Definitions of the term ''biologicals'' vary but generally

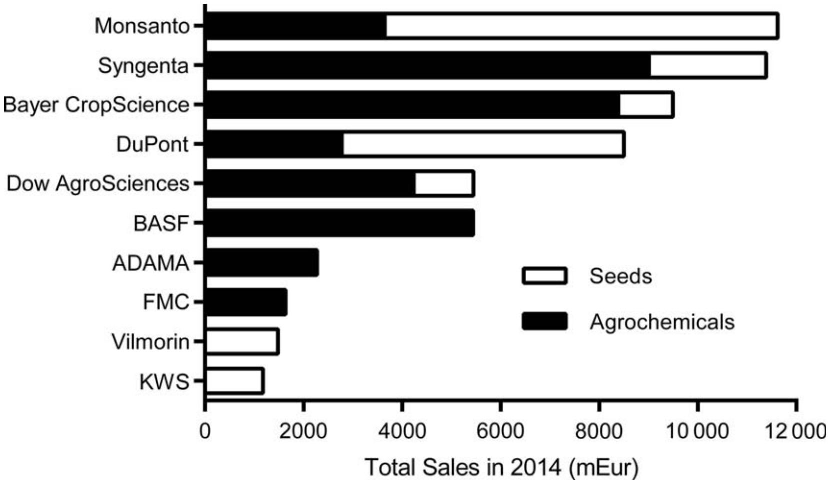

Figure 3 Estimated total sales of agrochemicals and seeds in 2014 for major crop protection companies (million euros) excluding non-agricultural business. Estimates based on company publications and Bayer CropScience internal market research.

encompass microbials, plant extracts or other organic material, and beneficial insects that can be used to control pests and diseases or stimulate crop efficiency. The variation in definition of the market makes its size difficult to measure but one estimate put the market at approximately \$3 billion, which included biopesticides at an estimated \$2 billion and biostimulants around \$1 billion, with the potential for continuing double-digit growth throughout the decade.[18]

Another emerging area related to the increase in global connectivity that has seen acquisition by the major agrochemical companies is precision agriculture, enhanced by digital farming technologies. The most notable of these was the acquisition of The Climate Corporation by Monsanto in 2013. This purchase signaled the importance that ready access to real-time field data will have to the grower of the future. Advanced analytics, synthesizing local conditions including soil type, weather patterns, crop varieties and patterns of disease outbreaks and insect infestation will all be amongst the decision-making tools available to growers in their efforts to maximize productivity. Approaches to data access, data ownership and data security will be an integral part of the implementation and success of these developments, and equipment manufacturers are a key link in this digital development. Self-driving, highly computerized planters, sprayers and harvesters are either available now or in development, with the ability to respond in real-time to satellite, drone and ground-based robots. In 2015, Deere & Company agreed to acquire the Precision Planting, LLC equipment business from Monsanto's Climate Corporation Subsidiary to enable exclusive, near real-time data connectivity between certain John Deere farm equipment and the Climate FieldView™ platform as part of the innovation alignment within this section of the industry. In related activities, Bayer CropScience has recently acquired proPlant, Inc., and Syngenta has acquired Ag Connections, LLC.

Major factors that are impacting the future of the crop protection industry are the enormous cost of product development and challenges of increasing regulatory hurdles. The cost of development of a new agrochemical is currently estimated at approximately \$290 million, with 11 years from discovery to commercialization,[19] while a new plant biotechnology trait costs approximately \$135 million, with 12 to 16 years from lab to commercialization.[20] Clearly, in a few years the appearance of the industry will be very different from today and is likely to be more far-reaching than the developments that occurred at around the millennium. Consolidation within the large research and development companies will be accompanied by venture capital and niche market investments as new and potentially disruptive technologies continue to evolve.

3 Improving the Sustainability of Crop Production

Since the introduction of synthetic chemicals as a key contributor in protecting plants and increasing yields, concerns have been raised about potential environmental impacts. Assessing and reducing these impacts has been a multidimensional process and the pace only increases as agronomy continues to encompass new scientific disciplines and technology. Some of these will be expanded upon later in this book but an overview is provided here.

3.1 Improved Properties of Synthetic Pesticides

While pesticide use has increased over time, the properties of pesticide products have evolved to minimize their risks to humans and wildlife. Two basic trends in new compounds have occurred over the past 2 to 3 decades: new compounds are designed with more specific modes of action, which tend to limit effects to specific taxa, and are more highly active, facilitating lower use rates. While potential environmental effects can be similar for a sensitive species with compounds with broad or more specific modes of action, fewer species are at risk from compounds with specific modes of action. In the insecticide area, for example, the use of the non-specific acetylcholinesterase (AChE) inhibitors (organophosphates and carbamates) was 51% in 1999. Together, the AChE inhibitors and those insecticides acting on the voltage-gated sodium channel (vgSCh), in particular the pyrethroids, accounted for approx. 70% of the world market.[21] By 2012, AChE-inhibitor use had dropped much further to 19%, while pyrethroids had remained relatively constant at 17% and neonicotinoid use (introduced in the 1990s) had risen to 24% to become the major classes of insecticides.[22] Both the neonicotinoid and pyrethroid classes of insecticides have modes of action which are highly toxic to insects, but have low mammalian and avian toxicity compared to organophosphate and carbamate insecticides. Risk mitigation strategies can, therefore, be much more targeted, generally focusing on aquatic species for pyrethroids and pollinator species for neonicotinoids. Furthermore, use-rates in the 1980s were typically 1–10 kg ha^{-1}, while many compounds today are applied at rates less than 1 kg ha^{-1} and average application rates of some sulfonylureas are as low as a few grams per hectare.[23]

The US Department of Agriculture (USDA), Economic Research Service conducted an exhaustive analysis of pesticide use on 21 crops from 1960 to 2008 and examined changes over time in environmentally relevant characteristics of pesticides on the market (Figure 4).[24] The most dramatic trend observed was the decline in toxicity to humans, but declines in average annual application rate and persistence were also observed. Declines in pesticide consumption have also been accompanied by major changes in application techniques, as well as stewardship efforts (*e.g.* integrated pest management, nutrient management and conservation agriculture) to maintain the sustainability of changing agricultural processes.

3.2 Emerging Technologies

3.2.1 Genetic Engineering. This technology encompasses Genetically Modified Organisms (GMOs) produced by recombinant DNA techniques and, more recently, techniques such as gene editing and RNA interference

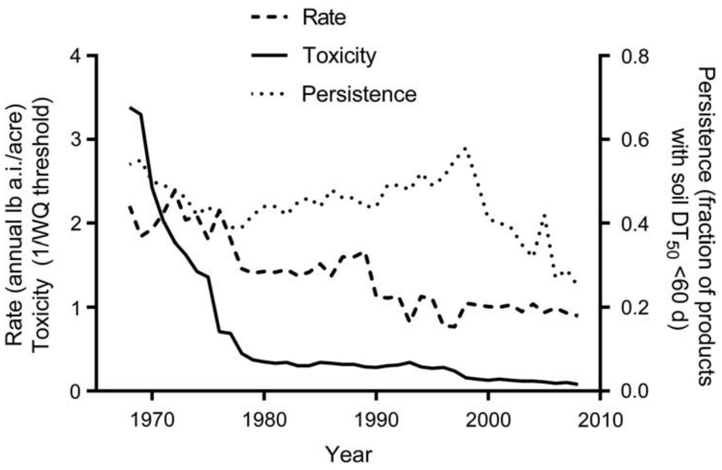

Figure 4 Average quality characteristics of pesticides applied to four major crops, 1968 to 2008, where Rate is the pounds of active ingredient applied per acre in one application times the number of applications per year; Toxicity is defined as the inverse of the water quality threshold in parts per billion, serving as an environmental risk indicator for humans from drinking water; and Persistence is the share of pesticide products in use with soil half-life less than 60 days.
Source data and figure adapted from ref. 24.

(RNAi). As was mentioned in Section 2, the overall rate of pesticide use in the USA has leveled off with the rapid adoption of GMO crops in the late-1990s, while farm productivity has continued to increase (Figure 1). Initially a single gene was inserted, producing herbicide-tolerant or insect-resistant plants. The technology has been very effective and has fundamentally changed farming practices in many parts of the world. However, the broad acceptance of the glyphosate-tolerant trait, coupled with use of the non-specific herbicide glyphosate, has, unfortunately, led to the evolution of glyphosate-resistant weed species.[25] Herbicide-tolerant and insecticide-resistant traits can now be stacked in cotton and in corn, and use of these stacked trait varieties has increased over time.[13] With these advanced GMOs, insecticide applications can be minimized and herbicide applications more targeted when weed pest pressure increases. Efforts are underway in academic, industry and government scientific circles to track weed resistance[26] and to increase stewardship programs to educate farmers on how to manage resistance.[27] Adoption of GMO crops has also led to increased adoption of conservation tillage practices, leading to beneficial effects on soil and water quality.[28]

Further advances in the technology are focusing on output traits which, for example, enhance yield, confer drought resistance, enhance nitrogen-use efficiency and confer desirable quality properties on the crop. An early entry into this field was the so-called ‘‘golden rice’’ engineered to produce β-carotene, the precursor to vitamin A, as well as an increased dose of absorbable iron.[29,30] Modified animals in our food supply are also being approved by the United States Food and Drug Administration (USFDA). For example, the AquAdvantage Salmon, which grows to market size more quickly than non-genetically engineered salmon, was approved by the USFDA in 2015.[31] Other potential developments from genomics include improved food safety (*i.e.* microbial contamination and allergen detection), edible vaccines and therapeutic monoclonal antibodies produced from plants.[32]

More recently, targeted technologies have been developed that have the potential for site-specific gene modification. These include site-directed zinc-finger nucleases (ZFNs) and transcription activator-like (TAL)-effector nucleases (TALENs). A recent entry into this field is CRISPR-Cas9, which is showing promise as a facile method of targeting specific genes.[33] An alternative technology is RNAi, whereby RNA molecules are used to downregulate the expression of genes.[34] An interesting aspect of RNAi is that, while it can be incorporated and expressed in the plant, it can be sprayed directly onto the plant as a biological.[35] The potential of this new area of research is enormous for numerous industries. Ideal products would be highly specific to certain insect pests while protecting beneficial organisms. It is also being envisaged that RNAi could be used to increase the nutritional value of certain crops or to limit the accumulation of allergenic proteins.[36]

3.2.2 Agricultural Biologicals. Agricultural biologicals cover a broad range of products. Generally they are considered to include products derived from naturally occurring microorganisms, plant extracts or other organic matter, but can also include macroorganisms such as beneficial insects, mites and nematodes.[37] They are typically separated into two major categories: biopesticides and biostimulants. Biopesticides include plant extracts, organic acids and semiochemicals (*e.g.* pheromones) and can also encompass such terms as natural product chemistry and secondary metabolites. Also included in this group are intact microbes (generally bacteria and fungi, but viruses, protozoans and yeasts also are being investigated). Biological products generally have multiple modes of action which make them resilient to resistance development. They are excellent tools in integrated pest management and are often used in conjunction with conventional crop protection products to reduce residues while maximizing yields. Biostimulants modify plant physiology to increase the vigor of the crop. They protect against abiotic stress; for example improving root establishment, facilitating the uptake of nutrients. Related to biostimulants are the biofertilizers, such as nitrogen-fixing bacteria, which also increase plant vigor.

3.2.3 Organic Agriculture. Land in certified organic production accounted for about 1% of agricultural land globally in 2010, the year for which the most recent figures are available.[38] While the current area of organic production is low, the demand for certified organic produce has increased to more than 4% of food sales in the USA.[39] The USDA defines organic agriculture as "the application of a set of cultural, biological, and mechanical practices that support the cycling of on-farm resources, promote ecological balance, and conserve biodiversity".[40] Organic agriculture also provides for: "As a last resort, producers may work with their organic certifier to use an approved pesticide, such as naturally occurring microorganisms, insecticides naturally derived from plants, or one of a few approved synthetic substances". Clearly there is a potential link between organic agriculture and biologicals, but not all biologicals are certified organic under the USDA National Organic Program. The impact of organic production and its role in addressing environmental impact will be dependent on its level of adoption. Overall organic yields have been shown to be lower than non-organic, while premiums for organic produce have to some extent offset this from a grower perspective.[38,41] The final adoption will, therefore, be an economic balance between pressure on arable land, yields, and societal demands as food requirements continue to pressure land resources.

3.2.4 Waste Reduction Strategies. A frequently overlooked strategy in increasing the world food supply is the adoption of methods to reduce waste. It has been estimated[42] that roughly one third of food produced for human consumption is lost or wasted globally, amounting to about 1.3 billion tons per year. These losses occur throughout the supply chain, starting from the initial phases of crop production through to consumption by the consumer. The source and magnitude of losses vary by region and country, with much more being lost in developed countries than in developing countries. The *per capita* figure for food wasted by consumers in Europe and North America is estimated[42] at 95–115 kg year^{-1}, while in sub-Saharan Africa and South/Southeast Asia it is only 6–11 kg year^{-1}. In developed counties disposal of edible food by the consumer is a major factor, while in developing countries deficiencies in supply chain management, infrastructure and access to advanced agricultural technologies all contribute. In the United States alone, estimates are that 31% (133 billion pounds) of the 430 billion pounds of the available food supply at the retail and consumer levels goes uneaten (2010 values).[43] This has led to efforts such as the Department of Agriculture and the Environmental Protection Agency Deputy announcing, in late 2015, a national food waste reduction goal, calling for a 50% reduction by 2030, largely through federal government-led partnerships with charitable organizations, faith-based organizations, the private sector and local, state and tribal governments.

3.3 Enhanced Application Technologies

3.3.1 Spray Drift Reduction Technology. Considerable advances in spray-drift-reduction technology, such as low-drift nozzles and application equipment, have been made in the last 2–3 decades.[44] Progress has also been made in the development of drift-reduction agents and low-drift formulations; for example, Dow AgroSciences has introduced an herbicide product, Enlist Duo™, with 90% less drift than other formulations of the same herbicides. Significant progress has also been made in establishing guidelines for studies to measure spray drift; for example, ISO 22856:2008,[45] and in modeling spray drift as a function of spray equipment and spray conditions.[46] All of these improvements have helped reduce the amount of material moving away from the field and impacts on terrestrial and aquatic non-target organisms.

3.3.2 Seed Treatments. The use of seed treatments has dramatically increased in the past 2–3 decades. Prior to the 1980s, seed treatments were used primarily as disinfectants. In the 1980s the introduction of low-rate, highly effective systemic fungicides provided seedling protection from soil-borne fungi, *e.g.* triadimenol and metalaxyl, followed by the systemic insecticides in the 1990s, imidacloprid being the first which protected against both below-ground soil insects and early-season above-ground pests. Anti-nematode activity appeared in the 2000s with abermectin and the biological treatment VotiVo®.

Seed treatments provide protection for young plants, with less pesticide material than if applied as broadcast, banded or in-furrow treatments. A major advantage of seed treatments compared to broadcast applications is that the treated seed is typically located below the soil surface, significantly reducing *runoff* losses of crop protection chemicals to nearby terrestrial or aquatic environments outside the field.[47] There are numerous additional benefits and uses of this technology. Improvements in the use of the technology continue to develop and progress has been made in the past few years in product formulations, application equipment and additives that reduce dust emissions during the planting of treated seed.[48]

Seed treatments have been associated recently with pollinator effects, although this is more of a function of the specific products used, since similar issues could occur with alternative application methods. Improved methodologies are being developed to assess the environmental risks to pollinators in general, including seed treatment.[49] Systemic activity can be a positive for a soil-applied compound since it has no effect on insects that do not consume the leaves or other portions of a plant, leaving most beneficial insects unharmed.[50]

3.3.3 Precision Agriculture. Precision agriculture uses a combination of geospatial information and sensors to optimize inputs to crops as a function of location in the field. Such an approach can increase yields by making certain that areas of the field benefiting from inputs (nutrients and crop protection products) receive them in the right quantities, while minimizing inputs by not applying a maximum rate required in one portion of the field to the entire field.[51]

Digital farming utilizes high-resolution geopositioning systems (GPS) and geographic information systems (GIS) to couple real-time data collection technology with accurate position information. Data collected from sensors mounted on satellites or unmanned aerial vehicles can be used to generate high-resolution imagery of crop fields and to automate nutrient and pesticide applications by farmers. Such an approach of minimizing inputs also reduces loss of nutrients and crop protection products in runoff and tile drains moving to nearby surface water bodies, thereby reducing potential effects on aquatic organisms. As mentioned earlier, enormous advances in digital farming technology are expected over the next few decades, providing seamless integration with farm equipment and leading to decreased use of fertilizers, pesticides and water resources while maximizing yields.

3.4 Better Land Management

3.4.1 No and Low Tillage. The use of no- and low-tillage has been heavily promoted for many years as a way of reducing the amount of soil moving off tilled fields during rainstorms and preventing impacts on aquatic organisms. In order to maintain a weed-free field, the weeds removed by tillage must be killed by herbicides. The lack of tillage helps promote infiltration of water (and nutrients and crop protection chemicals present in the water) reducing runoff as well as soil erosion. This practice was adopted for about 40% of combined corn, soybean, wheat, and cotton in the USA in 2010–11 (89 million acres per year)[52] and contributed to the health of surface water bodies in this region. Globally, adoption rates of no-till vary by region, with the largest percentages found in South America at 47%, North America at 38%, Australia and New Zealand 12%, and much lower rates in other regions of the world.[53]

3.4.2 Increased use of Drainage Water Management. The number of fields in which tile drainage has been installed continues to increase. Tile drains are typically installed in fields with poor drainage to allow access to the field by farm equipment and to prevent damage to crops by standing water. Concerns exist regarding tile drains as a pathway for nutrient and pesticide movement to streams.[54] However, drainage water management is now a USDA-Natural Resources Conservation Service practice[55] that can be used to increase yields by maintaining healthy soil moisture levels and to reduce off-site movement of nutrients, pathogen and pesticide residues. Water control structures function like underground dams that allow farmers to control the water level in the soil. During manure applications, for example, the drain outlet can be raised to minimize drainage and reduce nutrient and pathogen loading. During non-production periods, drainage management can be used in a manner beneficial to local wildlife. Combined with other conservation measures to reduce erosion, proper drainage management can improve water quality and increase protection of aquatic habitats.

3.4.3 Vegetative Buffer Strips. After the depression and dust bowl of the 1930s in the United States, vegetative buffer strips were encouraged as a way to prevent soil in fields moving into surface water bodies and also as a way of limiting movement of compounds tightly bound to this soil. Later, researchers began to realize that buffer strips could also be useful in removing compounds less strongly bound to soil.[56,57] The USDA promotes vegetative buffer strips as a conservation measure for improving surface water quality, providing financial assistance to growers for their implementation.[58] Considerable progress has been made in the past decade in estimating the effectiveness of vegetative buffer strips in removing crop protection products from runoff water.[59]

3.4.4 Treatment of Furrow Irrigation Outflow. In arid regions, furrow irrigation is sometimes used to provide water to crops. Typically there is outflow of water from such an irrigation system, which contains sediments, nutrients and crop protection products. The ultimate solution is either storing and reusing this water or switching to drip irrigation. However, such management practices have not yet been adopted by all growers. A number of technologies have been adopted to reduce the impact of furrow irrigation outflow on surface water bodies and these can be used individually or sometimes in combination with other technologies. The addition of polyacrylamide (PAM) can be used to minimize losses of sediment and crop protection products bound to sediment.[60] Sedimentation basins, often in combination with the use of PAM, can also be used to minimize losses of sediment and crop protection products bound to sediment.[61] Vegetative ditches and constructed wetlands receiving outflows from multiple fields[62] are other techniques used for removing sediment and promoting degradation of crop protection products in outflows from furrow-irrigated fields.

3.4.5 Management of Urban Applications. Recent work with pyrethroids has shown that switching from broadcast applications to spot or crack and crevice applications on impervious surfaces, such as driveways or garage doors with a direct pathway to street drains, can dramatically reduce movement of crop protection products applied in urban/suburban settings to urban streams.[63] Formulations can be optimized to reduce runoff losses of crop protection products in urban/suburban environments, but this effect is less than that obtained from switching from broadcast to spot or crack and crevice applications.[64]

4 Role of Regulation in Technology Development

Clearly the challenges being faced in increasing global production in a sustainable manner will be dependent on innovative approaches, integrating multiple technologies to minimize environmental impact while avoiding failure to control pests, diseases and weeds due to resistance development.

As government funding in agricultural development is reduced, increased private investment is anticipated and has been steadily rising. As outlined in Section 2, however, costs of bringing a new synthetic chemical or new plant trait to the market are substantial, leading to significant consolidation within the industry. More importantly, time frames from discovery to first sales continue to increase for both technologies, with each now surpassing ten years on average.

In considering environmental impacts, innovation would be improved by finding quicker and more effective ways of predicting and appropriately mitigating potential effects, while balancing these against the benefits such as higher yields, less land use, reduced water consumption and lower carbon footprint. Regulatory requirements for biopesticides[65] and gene-editing processes are still evolving, but these techniques are generally considered close to natural processes and may, therefore, be able to be assessed for potential risks and regulated under more rapid and less onerous regulatory burdens.

Since their introduction, there has been tremendous progress in reducing the potential risk that synthetic chemicals pose. Improved screening processes, identification of taxa-specific modes of action, extended and better validated testing protocols have all contributed to this.[66] Use rates have fallen significantly, environmental detections are generally tending downwards[67] and overall safety has increased, but paradoxically so has public concern. Incorporating the views of concerned citizens into environmental policy debates is a core value of a democratic society, but in the case of plant protection products its application is a complex one. Non-governmental organizations, regulatory authorities, the crop science industry, scientific community, consumers, food retailers and growers all have valid inputs from a domestic perspective, but the discussion also has implications for global trade. Lay persons and a range of technical experts have to be able to interact on the issue. Grounding such discussions by first undertaking a structured approach to assessing stakeholder values, rather than initially focusing on arcane technical details, has been proposed as a way of developing a more rational approach to the subject.[68]

Addressing and incorporating stakeholder concerns is well beyond the scope and remit of this chapter but it is important to recognize the role of risk assessment in the debate. Risk assessment quantifies the probability that an effect may occur and, therefore, attributes a number to it, even though that number may be extremely small and essentially *de minimis* or indistinguishable from background. Under this process, by definition, no technology is completely free from risk. At the same time, given financial constraints, no technology is likely to be widely accepted if it is without significant benefit. The focus of this debate, however, often centers on the risks of synthetic chemicals and then often on one component of the risk such as toxicity, *e.g.* levels at which effects are seen, or exposure, *e.g.* detections in monitoring studies. A compound with low inherent toxicity but high exposure because it is used in high amounts can pose the same risk as a compound with high inherent toxicity that is used in low amounts. Using a single toxicity or exposure value in isolation is not informative in making characterizations of risk. Any debate on the merits of a technology should quantify the risks and quantify the benefits while at the same time doing the equivalent calculation for the alternatives.

Greater interaction and cooperation is required between academic, government, industry and regulatory scientists to facilitate the adoption of innovative technologies which can enable farmers to increase production of healthy foods more sustainably. The crop protection industry is evolving in exciting new dimensions in the wake of a more connected world, but companies must be sensitive to the concerns of citizens and their many stakeholder groups. Research and development programs must address the needs of people, with the needs of our planet, and the need for profit. As an industry, new agricultural systems must maximize production while protecting public health and biodiversity, and minimizing environmental exposure.

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The Environmental Impact of Fertiliser Nutrients on Freshwater

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ABSTRACT

Fertilisers drive the productive potential of land, but inefficient use can cause issues such as the impairment of freshwater quality. This chapter outlines our current understanding of nitrogen (N) and phosphorus (P) use efficiency by crops, factors involved in the loss of N and P from land and the likely impact on freshwaters (surface and ground). This understanding is then combined with knowledge on the range and cost-effectiveness of strategies to mitigate losses and the associated implementation pathways (*e.g.* voluntary or regulatory instruments) to meet a water quality target. We end with some thoughts on where additional research is best focused to reduce the environmental impact of fertilisers on freshwater.

1 Introduction

Fertiliser-derived nutrients drive productive crop and livestock agriculture and fisheries. Their efficient use is important to grow fodder and feed for animals, and nutritious produce for human consumption at the lowest cost, and to minimise externalities. Two key externalities often highlighted are the extraction or consumption of resources to make fertiliser, and the off-site environmental impacts of fertiliser once it leaves the soil-plant-animal

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system.[1,2] World Bank data show that an average of 141 kg of fertiliser (nitrogen [N], phosphorus [P] and potassium [K], combined) was applied per hectare of arable land globally between January 2010 and December 2012, of which 92% was manufactured.[3] The manufacture of N from the atmosphere by the Haber–Bosch process is energy-demanding, accounting for over 90% of the total energy input into fertiliser production.[4] Energy supplies will become increasingly limited in the future and fertiliser costs may therefore increase quickly. There is also some concern that the quantities of mineable P and K are finite,[4] with estimates of existing resources varying greatly. To avoid increasing costs associated with the extraction of cheap and easily-accessed reserves or using those of poorer quality (*e.g.* contaminated by cadmium[5]), many call for greater effort in extending the use of existing supplies.[6]

Environmental externalities relate largely to the historic and current inefficient use of N and P within the food chain, leading to long-term storage in soils, sediments and groundwater and significant losses to air and surface water.[7–9] Potassium has no direct environmental impact, but plays an important role in optimising N and P uptake.[10] More efficient use of NPK fertilisers should help to decrease off-site water and air quality impacts. However, an agronomically efficient system can still degrade water quality because the quantities of N and P required to do so are much lower than would affect crop yield.[11] With increasing global demand for nutrients in food, the sustainable management of fertilisers to protect vital resources and avoid environmental damage represents a major challenge for the 21st century.

This chapter outlines the current state of knowledge relating – principally – to the impact of fertilisers on freshwater quality. We discuss this issue from source to sink and include manure nutrients, because fertilisers also indirectly influence the amounts of N and P excreted by animals. Sources are covered as the requirements and utilisation of N and P for different crops. Combining these sources with transport mechanisms, we then outline those processes that take N and P to sites of impact (*e.g.* surface and groundwaters), assess the various adverse effects that may result, and strategies to mitigate losses or impact. Finally, we discuss those research gaps and practices that need to be addressed if we are to improve nutrient efficiency and water quality.

2 The Requirements and Utilisation of N and P by Different Crops

Fertiliser nutrients are added to soils to maintain crop production. A large proportion (over 50%) of this crop production is fed to animals such that fertilisers also indirectly drive livestock production (in non-grazed systems) to meet the demand for meat, milk and fibre.[12–14] The N and P fertiliser requirements of different crops vary according to climatic conditions (*e.g.* rainfall, sunshine, warmth, *etc.*), the quantities of N and P already in the soil (as often indicated by agronomic soil tests like Bray I or Olsen's), the quantities of N and P supplied by inputs of different organic manures, and the management of the soil (*e.g.* crop rotations and tillage). Generally, fertiliser recommendations are made after assessing soil fertility, manure inputs and crop rotations with the aim of replenishing the N and P that would be removed by the following crop.[15,16] However, the efficiency of N and P fertiliser use by crops is reduced by abiotic and/or biotic immobilisation in soils, especially in the year of application; two examples from long-term experiments are shown in Figure 1. In many cases, the annual recovery of N and P by crops is poor, depending on nutrient input, soil type, crop type and management system; for example, $<50\%$ for N and $<10\%$ for P are common.[17–19] Overall, N and P use efficiency is lower in grassland systems than in arable systems because a large proportion of the N and P fed to animals is excreted and the conversion of nutrients into meat is consequently very low. Surpluses of N and P in livestock systems and risk of loss to water are therefore invariably greater than in arable systems.[13,20,21]

For P, fertiliser recommendations try to maintain a soil test P (STP) concentration that maintains and does not impair crop production (Table 1). Past recommendations were to add a little more P to the soil to maintain a STP concentration above this agronomic minimum on the basis that P, unlike N, is not lost to water and stays in the soil and that this would guarantee a response in years with poor growing conditions.[22] However, the recovery of fertiliser P by plant roots tends to decrease with increasing STP concentration above the agronomic minimum as an increasing amount is either stored in poorly available pools or lost to water.[22–25] Withers, *et al.*[26] argue that this insurance-based approach to P management, as well as the large uncertainties in assessing soil fertility status on different soil types by soil analysis, is inherently inefficient and that a paradigm shift towards more targeted P applications to the crop that minimise fertiliser-soil contact is required. Moreover, since the 1990s there has been increasing evidence to show that while non-point P losses from agriculture to water are rarely of agronomic significance, they have caused significant surface water quality issues (*e.g.* eutrophication).[27] Research has demonstrated that P losses in runoff tend to increase with increasing STP concentrations (Figure 2a), and this has led to the development of regulations or guidelines to reduce STP concentrations to the agronomic optimum, and to restrict P inputs (fertilisers and manures) to no more P than is agronomically required.[28] Despite adhering to this recommendation, if the soil is low in Al or Fe oxides or is highly erodible (*e.g.* has poor vegetative cover), environmentally significant losses of P can still occur,[29] requiring other strategies to mitigate P losses. These will be discussed later in this chapter.

Nitrogen is the most heavily-used nutrient applied to crops. Historically, farmers relied on mineralisation of soil organic N and manure additions to provide plants with available forms of N. However, the advent of synthetic fertiliser manufacturing has allowed farmers to supply crops with N in a

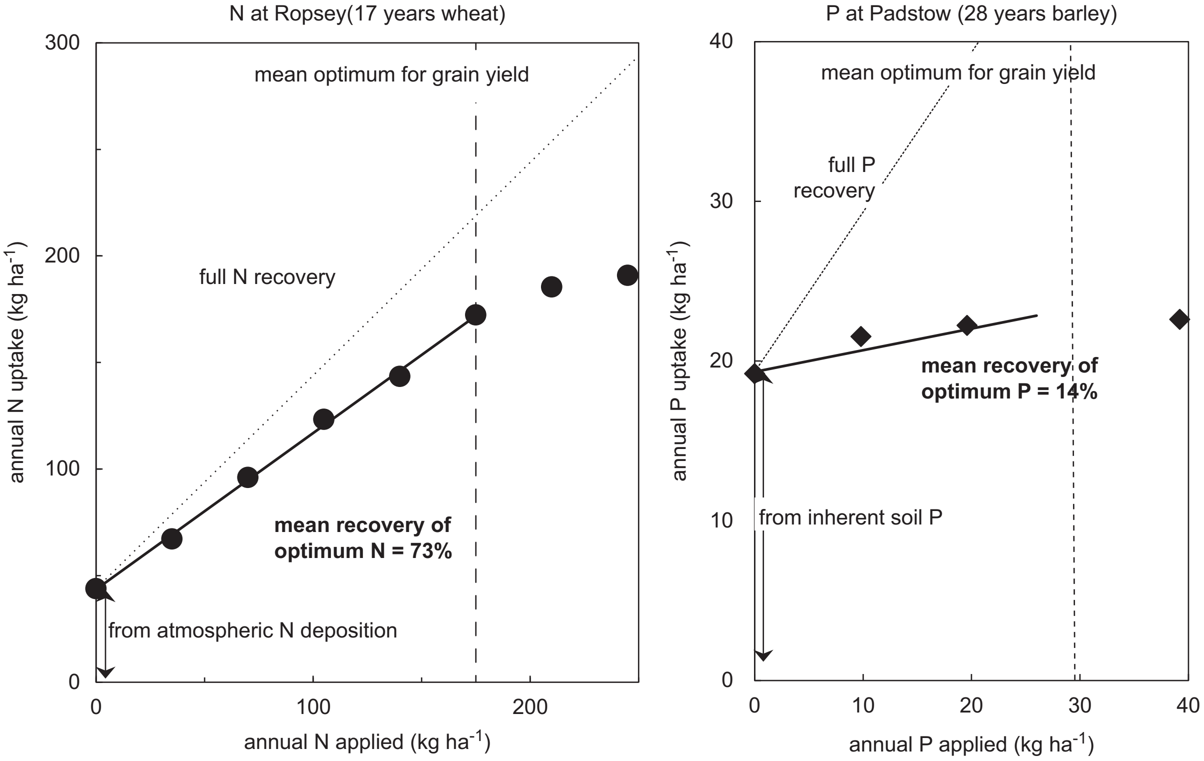

Figure 1 Mean recovery in above-ground crops of fertiliser N by wheat at Ropsley[129] and fertiliser P by barley at Padstow.[130] The recovery figure for N includes a carry-over of 10% from soil N residues and excludes that obtained from atmospheric N deposition or supplied from inherent soil P pools. The difference between N or P taken up by the crop and that applied at optimal yield represents mean recovery.
The figure is redrawn from Sylvester-Bradley and Withers[115] and reproduced courtesy of the International Fertiliser Society.

Table 1 Nutrient use application and removal rates for different crops (taken from Nicholls, *et al.*[128] unless otherwise indicated).

Crop	Yield[a] (t ha^{-1})	Recommended application rates (kg ha^{-1} yr^{-1})		Agronomic optimum Olsen P (mg kg^{-1})	Removal rates (kg ha^{-1} yr^{-1})	
		N	P		N[b]	P
Barley–grain	5.0–8.0	30–100[c]	10–30	20–25	100–160	20–32
Barley–straw[d]	4.5–5.5				21–25	2–2
Maize–grain	12.0	30–210[e]	20–60	15–30	168	36
Maize–silage	21.0	50–155	20–60	15–30	273	63
Oats–grain	7.0	55–120	15–30	15–20	112	21
Oats–straw	8.5				50	5
Peas–grain	5.0	0–30	12–20	10–15	170	19
Potato–tubers	60	150–300	35–50	35–55	210	30
Rice[f]–grain	3	40–50[g]	7–12[7]	N/A	25	6
Ryegrass–seed	2.0	150–200[h]	20–30	15–25	48	8
Ryegrass–straw	8.0				90	9
Soybeans[i]–grain	2.1–4.9	0–55	15–34	8–11	140–330	13–31
White clover–seed	1.0	0[j]	0[10]	10–15	52	6
Wheat–grain	5.0–12.0	100–200 (bread)	15–48	20–25	87–240	17–40
Wheat–straw	5.5–10.0	100–150 (feed)			38–69	4–8

[a] Yield is given as a range where there is appreciable variation.

[b] Amounts of N in the grain will depend on the desired protein concentration.

[c] Assumes soil N supply approx. 50 kg N ha^{-1} readily available plus another 50 kg N ha^{-1} becomes available during plant growth.

[d] Amounts of straw will vary with cultivar, sowing date and the use of a plant growth regulator.

[e] Assumes low-medium soil N supply (50–125 kg mineral N in 0–60 cm soil pre-sowing).

[f] Taken from recommendations provided by Olk *et al.*[133]

[g] Recommended rate to increase yield by 1 t ha^{-1}.

[h] Best yields occur when soil and fertiliser N are *ca.* 200 kg N ha^{-1}.

[i] Taken from recommendations provided by the Iowa, Ohio and Minnesota State Universities' extension programmes to maintain yield of 30–70 bushels acre^{-1}, available at: http://extension.agron.iastate.edu/soybean/production_soilfert.html, http://ohioline.osu.edu/e2567/, and http://www.extension.umn.edu/agriculture/nutrient-management/nutrient-lime-guidelines/fertiliser-recommendations-for-agronomic-crops-in-minnesota/soybean/, respectively.

[j] N typically not required while excess P increases vegetative growth.

readily available form. This development also allowed farmers to manage the amount and timing of N supply to meet crop demand. Poorly managed fertiliser inputs can result in an over-supply or incorrect timing of N, which can lead to significant amounts of N loss.[30] A typical example is given in Figure 2b and illustrates the major challenge that growers face in defining the appropriate rate and timing of N fertiliser applications.

As noted earlier, N requirements vary according to crop type, climatic conditions, soil N supply and soil management, with N applied tactically to achieve specific yields (Table 1). The supply of N from soil organic N pools can vary greatly, depending on previous crop rotations, soil type and depth, and climate.[15,31,32] For example, fields that have been continuously cropped for more than 20 years without a restorative crop rotation such as pasture can contain low concentrations of mineral N, or readily mineralisable N (*e.g.* 50 kg N ha^{-1} in the top 90 cm). In contrast, fields cultivated out of grassland

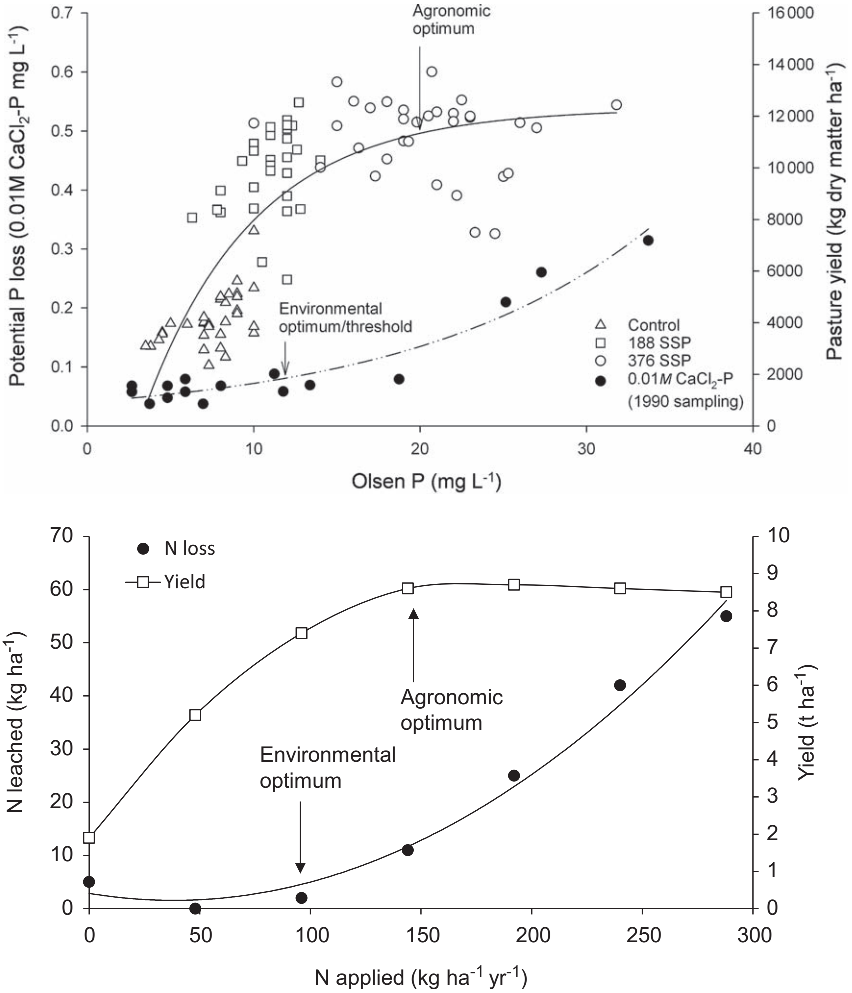

Figure 2 The relationship between optimising crop yield and increasing losses of (top) P in land runoff from grazed pasture [redrawn from McDowell and Condron[25]], and (bottom) N in leachate from arable land (adapted from Goulding[131]). For P, soil test P concentrations above the agronomic optimum lead to greatly increased P losses, providing a clear strategy to reduce soil P. For N, the amount of N required to minimise nitrate leaching will compromise crop yield.

or clover seed production may result in high rates of soil mineralisation, which can lead to more than 200 kg mineral N ha^{-1} being available for the next crop.[33] The amount of N fertiliser required for a crop with high N requirements will differ greatly for these two fields. To maximise the utilisation of soil mineral N requires better quantification of the soil N supply; fields can be soil sampled to depth (*e.g.* 60 or 90 cm depth) to establish the initial soil available N supply. This information is then used in conjunction with knowledge of a realistic potential yield to better determine the rate of fertiliser N required, rather than estimating this based on field crop history. Decision support tools are also increasingly used to help farmers and consultants to manage their fertiliser N inputs for crop production. These tools use deep soil mineral N test results, along with other key information such as crop cultivar, sowing date, soil type and climate data to optimise wheat, potato and maize yields while minimising N loss.[34]

Optimising fertiliser management on the farm can help to improve the utilisation of N and P by plants and minimise its environmental impact. For example, the International Plant Nutrition Institute 4R framework for nutrient stewardship recommends that optimising nutrient use efficiency requires that fertilisers are applied in the right form, the right amount, at the right time, and in the right location.[35] Applying fertiliser when plants are actively growing and avoiding times of poor growth and high runoff potential can maximise the opportunity for plant uptake.[36] Banding P fertiliser nearer the seed, or in areas of active root growth, instead of surface application, can improve utilisation and decrease losses *via* surface runoff.[37] Likewise if the crop is used for forage, regular grazing will ensure that N and P uptake is maximised by vegetative growth.[38]

3 The Loss, Impact and Management of Fertiliser N and P from Land to Water

Much research has quantified the factors influencing the loss of nutrients from agricultural land to water. Due to a wide array of catchment processes and farming systems, the mitigation of these nutrient losses is complex.[39] However, a way of reducing complexity is to consider losses as a function of the availability of nutrient sources to loss, a transport pathway to get them from their source to streams and rivers, and intervening attenuation processes along the transport pathway (Figure 3). Both availability and transport can be influenced by land use and land management; for instance, switching nutrient forms and concentrations between dissolved and particulate forms due to filtration, or release when runoff passes through arable and grassland areas of a catchment (Figure 3).

3.1 The Availability of Nutrient Sources to Loss

A surplus of N and P increases the availability of N and P for loss, irrespective of the farm type (Figure 2). As N is highly mobile in soils compared to P, there is often a strong relationship between agricultural land use intensity and nitrate concentrations in watercourses, especially in relation to the percentage of arable land (*e.g.* see Davies and Neal[40]). Although surpluses of N are much larger in grassland systems than in arable systems, the amount of N leached per unit of surplus is less under grazed systems, which largely reflects the much greater gaseous losses of N (*i.e.* ammonia emissions and

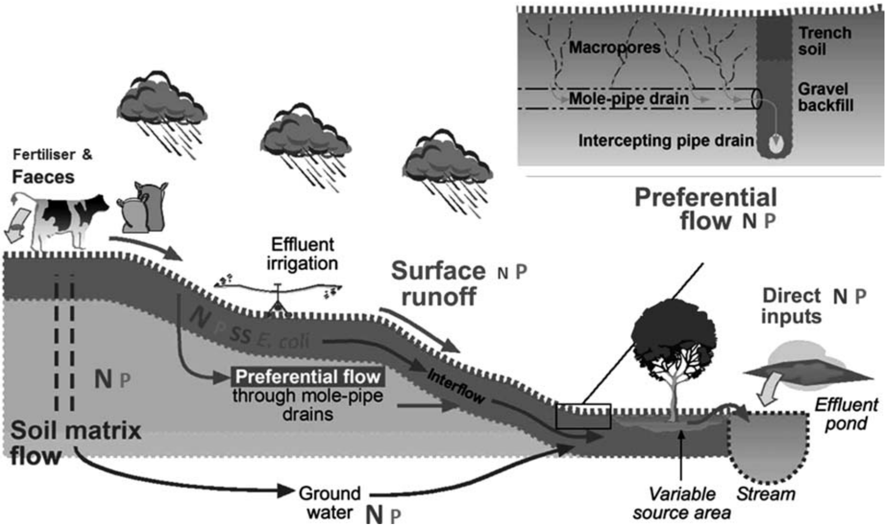

Figure 3 Conceptual diagram of the transport pathways involved in the transfer of nitrogen and phosphorus from land to water. The presence and relative font size for each of the contaminants indicates the importance of the pathway to contaminant-specific loss.

denitrification) from livestock manures and grassland systems.[14,41] Significant N leaching losses can also arise from soil N residues left by fertilisers applied to the previous crop, and direct linkages between fertiliser use, N surplus and river nitrate concentrations are therefore not always apparent.[14] Much of the N is contained in the soil in association with organic matter, which can be mineralised and released whenever the soil is tilled.[31] Planning crop rotations to consider the likelihood for drainage and the timing of fertiliser inputs is an important factor in helping to minimise the size of the N pool available for loss.[42] For example, in grazing systems the inefficient conversion of dietary protein to milk, meat and fibre by ruminants results in urine patches that can have equivalent N concentrations of up to 1000 kg N ha^{-1}.[43] This is well in excess of the N requirement of most grasslands, leaving the rest available for loss, either in gaseous form or *via* leaching. A key management factor for decreasing the amounts of N potentially available for loss from grazing systems is therefore manipulation of the amounts and timing of urinary N excreted and deposited to pastures by the animal. This can be achieved by considering animal stocking rates, dietary composition and the duration of pasture grazing.[44]

Unlike N, P is actively retained by soil and as P surpluses increase, the soil becomes progressively P-saturated, leading to increased availability of P to runoff.[45–47] Soils with lower anion storage capacity are particularly vulnerable because they saturate more quickly, and dissolved P release from these soils to surface runoff, sub-surface flow and into groundwater is a particular problem, especially as dissolved P is highly bioavailable.[48] The erosion of particulate-associated P occurs during periods when crop cover is minimal, and where the soil has been recently disturbed by cultivation,[49] and loss *via* surface runoff can be enhanced by soil compaction due to treading by grazing animals.[50] Intensively farmed soils are an endemic P source for water because loss occurs every time it rains and runoff is generated. Key management options to reduce soil P loss are therefore to ensure soil P remains well below P saturation levels (typically 10–30% of P sorption capacity, depending on the method used; *e.g.* see Withers *et al.*[51,52]), to provide crop cover to protect the soil surface, and avoid soil structural damage by machinery and livestock. However, in contrast to N, cover crops are much more variable in their effects on P leaching losses.[53]

In addition to soil, fresh applications of N and P may also enter into streams either directly, due to poor fertiliser and effluent/manure management in riparian areas, or in rapid surface runoff and drain-flow during storm events that follow fertiliser and manure applications to the soil surface.[54–56] In contrast to the soil losses, these losses only occur when N and P are freshly applied, depending on the type of manure, the rate, method and timing of application, and the frequency and timing of rainfall events after application. In an arable system, Withers, *et al.*[57] found the largest P concentrations (up to 90 mg L^{-1}) and losses in runoff following application of water-soluble inorganic fertiliser and cattle slurry. Similarly high P losses were related to the water solubility of P fertilisers used in a pastoral system.[58]

A key feature of N losses in surface runoff from N fertilisers and manures is that they are dominated by ammonium (and soluble organic N) rather than nitrate, presumably because of the lack of nitrification of the N in manures, and infiltration of fertiliser nitrate into the soil. For example, Smith, *et al.*[54] measured concentrations of ammonium N in surface runoff of up to 30 mg L^{-1} following high rates of slurry application. The largest N and P concentrations occur soon after it rains and decrease exponentially thereafter.[59,60] If the soil is artificially drained and has preferential flow paths, the application of slurry, especially to wet soils, can result in enriched ammonium-N and P concentrations in field drain runoff (Monaghan *et al.*[61,64,65]). This suggests that farmers should have sufficient (over-winter) slurry storage capacity to provide the flexibility to spread slurry when soils are relatively ‘dry’ in spring and summer (*i.e.* ideally when the soil moisture deficit is >20 mm). In a similar manner, inorganic fertilisers are best applied to match crop needs, and during spring and early summer when crops are actively growing and soils are not too wet or too dry.[62]

Another potential source of N and P loss on grazed dairy farms is plant residues. Where, in arable systems, P may be lost from plant residues *via* freeze/thaw conditions,[63] grazing and treading by the cow rips and crushes pasture shoots, making them temporarily available for loss in runoff.[64] Losses of P to water can be enhanced by dung deposition, the availability of which decreases rapidly as a crust forms on the dung, thus impairing interaction with rainfall.[65]

3.2 Pathways of Nutrient Loss

Nutrient losses from fertilised land are mediated through the hydrological cycle. As water moves through the landscape in response to rainfall, dissolved and particulate forms of N and P are mobilised in land surface and sub-surface runoff and delivered to the receiving waterbody.[66] Travel distances and times for nutrient runoff are dependent on the proximity of the nutrient source to the waterbody and the major flow pathway involved. Hydrological travel times can vary from minutes in surface runoff to decades for nutrient transport through aquifers.[67] For example, Howden, *et al.*[68] estimated a travel time of 37 years for N applied to a small groundwater catchment in Dorset, England, with clear implications for the speed of recovery if N inputs ceased. The longer the travel time, the greater the opportunity for attenuation of nutrient loss. The continuum of hydrological travel times and the variable degrees of attenuation combine to give a large degree of complexity in solute behaviour in catchments, including those derived from fertiliser additions and intensive farming.[69,70]

Storm-generated land runoff can be split into true surface runoff and subsurface flow paths that may or may not involve interflow, flow through field underdrainage systems (tiles, plastic pipes or mole drains), or flow through the unsaturated zone and into groundwater. For surface runoff, nutrient losses can occur *via* infiltration-excess and saturation-excess runoff mechanisms.[71] Under infiltration-excess conditions, the infiltration capacity of the soil is exceeded, resulting in direct surface runoff. In temperate ecosystems, this can occur all year-round, usually under high-intensity rainfall (or hydrophobic soil conditions[72]) and is most prevalent in areas that have been severely compacted by overgrazing, heavy machinery or overcultivation,[73] or where soil pores have become blocked or sealed at the surface by excessive manure applications.[74]

In contrast, saturation-excess surface runoff only occurs when soils are saturated (largely in winter and spring) resulting in any excess rainfall running off. In continental ecosystems, saturation-excess is generally associated with snow melt or other lengthy wet periods.[75] Due to topography, the areas affected by saturation-excess surface runoff are generally located near the stream channel and expand and contract in response to rainfall events and evapotranspiration.[76] However, saturation-excess runoff can also occur in very poorly-drained soils where a perched water-table results. As previously noted, fertiliser and manure applications to already saturated soils are the most vulnerable to direct loss in runoff, and runoff is perhaps a more important contributing factor to manage than nutrient inputs.[55,66] Due to the energy of high-intensity rainfall events, infiltration-excess surface runoff can contain more soil particles than saturation-excess surface runoff.[77]

For subsurface flow paths, the confined pore size of soils, the vadose zone and aquifers impart a much greater attenuation effect in transport and longer travel times to surface water than is likely in direct transport *via* surface runoff. Flow rates will depend on soil type and aquifer lithology and whether subsurface flow is intercepted by artificial drainage. In drained soils, macropores can provide a rapid conduit between surface sources of N and P and transport them *via* subsurface drains to open drains or directly into streams.[78] In grassland systems where surface runoff has been identified as a significant pathway of, for instance, P loss, evidence exists to show that losses may simply be transferred in subsurface flow when artificial drainage is installed.[79] Over time, artificial drainage networks may also serve as a source of P where, for instance, the banks of surface drains collapse and erode or mole channels linked to pipe drains collapse.

3.3 Attenuation

Attenuation refers to the loss or temporary storage of nutrients as they are transported from where they are generated to where they impact water quality (*i.e.* a stream, lake or estuary). Generic attenuation processes include filtration and deposition, adsorption and precipitation, microbial immobilisation and transformations (*e.g.* denitrification), assimilation in vegetation and other physical and biogeochemical processes. These processes can decrease nutrient concentrations and loads, and modify availability (*e.g.* particulate organic compared with dissolved inorganic), and their expression differs between individual catchments.

Filtration restricts nutrient transfer *via* groundwater to those contaminants that exhibit a dissolved phase and are not well sorbed, or retained. Nitrate is readily mobile, and is the most important agricultural contaminant of groundwater due to the perceived linkage between high nitrate and adverse human health.[80] Although generally well sorbed, some evidence exists to show P can also move through soil and into groundwater. For instance, McDowell *et al.*[48] found groundwater enrichment with P in certain areas of New Zealand where there was a land use regularly supplying P, a soil type of low P sorption capacity, and sufficient drainage (by rainfall or irrigation) to transport P to groundwater. Enriched groundwater P concentrations have also been recorded beneath slurry lagoons on farms.[81] Flow into aquifers of low P sorption capacity (*e.g.* sand and gravel) and well connected to surface waters, has resulted in baseflow enrichment in streams that reflected land use P leaching losses. Extensive areas of Europe have severe groundwater P contamination of this kind in low-lying areas with shallow groundwater and where nutrient surpluses are high.[82] Groundwater enrichment of river baseflow, especially in warmer months, is a major concern, not only because this is the period when nuisance algae grow best, but also because river P concentrations may continue to increase even when P inputs to land cease.

The main attenuation process for nitrate in groundwater is microbially-mediated denitrification, which occurs once oxygen levels are low or absent (anoxic, reducing). The rate of removal depends on the amount of nitrate-containing water that flows through reducing zones. This can also vary seasonally with rises and falls in groundwater levels. Woodward, *et al.*[83] demonstrated how nitrate concentrations changed in the Toenepi

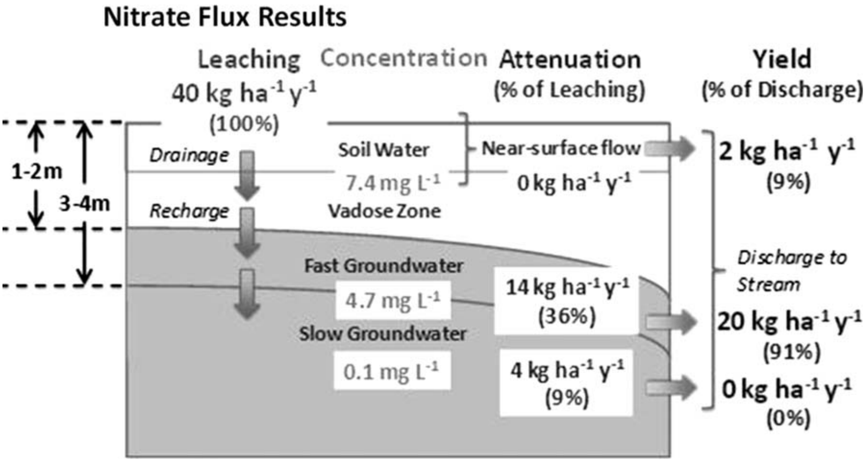

Figure 4 Schematic of N fluxes in Toenepi catchment based on Woodward *et al.*[83] Figure courtesy of Roland Stenger, Lincoln AgriTech Ltd.

catchment, Waikato, New Zealand (Figure 4). Summer flows were sustained by deeper, slower flowing groundwater from a reducing environment that was relatively nitrate-free. During winter, shallower water, which flowed more rapidly through a partially reduced zone, dominated stream flow and was responsible for 91% of the nitrate load. Calculations showed that nitrate concentrations in this shallow groundwater were significantly less than expected and, even though the nitrate load was greatest from this source, the amount of denitrification was also greatest in this zone because of the high N flux combined with the partially reduced environment.

Similar to groundwater, filtration is also the main attenuation process for P in surface and sub-surface runoff. For example, buffer or riparian zones can be very effective at attenuating sediments and attached contaminants from surface runoff originating from cropped land upslope. Studies of riparian buffers[84] show particulate-associated P removal rates of 53–98% that tend to increase with buffer or riparian zone width and decreasing slope. However, removal of dissolved nutrients from surface and subsurface flows can be poor, especially if originating from similar vegetation,[85] *i.e.* a grass buffer strip is unlikely to stop large amounts of nutrients generated from grass. Losses of particulate P in drainflow are invariably lower than in surface runoff because of the filtering effect as water passes through the soil matrix, but losses of particulate P mobilised at the surface and transported along preferential flow paths in drain runoff can still be substantial.[86] Losses of dissolved P in drain runoff are also lower because of adsorption of P lower down in the subsoil where soil P sorption capacity is often high. Differences in filtration and adsorption between hydrological pathways leads to variation in the forms transported to the waterbody; for example, drainflow typically has a higher percentage of dissolved P and nitrate compared to surface runoff which is dominated by particulate P and ammonium-N.[87]

Edge of stream processing of nutrients in headwaters generally involves a seepage wetland area. Nitrate removal can exceed 75% under base-flow conditions.[88] Removal rates for P tend to be much less as wetlands become clogged with sediment and because the anaerobic conditions that promote denitrification solubilise Fe–P minerals in the sediment and release dissolved P.[89] In some cases, attenuation can be enhanced by dredging or re-planting degraded systems,[90] constructing surrogate artificial systems before wetlands, such as sediment ponds or oxygenation areas to improve dissolved P removal,[91] and denitrification walls to improve nitrate removal.[92] An important dilemma for attenuation strategies at the edge of stream is that without careful management, they can become a source instead of a sink for N and P.

3.4 Processing of N and P in Freshwaters

Once in surface waters, NO_3^- (and NO_2^-) can be assimilated by biota or lost in gaseous form to the atmosphere as N_2 and N_2O *via* anaerobic conditions and denitrification in the bed sediments.[93] Regeneration NH_4^+ and NO_3^- from the stream bottom back to the water column can occur *via* several interacting processes, including mineralisation, nitrification, denitrification, and release by organisms. Phosphorus in the water column can be in dissolved reactive or organic forms or associated with sediments or assimilated by biota (*e.g.* periphyton, macrophytes or microorganisms).[94] The abiotic uptake and release of filterable reactive P under oxic conditions is controlled by the composition (Al, Fe, Ca content and grain size) of bed sediments.[95]

The timing of nutrient loss is crucial to impact. Due to lower flows and warmer temperatures, losses of N and P can have a greater impact on periphyton growth in freshwaters in summer and autumn than in winter and spring. This is exacerbated if the form of N and P is immediately bioavailable.[96] Changes in the supply and assimilation of N and P are reflected in the dissolved inorganic N-to-dissolved reactive P ratio. Typically, the supply of P ‘limits’ periphyton growth in freshwaters for most of the year, except during late summer when N-limitation is evident due to little loss through leaching. During this time of vigorous plant growth in streams, demand for N may exceed supply, causing NO_3^- concentrations to be negligible. As soil moisture increases, NO_3^- is flushed from the soil causing concentrations in streams to increase to a maximum value in mid-winter.[97]

For rivers with low water residence times, having most agriculturally-derived N and P fluxes delivered during high flows in autumn and winter, and/or removed from the water column *via* N and P-sediment interactions, helps lower bioavailable N and P concentrations and algal growth during low flows in spring and summer.[7] This is in sharp contrast to lakes and reservoirs, where higher water and sediment residence times mean that more P is available for algal growth.[98]

3.5 Strategies to Mitigate N and P Losses

There are numerous options and strategies available to mitigate the loss of N and P from agricultural land to surface waters. Many are nutrient-, source- or pathway-specific, while others can simultaneously tackle both nutrient sources or transport pathways. Mitigation can be applied at different scales from field to farm to catchment or river basin scale. For a full explanation of the range of options available the reader is directed to review articles such as Cherry, *et al.*,[99] Goulding, *et al.*,[100] McDowell and Nash,[101] and Schoumans, *et al.*[102] Many of the farm-scale mitigations involve increased efficiency of resource use (*e.g.* tailoring nutrient applications to optimal concentrations), which can also decrease farm costs, thereby improving farm profitability. If these options are insufficient to achieve desired targets, then further improvements often have economic implications for the profitability of farming, and/or require co-ordination and action beyond individual farms that may result in some prioritisation of land use.

The applicability and cost-effectiveness of the different options may vary substantially for different landscapes and farm systems,[103,104] not least because their effectiveness is highly site-specific, depending on landscape characteristics and land management (*e.g.* see Ockenden *et al.*[105]). They may also fit differently with the farming styles, knowledge-base, financial status, and preferences of individual farmers.[106] Some options such as re-vegetation of erodible lands or restoration/construction of wetlands may have ancillary benefits (*e.g.* biodiversity, carbon sequestration, aesthetic, cultural or recreation values) that provide value to the wider community. In these cases, cost-sharing between farmers, other interested parties and the community may be appropriate to achieve multiple goals.[107]

Management at the farm-scale can include both strategic approaches that move a farm towards a goal of lower contaminant loss (strategic), and tactical approaches that make the right steps in the short-term to implement the goal. One example combining both approaches would see P losses decreased by the strategic lowering of fertiliser-P inputs to reduce soil Olsen P concentrations and P loss in runoff from soil year-round, and tactical targeting of fertiliser or manure applications to periods when surface runoff is unlikely, decreasing the likelihood of direct fertiliser-P losses.[108] Importantly, such a combined approach addresses both current management issues (directly under the farmer's control) and the legacies of past management (outside the farmer's control). However, on-farm management only addresses local pollution risks and does not address the wider inefficiencies that fertiliser use creates at a larger, regional scale.[109]

Strategic decisions are often set by catchment objectives such as decreasing a load of N or P at the outlet of the catchment. After establishing the need to mitigate losses, there have been a number of methods of implementing mitigations. In many countries, a regulatory approach is preferred (*e.g.* for N in England[110]). However, this relies on regulation being applicable across all possible soil and climatic permutations, which is seldom the case.

This approach can also hinder innovation on new ways and systems to decrease nutrient losses. However, a strictly voluntary approach is also seldom effective.[111] While a proportion of land owners and producers might lead by taking up or adopting new technologies and practices to mitigate nutrient losses, the bulk will continue with the status quo which is to intensify production at a rate often greater than the mitigation of nutrient losses. The key may be to adopt a mixed approach, whereby regulation (backed by science to prove the spatial extent of the problem) prohibits practices that cause substantial nutrient losses. Limits can then be set that allow flexibility (outside of prohibited practices in specific areas) to do what the land owner or producer wishes, provided they cause no additional losses.[107]

A major problem with a mixed approach is that it requires a good understanding of where and when nutrient losses are occurring and then what to do about mitigating them. Trade-offs between N and P may arise, requiring some prioritisation of actions outside of any regulatory controls.[112] For example, under the Nitrates Directive in the EU, closed periods for spreading manure N during winter months to reduce the risk of runoff and nitrate leaching restrict manure applications to spring, but any nutrient loss occurring in spring is more likely to give rise to eutrophication (in rivers). Recent research has made substantial steps in defining the areas that account for the majority of nutrient (and other water quality contaminants) losses. For example, sediment and P loss often occurs from only a minority of a field, farm or catchment's area. These areas, termed critical source areas, can be targeted with mitigation strategies that are far less costly to the land owner or producer than strategies that are imposed across all areas.[113] For instance, highly productive land uses that also leach much nitrate-N could be located in areas where recharge from these land uses passes through a reducing environment (*e.g.* groundwater or riparian zone), decreasing their impact on catchment load limits.[83] More challenging landscapes are those with multiple hydrological pathways; for example, under-drained land where it is more difficult to define contributing areas.

Additional work indicates that when applied on the basis of cost-effectiveness, and giving the producer the opportunity to choose strategies, the mitigation of, for example, P losses can be achieved at little cost.[103] It is also well known that strategies to decrease P loss (and that of other contaminants like sediment) are more cost-effective the closer they are to the source of loss.[101] For instance, losses associated with stream bank erosion, or drainage of P-rich farm dairy effluent, can be alleviated by simple strategies such as better fencing and only applying effluent to dry soils, both of which are much more cost-effective than relying on a constructed wetland to mop up P farther downstream.[101] A perennial problem is that mitigation practices are usually only tested in a few sites, which means that their effectiveness may vary under different soil types and climates. This often leads to cost-curves that are farm- or regionally-specific[114] (*e.g.* Figure 5). Such uncertainties suggest a combined source and transport approach is required.[99] An alternative approach is to bundle mitigations by cost-effectiveness and

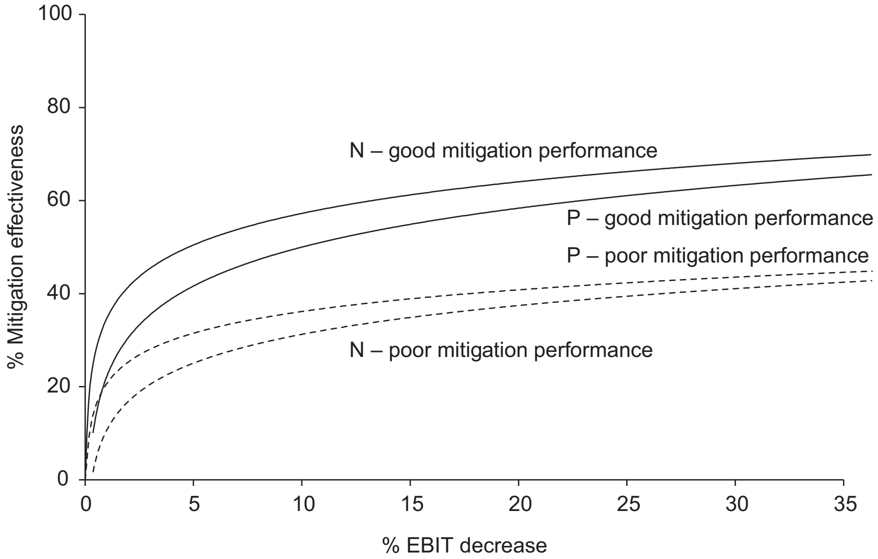

Figure 5 Cost curve showing the percentage change in earnings before interest and tax (EBIT) against the percentage N and P mitigation effectiveness for an example Canterbury dairy farm – provided mitigations are applied on the basis of cost-effectiveness. Curves are generated to account for good and poor mitigation performance associated with spatial and temporal variation. Data calculated from McDowell *et al.*[132]

ease of use (Table 2). While the difference in cost-curves and mitigation effectiveness may be wider (*cf.* Figure 5), variation in uptake and implementation by land owners means that impacts on water quality may be just as good as strategies implemented strictly on the basis of cost-effectiveness. Data on cost-effectiveness (*e.g.* Figure 5 and Table 2) at the appropriate scale can then be used in estimating the ability and cost of meeting water quality objectives, such as those requiring a percentage decrease in nutrient load at catchment, regional and national scales.

4 Future Directions and Research Gaps

Fertilisers are an essential if increasingly expensive input into modern farming systems and they have been indispensable in meeting current levels of global food production. However, their continued use in supporting agricultural intensification may be unsustainable through inefficient utilisation at the farm scale and in the wider food chain, causing issues such as water quality impairment.[115] A key cause of inefficiency is our inaccuracy in predicting the seasonal variation in local crop nutrient requirement, soil nutrient supply, and manure nutrient availability. This will likely remain a challenge requiring different strategic solutions, and a shift towards increased innovation in precision nutrient management, plant breeding to

Table 2 Bundles (grouped according to ease of implementation) of mitigation strategies for dairy and lowland sheep farms targeted to specific or multiple contaminants. Annualised costs are given in \$ ha^{-1} yr^{-1} and effectiveness (in parentheses) is the percentage expected decrease in anthropogenic contaminant loss.

Bundle	Measure	N	P
Dairy			
Easy	Stock exclusion from streams[a]	Y	Y
	Infrastructure for better FDE practice[a]	Y	Y
	laneway runoff diverted[a]	Y	Y
	Decreasing Olsen P to agronomic optima[a]		Y
	Using low water solubility P fertilisers[a]		Y
	More efficient irrigation[a]	Y	
Cost (effectiveness)	Minimum	5 (0.1)	8 (12)
	Median	7 (1)	10 (21)
	Maximum	12 (2)	15 (75)
Medium	Less fertiliser N applied[b]	Y	
	Installing wetlands and/or sediment traps[a]	Y	Y
	Autumn substitution of N-fertilised pasture[b]	Y	
	Using winter-active pasture species[b]	Y	
	Split grass-clover pastures[c]		Y
	Tile drain amendments to sorb P[a]		Y
Cost (effectiveness)	Minimum	95 (15)	30 (39)
	Median	230 (25)	70 (54)
	Maximum	450 (35)	125 (85)
Difficult	Off-paddock wintering[a,b]	Y	Y
	Restricted grazing of pastures[a]	Y	Y
	Restricted grazing of cropland[a,b]	Y	Y
	Alum application to pasture[a]		Y
	Alum application to crop[a]		Y
Cost (effectiveness)	Minimum	395 (46)	330 (65)
	Median	750 (58)	640 (76)
	Maximum	1195 (70)	970 (94)
Sheep (lowland)			
Easy	Stock exclusion from streams[a]	Y	Y
	Using low water solubility P fertilisers[a]		Y
Cost (effectiveness)	Minimum	0 (0)	5 (5)
	Median	5 (0.1)	10 (9)
	Maximum	11 (0.2)	17 (42)
Difficult	Installing wetlands and/or sediment traps[a]	Y	Y
	Using winter-active pasture species[b]	Y	
	Tile drain amendments to sorb P[a]		Y
	Split grass-clover pastures[c]		Y
Cost (effectiveness)	Minimum	12 (4)	25 (36)
	Median	25 (8)	70 (52)
	Maximum	90 (19)	140 (65)

[a] Outlined in McDowell and Nash.[101]
[b] Outlined in Monaghan *et al.*[134]
[c] Outlined in McDowell, *et al.*[132]

lower crop nutrient demand, incorporation of crop traits and microbial engineering to utilise untapped soil nutrient reserves, and the chemical formulation (*e.g.* nanofertilisers) and targeting of fertilisers (*e.g.* seed dressings or foliar applications) to improve N and P recovery and decrease N and P immobilisation in soils.[116–118] A key requirement for the successful adoption of these innovative strategies is an informed and involved farming community.[119]

Whilst future research must meet these on-farm challenges, there is also a need to consider the wider governance of nutrients at larger spatial scales to overcome the inefficiencies associated with the current lack of integration of crop and livestock production, and the spatial and temporal disconnects between where fertilisers are produced, where they are used and where food is consumed.[120,121] Fertiliser nutrients end up being concentrated in high-producing agricultural areas where they can be lost to surface and groundwaters, or in urban areas where there is very little recovery and recycling of nutrients back to the land, because it is economically not worthwhile to do so.[122] The nutrients discharged to surface waters result in global water pollution that is of considerable cost to society. For example, it is estimated that freshwater eutrophication in the US costs $2.2 billion every year.[123] The costs of these externalities must be taken account of in some way if progress towards a more nutrient-efficient world is to be achievable. The development of policy strategies towards a circular economy, and greater societal awareness of nutrient management with zero waste, will help to overcome these food chain inefficiencies. Voluntary frameworks for improved nutrient stewardship have been proposed (*e.g.* the 4R stewardship for P[124]) but, while they may yield some positive outcomes, they will not be successful without some regional governance and acceptance of responsibility for nutrients.[107] Given that the main environmental impact of fertiliser nutrients is on water quality, it makes sense to focus such governance at the river-basin scale. However, the best outcome relies on finding an approach that provides for innovation and flexibility to produce profitability, while meeting the regulatory needs associated with water quality. Inevitably, this will require greater co-operation between all stakeholders involved and an economic and/or regulatory incentive or driver to produce in such a way that minimises effects on water quality.

It is unlikely that improvements in fertiliser use efficiency and improved governance of nutrient use will halt aquatic eutrophication without investment in strategies that also mitigate nutrient losses at the farm and catchment scale. Nutrient losses to freshwater are inevitable, but the question is whether they can be constrained sufficiently to limit their impact on freshwater ecosystem function. This is a particular issue for N because of the larger amounts applied and its greater mobility in the environment.[125] For P, a greater emphasis on the identification and targeting of critical source areas with mitigation strategies shows some promise for doing so at little cost at the farm scale.[113] However, at larger catchment and regional scales there has been relatively little evidence to suggest that diffuse pollution control strategies have been successful (*e.g.* see McDowell *et al.*[107]). This may be because: (a) controls over nutrient transfers from agricultural land are not yet strict enough or have not been implemented for long enough or sufficiently widely, (b) agricultural nutrient loads and/or their ecological relevance are overestimated relative to other sources, and (c) other site and environmental factors are more important than nutrient status in determining ecological status.[7] Further progress is required to understand the heterogeneity in these linkages between land use and water quality across and between catchments so that land use and farming systems can be optimised for maximum water quality protection, functional land management and ecosystem service delivery.[126]

The threat of climate change represents an additional challenge for nutrient management, not only in terms of its effects on land use change, farming systems and nutrient use efficiency (*e.g.* effects of drought), but also in terms of effects on nutrient transfer in land runoff,[127] and likely impact on the receiving water because of changes in river flow, water residence time and water abstraction for irrigation.[94] These effects remain highly uncertain and will clearly differ from region to region. Further research is needed to better understand the threat of climate change so that greater resilience can be built into soil resources, the viability of farming systems and sustainable nutrient management.

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Pesticides

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ABSTRACT

Three current issues of concern surrounding pesticides are discussed: pesticides and terrestrial wildlife, pesticide resistance and pesticides in water. Each section describes the magnitude and current understanding of the issues and what is being done or might be done to overcome the problems raised. Some of the emerging technologies and issues are described and the likely concerns they will create.

1 Introduction

Pesticides, (including fungicides, herbicides, insecticides, molluscicides and plant-growth regulators), have had concerns and issues surrounding their use for as long as man has used them. Whether the issue is to make a more effective pesticide, or to overcome an undesirable effect, there is a commonality in the course of events and man's response and its consequences: a problem becomes recognised; we overcome the problem, with a different pesticide or a change of practice; a new problem arises. In this apparently unending struggle for trouble-free crop protection, problems of efficacy against targets and unwanted or unforeseen off-target effects remain at the forefront. However, in reaching the current situation, our knowledge and experience has grown and – hopefully – better equips us to foresee new problems. This chapter provides an overview of our knowledge and

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understanding of three current, major issues and, as such, offers a contribution to overcoming or avoiding future problems. Two issues – wildlife and water – deal with off-target effects and one, resistance, with efficacy. One, wildlife, is a very old problem; two, resistance and water, have come to prominence more recently. In all cases, we have not yet solved all the problems. We continue to fail to see consequences and we do not understand enough. However, as our knowledge and experience grow, so should our predictive abilities: the ever-increasing regulatory requirements for pesticides are based on this assumption.

The discussion concentrates on pesticides for crop protection, but also refers to other pesticide uses and to rodenticides where these have closely-related issues.

2 Pesticides and Terrestrial Wildlife

2.1 Introduction

This section focuses on the potential impact of pesticides on UK terrestrial biodiversity, paying particular attention to plant-protection products (PPPs). Plant-protection products include insecticides, molluscicides, fungicides and herbicides, and, where relevant, biocides (*e.g.* rodenticides). Human health considerations are beyond the scope of this section as is consideration of the wildlife impacts of use of veterinary medicines, although veterinary medicines in agriculture have posed significant wildlife risks both in the UK and abroad, and concerns remain over potential ongoing impacts.[1–3] Progress has been made in addressing acute effects of PPPs that resulted in significant wildlife mortality incidents from their authorised use, and in dealing with the impacts of bioaccumulative pesticides.[4] Today's challenges are primarily related to indirect effects and potential direct effects through sublethal impacts especially, as well as uncertainties surrounding confounding factors such as the use of adjuvants, or the effect of several pesticides acting together.

Population-level effects on wildlife have provided a stimulus for regulatory action on some groups of pesticides such as the organochlorine and organophosphate insecticides.[6,10] However, unless caused by obvious large scale and/or mass mortalities, such effects can be difficult to tease out. Whilst some higher-risk active substances have been removed from market, there is continued reliance on management during use to ensure exposure to pesticides remains within acceptable limits. Monitoring of pesticide exposure and effects on wildlife in Great Britain is through incident reporting from schemes like the Wildlife Incident Investigation Scheme (WIIS) that are mainly (80%) funded by the industry as part of the regulatory regime. Further work is required to ensure regulatory mechanisms continue to address fully the potential risk to wildlife from pesticides. Current criteria for acceptability of effects (and endpoints) may not always meet requirements for protection of biodiversity and further understanding of the actual impact from today's pesticide formulations and usage patterns is needed.

In this section, we give a brief overview of pesticide impacts and the goals for wildlife protection in the pesticide regulatory process, and highlight areas of ongoing risk. Current regulatory approaches to non-target organisms, risk assessment and definitions of harm are explored. Direct effects are illustrated through examples of sublethal impacts and potential effects of additives such as adjuvants. Indirect effects are then described with particular focus on farmland birds. Finally, the challenge of pesticide use and protected sites and habitats is examined in relation to pesticide drift and herbicide use in nature-conservation management.

2.2 Pesticide Use and Impacts on Terrestrial Biodiversity: Past and Present

Publication of Silent Spring in 1962 raised awareness of the potential for the widespread use of agricultural pesticides to have population-level impacts on wildlife.[7] In the case of the organochlorine insecticides, their persistence and bioaccumulation led to effects on wildlife well outside the farmed environment. In the UK, progressive restrictions on the availability and use of organochlorine insecticides in agriculture between 1961 and 1974 (and into the 1980s) led to measurable changes in sublethal effects (eggshell thinning) and subsequently recovery in populations of a range of top predators.[8,9] The organophosphate insecticides which succeeded them for many crop-protection uses had lower persistence and bioaccumulation potential, but high vertebrate toxicity, and some were associated with significant mortality events, with probable population impacts on some bird species using farmland.[5] Subsequent regulatory changes have successively addressed the major direct lethal impacts and major field-scale vertebrate mortality events which were once a feature of the WIIS reports. WIIS investigates death or injury to wildlife, beneficial invertebrates (honeybees) or companion animals (dogs/cats) where pesticides and poisoning are thought to be involved. These incident data contribute to monitoring of the impact of pesticides on animals when in use and so provide a measure of the effectiveness of the pesticide regulatory process. WIIS data can also trigger a need for changes in approval if unacceptable effects are identified. Significant vertebrate mortality events involving approved use of pesticides reported through WIIS are now rare (Figure 1).

Today, although rodenticides and carbamate insecticides feature strongly in UK misuse and abuse cases, there are few if any WIIS incidents involving vertebrate mortality on the scale observed in the 1970s and 1980s. Nevertheless, risks of direct acute effects on vertebrate wildlife do remain and, for example, some seed treatments and granular insecticides pose high risk of direct acute toxicity.[11] In such cases conditions of use (*e.g.* adequate burial of treated seeds or granules) are required to bring risks to an acceptable level. Alternatively, as is currently the case for anticoagulant rodenticides in the UK, conditional authorisation based on product stewardship may be used to monitor and mitigate potential risks. In this case, where regulatory risk

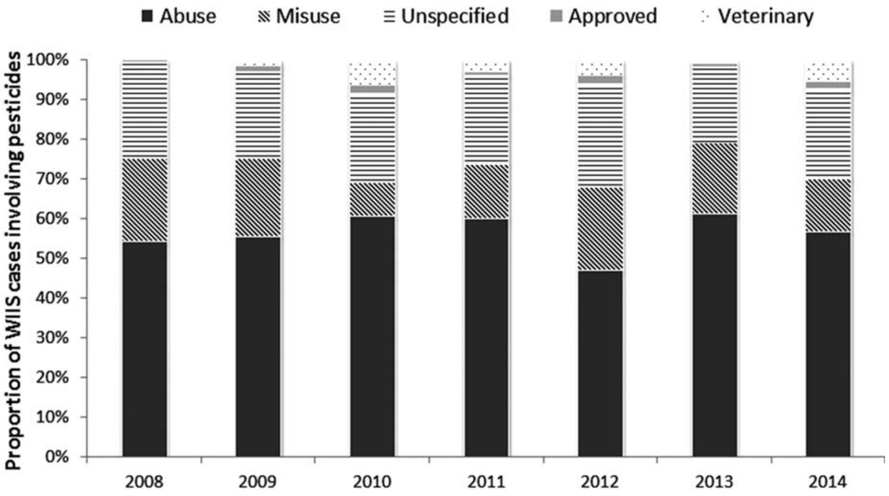

Figure 1 WIIS cases confirmed as involving pesticides. Abuse and misuse cases are outside of label restrictions while cases involving approved usage methods or veterinary product are quite rare. Unspecified cases have confirmed involvement of pesticides but the cause is unknown or outside of the other classes.

assessments point to the risk of exceedance of acceptable safe thresholds for wildlife, but where the products are required for public health reasons, ongoing approval is dependent on compliance with a stewardship programme which includes wildlife-exposure monitoring, conditions at point of sale and training.[12] Fundamentally, acceptance of these risk-mitigation measures relies on the specific activity of users and our understanding of the behavioural responses of wildlife. In the UK, schemes such as WIIS offer the potential for post-registration risk assessment in such circumstances, but these incident schemes are not designed for this specific purpose. Monitoring of exposure or impacts on potentially affected wildlife populations is particularly important where there is heavy reliance on such management measures, but is rarely done.

2.3 *Wildlife Protection Goals in Pesticide Regulation*

The protection goals set by regulatory authorities are important in understanding the role that regulation plays in protecting wildlife from the potential impacts of pesticides. Protection goals in Europe have evolved as our understanding of impacts and risks has advanced and in response to different drivers for protection of biodiversity and the functional role of ecosystems associated with farmland. The protection goals established under EU legislation are closely linked to ecosystem services and functions, and include protection of water resources, supporting food-web processes in farmland (such as pollinator and decomposer ecosystems), aesthetic considerations and wildlife-protection requirements. In this section, we examine the overall stated objectives for regulation of pesticides for wildlife protection in Europe, and the nature of the protection goals for mammals and birds, and for non-target plants and arthropods. Of particular importance is the focus of attention at the individual or at the population level, and whether risk assessment should encompass not only direct (lethal and sublethal) effects, but also indirect effects.[8,13,14]

The EU Plant Protection Products Directive (91/414/EEC), updated in EU Regulation (EC) 1107/2009, requires pesticide registration authorities to ensure that pesticides do not cause unacceptable levels of harm to the environment, but does not provide a detailed definition of the level of protection required. The European Food Safety Authority (EFSA) has proposed a framework for deriving specific protection goals, but final decisions on applying these goals are left to individual Member States, since they require judgements on the role of risk-management measures (such as the provision of alternative resources for wildlife), which lie outside the remit of the pesticide regulatory regime at EU level. In most cases protection is determined at the level of population, rather than individuals, although individual impacts may be considered in the case of vertebrates, and at the level of functional groups in relation to some supporting ecosystem services (*e.g.* the role of non-target arthropods as natural enemies of pests, decomposers in soil communities and as food for farmland birds).

In the case of birds and mammals EFSA has recommended (and officially noted in guidance) regulatory risk-assessment approaches which aim to meet a protection goal of clearly establishing that there will be no visible mortality and no long-term repercussions for abundance and diversity.[14] Higher-tier risk assessments are based on ''focal species'' representative of species of concern, which are known to occur within the crop when the pesticide is being used. The actual measure of risk may then be based on traditional lethal end-points or alternative measures of population impact, such as reduced reproduction attempts or population change over a specified period. The latter may require field studies to determine population-level effects, though internationally agreed protocols for such field studies do not yet exist and the level of population effect considered acceptable will be determined at member state level.

Where pesticide products are reviewed after a period of use, reports of incidents involving wildlife may be useful as a measure of visible mortality (one of the protection goals), but such wildlife incident reporting is inadequate for assessing impacts of sublethal or indirect effects. The recorded frequency of poisoning incidents is very likely to underestimate the level of mortality actually occurring, due to difficulties in noticing, collecting and alerting authorities to incidents, with underreporting particularly likely for smaller species and those less likely to feed in flocks.[15]

Protection goals for non-target plants and arthropods present particular difficulties, as plant and arthropod taxa within the crop will frequently be the target for crop-protection measures. Much recent effort has been devoted to identifying suitably protective approaches to pesticide approval for within-field as well as off-field effects for these groups of wildlife. Impacts on both target and non-target weed or arthropod species have the potential for significant ecological impacts through indirect effects on dependent herbivorous or insectivorous species. In addition, non-target plants and arthropods in areas outside fields are important for the maintenance of off-crop biodiversity, whilst some rare arable plants occurring within fields may need specific protection.

The EFSA Panel on Plant Protection Products and their Residues has recommended specific protection goals for off-field, in-field and endangered species of non-target plants, though these recommendations have not yet been officially noted in guidance for regulators.[16] This work has identified a range of gaps in existing assessment processes for non-target plants, including the effect on the whole life-cycle and several plant taxa that may not be adequately represented (*e.g.* ferns, bryophytes, lichens or woody species). The protection goals recommended for terrestrial higher plants are intended to protect both plant-species abundance and plant diversity in an agricultural area, including temporary effects at critical times of year (*e.g.* if depletion in food resource occurs at a sensitive period in the life-cycle of dependent herbivore species). For within-field non-target plants there should be a negligible or medium level of impact (depending on spatial scale) on functionally important plant groups. In addition to the population status of dependent herbivorous species, the availability of alternative food sources may be taken into consideration in determining whether risk-management measures are required. A valid consideration might be the availability of agri-environment schemes in providing compensatory food or habitat resources in otherwise intensively farmed landscapes. Pending adoption of these EFSA recommendations on how possible risks should be characterised and management options proposed, the approach, in practice, is left to individual Member States and is often not yet taken into account in determining scale of risk for individual pesticide approvals.

In setting protection goals for non-target arthropods, as for plants, a key consideration is to define the temporal and spatial boundaries for risk assessment. As for non-target plants, distinction is made between within-crop and off-crop effects, although in this case off-crop effects may include buffer strips which are important refuges for arthropod natural enemies as well as pollen and nectar sources. EFSA has recommended that the aims for non-target arthropod protection within the crop should include protection of their role in important ecosystem services, such as pollination, decomposer systems, as natural enemies of crop pests and to maintain an appropriate level of arthropod biodiversity in the landscape.[17]

Whilst the EFSA panel has proposed that only negligible off-crop direct effects on non-target arthropods should be acceptable, there is potential for in-field impacts on non-target species to affect off-field populations.[18,19] To ensure that the effects of pesticide use within the crop does not affect non-target arthropods more widely, it has been suggested that a landscape-level risk assessment be conducted in order to understand potential population-level effects, especially for more mobile species. EFSA advice is that pesticide use should not result in year-on-year declines in population size and that impacts on population range should be "negligible". In the case of certain ecosystem services, such as provision of arthropod food items for survival of bird chicks, other minimum thresholds for acceptable impact might be applied (where these are known or can be modelled).[19]

2.4 Direct Effects

Whilst large wildlife-mortality events (*e.g.* involving hundreds of individuals) are now rarely recorded in the UK, concerns remain about the potential direct effects of pesticides on wildlife, especially in circumstances where approval is dependent on risk mitigation measures being applied. In the case of rodenticides, monitoring of wildlife exposure through the Predatory Bird Monitoring Scheme[20] has demonstrated widespread exposure of birds of prey to second-generation anticoagulant rodenticides (SGARs) in Great Britain. For example, Shore *et al.*[21] reported more than 80% of barn owls sampled under the scheme during 2010–2013 had detectable levels of SGARs through secondary exposure to treated rodents, and it is estimated that of the order of 5–10% of the exposed population experiences levels likely to be associated with mortality (Richard Shore, *pers comm*). The rodenticide stewardship campaign now underway in the UK has the aim of reducing overall levels of exposure and hence risk of direct toxic effects.

Of wider concern are ongoing direct effects on wildlife that are sublethal and that may, in turn, lead to population-level impacts. These impacts are explored with particular reference to work on systemic insecticides such as the neonicotinoids, although the effects described are not restricted to this class of active substances. Risks of direct effects arising from additives to pesticide formulations, such as adjuvants, and interactions with other factors are not well-understood. Through the case study of glyphosate, direct effects from some adjuvants used in combination with the active substance are explored.

2.4.1 Systemic Insecticides and Sublethal Effects.

Neonicotinoid insecticides were introduced in the 1990s and now represent almost one-third of global insecticide use by value. Although used in foliar treatments, these systemic insecticides are commonly applied as a crop-seed treatment; plants absorb and translocate the neonicotinoid throughout plant tissues, including to pollen and nectar. As a group, neonicotinoids vary widely in toxicity and environmental fate and are considered in three functional groups: nitromethylenes (nitenpyram), *N*-cyanoamidines (thiacloprid and acetamiprid) and *N*-nitroguanidines (*e.g.* clothianidin, imidacloprid and thiamethoxam). Toxicity varies between the different neonicotinoid compounds and between different species-specific sensitivities of terrestrial and aquatic vertebrates.[22,23] Non-target wildlife potentially exposed to systemic insecticides through seed treatments or sprays includes granivorous or omnivorous vertebrates (*e.g.* farmland birds and mammals), non-target insects, including pollinators, aquatic organisms (fish, insect larvae, crustaceans) and soil-dwelling organisms (*e.g.* earthworms, molluscs, arthropods).[24] Exposure can be a result of consuming treated seed (pulled after drilling or from spillages), exposure to residues translocated within crop plants, or exposure to residues leached from seeds into soil and water bodies. There are also alternative exposure routes for birds and other wildlife, such as overspray to margins and dust (during drilling of treated seed or post-treatment with sprays). Risk assessment of potential exposure to systemic insecticides derived from translocated residues within plants typically focuses on crop-plant concentrations in various plant-growth stages and compartments.[24,25] It is more difficult to ascertain exposure *via* non-target plants taking up such insecticides from overspray or through soil-pore water and runoff reaching field margins.[26] In the case of the more-persistent products, there is potential for an extended period of exposure through non-crop plants taking up such insecticides from the soil or *via* drift, and expressing residues in nectar, pollen and tissues.[27,28]

Due to their presence in pollen and nectar and sublethal effects at low concentrations, several neonicotinoid insecticides have been investigated in relation to impacts on bee and other pollinator populations.[26,27,29,30] Imidacloprid, clothianidin and thiamethoxam are highly toxic to bumblebees (and solitary bees) in lab studies, with sublethal effects on individual bee fitness, foraging activity and navigation, and proposed colony impacts as a result.[31,33] Field-concentration studies have produced more variable results, with some experiments unable to replicate effects found on honeybees and bumblebees exposed under laboratory conditions.[34] Interaction between pesticides is considered a potential challenge for bees and colony survival. Some fungicides reduce the honeybee's ability to metabolise or excrete other pesticides, so when applied in combination with other insecticides can generate synergistic toxic effects at thiamethoxam and thiacloprid concentrations considered to be sublethal.[28] Bumblebees simultaneously exposed to field-realistic concentrations of the pyrethroid λ–cyhalothrin and imidacloprid showed reduced worker-survival over the four-week field study and impaired foraging behaviour.[35] Computer modelling could provide a mechanism to test complicated, multivariate contributions to honeybee decline.[36] Other purely correlative studies have suggested the potential involvement of systemic insecticides in UK *Lepidoptera* population decline which, whilst not directly linking such insecticides to specific decline, indicates a need for further investigation.[29]

Neonicotinoid levels recorded in a national study of streams near agricultural areas in the United States indicate potential risk of sublethal effects on aquatic biota. In this study, clothianidin registered in 75% of samples and occurred at levels up to 257 ng L^{-1}.[37] Surface-water contamination with certain neonicotinoids (especially imidacloprid) was found widely in

29 studies from 9 countries, including Australia, Canada, Japan and Brazil, with the majority of average concentrations for a specific sample area in excess of assigned short and long-term guidelines for water quality (0.02 and 0.035 μg L^{-1} respectively).[38] Certain neonicotinoids have been recorded in the aquatic environment at levels found in laboratory studies to cause both lethal and sublethal direct effects to aquatic invertebrates including mayfly nymph,[39] caddis fly and midge[38] exposed to imidacloprid. Waters that contain a combination of neonicotinoids could reasonably be expected to further increase risk to non-target aquatic invertebrates as these compounds have similar modes of action and potentially additive toxicity.[38]

Soil provides another pathway for exposure of terrestrial invertebrates to seed treatments and in some arable soils where treated seeds were used, imidacloprid (up to 10 μg kg^{-1}) was found to be more persistent than thiamethoxam and clothianidin.[40] Some neonicotinoids are found to persist in soil[41] with knock-on effects for the soil trophic chain and even crop yield. Douglas *et al.* found that ground beetle (*Chlaenius tricolor*) mortality increased because of lethal levels of thiamethoxam in their primary prey, grey field slugs (*Deroceras reticulatum*).[32] The slugs were tolerant to thiomethoxam in the soybean seedlings (treated *via* seed coating) and able to consume enough treated plant material to reach a lethal concentration for the ground beetle. This increased crop damage in field trials as, in the absence of predation, slug numbers increased as did seedling damage, which decreased soybean yield by preventing seedling establishment.

A recent review of the systemic insecticides neonicotinoids and fipronil identified a range of sublethal effects on vertebrates including behavioural and cytological changes as well as more conventionally studied impacts on survival, reproduction and growth or development.[11] In the case of those neonicotinoid insecticides reviewed, exposure in aquatic situations was at levels much lower than lethal effects for fish and amphibians, though there was some potential risk that sublethal exposure may occur, and in the case of fipronil potentially at lethal levels.[11,46] Treated seed contains some of the highest concentrations of neonicotinoids, so potentially constitutes an important route of exposure for granivorous farmland birds.[42] Risk models indicate that risks of toxic effects from seed treatments are comparatively high, and only a few treated seeds in some cases may need to be eaten to cause toxic (lethal) effects.[43] The number of seeds required to reach the Imidacloprid LD_{50} for some sensitive species like grey partridge (*Perdix perdix*) has been estimated as 5–6 maize (*Zea mays*) or sugarbeet (*Beta vulgaris*) seeds, or 32 oilseed rape (*Brassica napus*) seeds.[26] In laboratory studies, inhibited reproductive-fitness, reduced chick-health and general behavioural change (foraging and mating) in red-legged partridge (*Alectoris rufa*) has been observed after ingestion of imidacloprid-coated seed (20% of average application rate to account for likely consumption of treated seed in field) in a Spanish study.[44] As such, efforts are made to investigate coated-seed avoidance to understand likely feeding behaviours and potential exposure, although this is limited to lab or semi-field tests.[45] There is a reliance on behavioural responses of feeding birds, and effective incorporation of seed during drilling, to bring risks to acceptable levels.

2.4.2 Herbicides and Adjuvants. Glyphosate (in Roundup® and other herbicide formulations) was introduced in the 1970s and rapidly adopted for weed control in household, agricultural and industrial environments, due to its recognised effectiveness. Glyphosate now represents approximately 25% of the global herbicide market and is widely used for control of weeds in crops, particularly cereals, maize and sugar beet. Often glyphosate is used as a replacement for mechanical weed control as farmers are encouraged to use low-till and no-till methods to preserve soil quality and reduce fuel use.

Once absorbed by the plant through the leaves and shoot (photosynthetically active tissues), glyphosate is transferred throughout plant tissues to plant roots and eventually to the rhizosphere (soil surrounding the roots).[47] Glyphosate is not metabolised by plants and, as the plant dies, organic material containing glyphosate is directly deposited into soils. For plants with deep-rooting structures, this can transfer glyphosate over 60 cm below ground-level to soil with lower microbial activity, where it is sorbed to soil particles and can be deactivated by aluminium and iron oxides and hydroxides in soil minerals.[48] Effects on fungal and bacterial communities have been observed.[49] If soil microbiota are affected, this may potentially influence plant-nutrient uptake, soil-nutrient availability and carbon/nutrient cycling in soils,[50–52] however the majority of studies have found little evidence for herbicide impacts on soil processes under approved conditions of use.[50] Laboratory studies show the mobility of glyphosate may be influenced by soil phosphorus concentrations making glyphosate more bioavailable in soils.[53] Glyphosate can then be encountered by soil biota such as earthworms and other macrofauna or enter watercourses through runoff (as well as *via* other routes such as overspraying) as seen in studies from the United States.[54]

Several adjuvants are used to ensure that glyphosate is quickly absorbed through plant tissues before it can be washed away by rain or irrigation water.[55] These can include surfactants to enable even spread and quick uptake of the active substance. Adjuvants are added either as part of the formulation at manufacture or can be added by the user as part of a tank mixture. In laboratory *in vitro* studies, the addition of certain adjuvants to glyphosate formulations has been found to increase cytotoxicity.[56] Such enhancement in wildlife populations under field conditions is more difficult to document both for acute lethal and sub-lethal effects. In laboratory studies, glyphosate toxicity was found to be six times greater to Western toad (*Anaxyrus boreas*) tadpoles with the addition of an esterified vegetable oil as adjuvant when compared to glyphosate alone, though the magnitude of effect varied between adjuvants.[57] Evidence gathered in greenhouse and microcosm studies shows that commonly used formulations may affect interactions between earthworms and soil microflora, and can affect burrowing activity and reproduction rate, which has potential consequences for nutrient cycling as well as herbicide movement in these soil environments.[48,58] Whilst there are uncertainties in drawing conclusions on potential field effects based on such studies, further work is required to understand the role of adjuvants in sublethal direct effects on wildlife of PPPs in the field.

2.5 Indirect Effects

The impacts from indirect effects of pesticides on farmland-bird populations in Britain are potentially more significant than direct effects.[11,59,60] Indirect effects operate principally through changes in invertebrate prey abundance *via* insecticide use (through their direct effect on invertebrate prey) and herbicide use (*via* their indirect effect on invertebrates by removing host plants) and non-crop plant availability (especially weed seeds) within crops.[61] Studies carried out over a 40-year period within the Game and Wildlife Conservation Trust (GWCT) Sussex study area have confirmed clear long-term declines in abundance of a range of invertebrates that form an important part of the diet of many farmland birds; these declines have been associated with increasing intensity of pesticide use.[62] Recent re-analysis of these data indicates little change in the intensity of pesticide use in the study area over the period 2005–2012 and spatial analysis showed that foliar insecticide use was associated with a lower abundance of all groups of chick-food invertebrates.[63]

Evidence elsewhere points to significant changes in non-crop plant species composition in arable areas in recent decades, which may reduce the availability of weed seeds for birds as well as removing host plants for invertebrate prey.[64] Other studies have shown that overwinter stubbles in various cereal crops with reduced herbicide regimes supported a higher cover of arable weeds that are important in the diet of farmland birds than in conventionally treated crops; lower rates of herbicide use pre- and post-harvest were found to be a key determinant of birds using fields to forage in during winter.[65,66] Impacts on the potential plant and invertebrate prey of farmland birds have also been demonstrated in a number of large-scale trials in the UK[67] including large-scale nationwide trials on the possible effects of commercially growing genetically modified herbicide-tolerant (GMHT) crops.[68] Where the broad-spectrum herbicide (glyphosate) used in the trials on GMHT crops had a more severe impact on non-target plants (in spring oilseed rape and sugar beet trial plots), weed seed deposition was significantly reduced. Similarly, densities of invertebrate species dependent on a high weed population were reduced in oilseed rape and beet crops receiving broad-spectrum herbicides, with the reverse observed in GMHT maize where conventional herbicide use had a greater impact on weed populations. Whilst bird populations themselves were not evaluated in these trials, the implications are that broad-spectrum herbicides may deplete food resources and so potentially have indirect effects on survival and/or reproductive success.[75]

The most robust evidence for population-level indirect effects of pesticides on farmland bird species remains that of the grey partridge, based on both field-correlative and experimental evidence[69] and on evidence for recoveries in grey partridge population densities where use of summer insecticide and broad-leaved weed herbicides was reduced.[70] A mechanism for the operation of indirect effects *via* reduced reproductive success is also well-established for other farmland granivorous bird species such as yellowhammer (*Emberiza citrinella*)[71,72] and corn bunting (*Miliaria calandra*).[73] However, effects at the population level through this mechanism on these other farmland bird species are not confirmed by population modelling[9] and population declines have also been linked to reduced overwinter survival, associated with reduced availability of weed seeds. The relative significance of pesticides on summer (invertebrate) or winter (weed seed) food availability over the course of their life-cycles in determining overall bird population density has not yet been established. Due to the complex interactions between food availability and other factors such as risks of predation, it is very difficult to provide conclusive evidence for pesticide effects on any particular demographic parameter and hence to determine their role in driving farmland bird population change.

A recent review of the newer class of systemic insecticides, the neonicotinoids, has identified that along with potentially significant direct effects, such insecticides have the potential to contribute to invertebrate-prey declines and hence contribute to indirect pesticide effects on farmland bird species. The review noted that indirect effects of this group of insecticides have also been reported in reptile reproductive indices and fish growth rates as a result of declines in their invertebrate prey.[11] However, other work, including further analysis of long-term changes in invertebrate populations associated with changes in pesticide use in the GCWT Sussex study area, has indicated the importance of considering other insecticides concurrent with neonicotinoid use in understanding the significance of pesticides on within-field non-target invertebrate populations, including those important as chick food.[63]

Approaches to assessing the risk of wider biodiversity (indirect) effects of pesticide use have been considered, suggesting a plausible risk-assessment approach to assessing indirect effects on farmland bird populations.[59,76] One approach to mitigating such indirect effects may be through techniques to reduce pesticide use, such as integrated pest management (IPM). However, unless there is an explicit focus under an IPM programme to restore food availability in the form of increased invertebrate and weed resources, it is not evident that the objectives of IPM and of restoring declining farmland biodiversity will necessarily coincide. Alternative mitigation and compensatory mechanisms have been reviewed[77] and, in the UK, environmental schemes funded under the Common Agricultural Policy provide one of the main mechanisms for compensating for the reduction in invertebrate prey and weed seed food items.[66] As yet, these compensatory mechanisms have not been linked with risks associated with indirect effects of specific pesticide use through the regulatory process, although possible ways of doing so have been proposed and their value in relation to compensating for potential pesticide-related farmland bird declines has been reviewed.[9,78,79]

2.6 Pesticides and Protected Sites and Habitats

The foregoing sections relate principally to the impacts of pesticides in lowland arable or horticultural situations. In this section, risks to protected sites or semi-natural habitats from pesticide use in upland and grassland situations, as well as off-site effects due to pesticide drift are considered.

2.6.1 Pesticide Drift. The effects of pesticide drift on protected areas such as Sites of Special Scientific Interest (SSSIs) are difficult to measure. Whilst theoretical impacts are predicted based on drift models and experimental studies, pesticide impacts due to drift or runoff are very seldom recorded as a cause of adverse condition on SSSIs in England.

The UK conservation agencies originally developed buffer zones suitable for protection of aquatic SSSIs from pesticide drift, based on relatively simplistic bioassays,[80] whilst statutory pesticide-label requirements set a range of conditions intended to prevent harm to watercourses more generally. Effects of pesticide drift on terrestrial non-target arthropods in off-crop habitats are possible at considerable distances from sensitive features. For example, studies using invertebrate bioassays have proposed buffer zones of between 16–24 m for some insecticides to limit mortality to 10% or less.[81] In the UK, either statutory or advisory buffer zones (unsprayed field margins) may be required to protect non-target arthropods and to mitigate for potential off-field and within-field risks to that group of organisms.[82]

Assessment of risks and impacts of pesticide drift to non-target terrestrial flora has been given less attention in regulatory risk assessments, basing conclusions primarily on non-field toxicity tests.[83] Studies have been undertaken on risks to protected habitats (such as SSSIs and woodland) adjacent to treated areas. Natural England advises buffer zones for protection of sensitive habitats from drift during aerial spraying of asulam (commonly used in the UK for management of bracken on upland and lowland heathland within or adjacent to SSSIs), based on laboratory and field bioassay studies on sensitive plant taxa.[80,84] Elsewhere, studies have found evidence of impacts from glyphosate drift into adjacent woodland, with effects occurring up to 4–10 m in from the woodland edge, with differences observed in species most sensitive to herbicide at least 4 m into woodland margins.[85] On this basis, 5 m no-spray zones to protect the majority of woodland species and prevent changes in plant species composition from drift of herbicides and fertilisers have been suggested.[86] Furthermore, pesticide overspray has been recorded in wildflower buffer strips and pesticide transfer to pollinators has been demonstrated.[27] Given the nature of the flora and potentially longer flowering season than the adjacent crop, there is potential to prolong exposure times to wildlife, particularly pollinators.[27,28] This extended exposure season is not typically included in risk assessment since often approvals are based on an assessment that focuses on crop-flowering periods.

A range of measures eligible for grant under various agri-environment schemes is available to encourage uptake of buffer zones for protection of features in the countryside. Such buffer zones offer two benefits for nature conservation: to provide a non-cropped habitat to enhance biodiversity (for example, rare arable flora, habitat for ground-nesting birds, or a pollen and nectar resource for invertebrates) and to act as a buffer for adjacent habitats such as hedgerows, watercourses or protected sites such as SSSIs. To be eligible to receive rural payments under the EU Common Agricultural Policy, farmers must meet rules for cross compliance. These include requirements to protect watercourses by 1 m buffer zones for pesticide application (measured from the edge of the watercourse) or 2 m from the centre of a hedgerow. Farmers must also follow the pesticide Code of Practice advice on water protection, which includes statutory compliance with LERAPs (Local Environmental Risk Assessment for Pesticides) to minimise effects of pesticide drift. In addition, grants are available for enhanced protection of watercourses (buffer strips of 4–6 m or 12–24 m), or other sensitive habitats such as woodland edge (buffer strip of 6 m), from agricultural activities such as pesticide drift or overspray, under the Countryside Stewardship scheme in England.

2.6.2 Herbicides and Nature Conservation Management. Herbicides, by reducing competition from aggressive native or invasive non-native species, can play an important role in the conservation management of habitats (*e.g.* scrub management in grassland, aquatic weed control).[87] As many of the narrower-spectrum herbicides have become less available, both for aquatic and terrestrial nature-conservation management, so other approaches to usage have become more important. For example, applying glyphosate *via* a weedwiper can be used to achieve some degree of selectivity in weed management in grassland sites provided a height differential can be achieved between the weed species and other non-target vegetation.[88]

The widespread agricultural improvement of UK grassland that has taken place over the past 50 years has resulted in significant increases in productivity, allowing repeated silage cuts to be taken and higher stocking densities sustained. Increased applications of pesticides, particularly herbicides have played a key role in increasing grassland productivity, alongside improved drainage, and higher applications of fertilisers.[89] The accompanying significant losses in species-rich unimproved grassland is well documented.[74] Options to restore and re-create these grasslands under agri-environment schemes such as HLS and ELS (High and Entry Level Stewardship Schemes) have been developed to reverse these losses through targeted management agreements.

In contrast to the very limited extent of species-rich grasslands, large areas of semi-improved grassland (1.8 million ha in England) remain and where these are sympathetically managed these can support many species of invertebrates and other taxa.[90] However, the use of herbicides on such grasslands, which is often aimed at controlling a handful of injurious weed species, limits the potential to increase their species diversity and wildlife value. Whilst each individual treatment may cause relatively little damage to plant communities, the cumulative impact of multiple applications over time may have an impact on the number and frequency of desirable plant species, with possible knock-on effects for insects and birds. So far, there has been only limited investment into the wider development of methods of using herbicides in a more targeted way, such as cultural control methods or weed wipers to enable their practical application in a wider range of conditions. Broader consideration is needed on how herbicide use can be more highly targeted on grasslands to facilitate widespread improvements in grassland biodiversity.

Bracken control presents a special case of marrying the twin wildlife-management requirements of dealing with an invasive species of grassland and heathland habitats, alongside preventing unintentional side-effects from herbicide use in its control.[91] Bracken is widely controlled in upland as well as lowland situations, often through aerial application of herbicide. Between 1980 and 2002, 1057 km^2 were treated in Great Britain.[92] Asulam is the most-widely used herbicide for bracken management. Although partially selective in its toxicity, it can affect a range of non-target plants, so conservation agencies have recommended buffer zones adjacent to protected sites to ensure that risks to non-target plants are minimised during aerial spraying.[84,93] The Sustainable Use Directive (Directive 2009/128/EC) restricted the circumstances under which aerial application can take place and asulam authorisations were also restricted at around the same time. The loss of a partially selective herbicide for bracken management poses a risk to management for nature conservation, as well as for protection of archaeological sites (which can be damaged by bracken rhizomes) and grazing management more generally. Whilst herbicide management currently depends on ongoing emergency authorisation for asulam, additional herbicides for bracken management are being trialled alongside pursuance of its re-registration.[94]

2.7 Conclusion

Progress has been made in Europe to refine wildlife protection goals and to develop assessment processes to enable informed judgements of risks to be made. However, risks do remain and the evidence of potential population-level effects arising from sublethal impacts points to future directions in risk-assessment processes that may need to be developed further. Whilst an underpinning rationale for the assessment of indirect effects has been developed, this remains to be applied in practice in pesticide authorisation procedures. To address indirect effects of pesticides through a regulatory regime, common objectives between food production and conservation (wildlife and habitat) need to be maximised.[95,96] Further sustainable

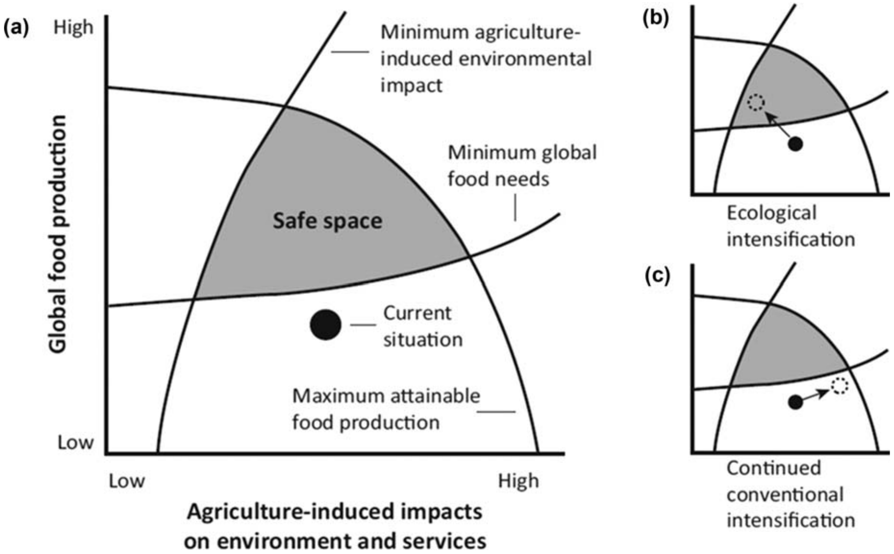

Figure 2 Agricultural production and the drive for food must be balanced with ambitions for ecological protection. One cannot advance unchecked without compromising the other (Reprinted from Bommarco *et al.*, Ecological intensification: harnessing ecosystem services for food security, *Trends Ecol. Evol.*, **28**, 230–238, Copyright (2013), with permission from Elsevier).[96]

intensification will require compromises to achieve both increased productivity and enhancement and protection of wildlife and the natural environment (Figure 2).[96]

Given the uncertainties remaining in understanding pesticide impacts on wildlife, environmental monitoring remains important. A focus on post-authorisation monitoring is required to provide reassurance on the effectiveness of the PPP regulatory regime in dealing with some of the gaps which remain. These include indirect effects, sublethal effects, interactions with other abiotic factors, reliance on generic sets of behaviours by PPP users and on behavioural responses by wildlife as risk-reduction measures. The model for assessing exposure in sentinel wildlife as part of the rodenticide stewardship campaign might be adopted more widely in situations where similar reliance is placed on risk-management measures in order to maintain authorised pesticide use. Monitoring should also include investigations, assessments and wildlife-population monitoring at an appropriate scale to determine the actual impacts of PPPs once in use. Risk assessment for PPPs will also need to adapt to technological change (*e.g.* use of microbeads,[97] nanoparticles[98] or new modes of action), interaction between active ingredients, adjuvant effects, and interaction with factors such as climate change. Finally, many of the problems faced by agriculture and horticulture in maintaining access to PPPs in the face of a diminishing range of minor-use products are shared with nature-conservation management. There is scope for looking for synergies between these sectors in developing novel solutions *via* application technology or non-chemical interventions.

3 Pesticide Resistance

3.1 Introduction

In 2014 Andy Dyer published "Chasing the Red Queen",[99] in which he postulated an evolutionary race taking place between agricultural weeds, pests and diseases, and the industry producing agrochemicals to combat them. This is undoubtedly the case, and the rise of pesticide resistance over the last 50 years suggests that weeds, pests and diseases are winning the race. What is pesticide resistance? A good definition is "the inheritable ability of an organism to survive a pesticide dose that would be expected to be lethal to a member of a normal population of that organism".[100] Resistance is inheritable and is encoded in the genetic material of the organism; it is not a response by an individual organism to environmental or imposed conditions. Also it should be noted that an organism is only described as being resistant if the pesticide in question, under normal (and controlled) conditions, will result in control of susceptible individuals of the same organism. Resistance is a population event. Development of resistance involves an increase in the proportion of a population that is resistant, not a change in an individual organism within that population. Resistance is also often detected as a change in susceptibility of a population of a weed, pest or disease over time, as repeated selection pressure increases the proportion of resistant individuals in that population.

3.2 Herbicide Resistance

3.2.1 Background. The first confirmed case of herbicide resistance is generally accepted to be that of a triazine-resistant population of *Senecio vulgaris* from the USA, reported in 1970 by Ryan.[101] This population had demonstrated reduced sensitivity to the triazine herbicides atrazine and simazine since the late 1960s. The area in which the population was growing had been under annual triazine treatment since at least 1958, indicating a decade or more of selection pressure for development of resistance.[101] Increased reliance on herbicides as a major or sole component of weed-management strategies over subsequent decades in many parts of the world has resulted in an incredible rise in the number of herbicide resistant weed populations. As of January 2016 Heap[102] reports 462 unique cases of herbicide-resistant weeds globally, consisting of 248 separate species (144 dicotyledonous species and 104 monocotyledonous species).[102] Resistance has been confirmed against 22 of the 25 currently exploited herbicide modes of action. The three modes of action for which resistance has yet to be confirmed are DHP (dihydropteroate synthase inhibitors), dinitrophenol uncouplers, and auxin transport inhibitors.[102] This is without doubt an underestimation of the true level of herbicide resistance, as it only represents cases that have been confirmed under controlled conditions and subsequently published in peer-reviewed journals. Worldwide, the herbicide-resistant weed populations covering the largest areas are *Lolium rigidum*, *Avena fatua*, *Ameranthus retroflexus*, *Chenopodium album* and *Setaria viridis*.[102] Within the UK, the largest areas of herbicide-resistant weeds are represented (in order) by the grass weeds *Alopecurus myosuroides*, *Lolium perenne* ssp. *Multiflorum*, *Avena fatua*, and the broad-leaved weeds *Papaver rhoeas*, *Stellaria media* and *Tripleurospermum perforatum*.[103] Although only introduced in the 1980s, the herbicide mode of action for which the greatest number of worldwide cases of herbicide resistance have been reported is that of the ALS (acetolactate synthase) inhibitors. This is largely due to the number of naturally occurring mutations to the ALS enzyme which, although less sensitive to the herbicides targeting them, are still enzymically active.[104] In addition, the ALS herbicides have been used extensively and exclusively for weed management over large areas due to their efficacy and low active-ingredient dose.

3.2.2 Mechanisms of Herbicide Resistance. The vast majority of cases of herbicide resistance are due to either modified target site, reducing efficacy of herbicide binding (target site or TS resistance), or enhanced rate of metabolism of the herbicide to less- or non-toxic metabolites (enhanced metabolism or EM resistance). In a number of cases, more than one resistance mechanism is found within an individual weed species, and this is termed multiple-resistance. Where an individual resistance mechanism results in resistance to more than one herbicide, the term cross-resistance is used. Target-site resistance to ACCase-inhibiting (acetyl–CoA carboxylase) herbicides has been demonstrated to be due to single amino-acid substitutions within the ACCase enzyme. These have been reported in *A. fatua*,[105] *L. rigidum*,[106] *S. viridis*[107] and *A. myosuroides*.[108] Different sites of this single amino-acid substitution demonstrate different cross-resistance patterns to a selection of ACCase-inhibiting herbicides. Similarly, single amino-acid substitution mutations in the ALS enzyme confer TS resistance to herbicides of this mode of action. Cross-resistance patterns between different categories of ALS inhibitor linked to these mutations are complex and have been presented and discussed by Gressel.[104] The first reported case of herbicide resistance, that of triazine resistance in *S. vulgaris* described by Ryan[101] is also an example of TS resistance.

EM resistance represents a different method by which plants may demonstrate resistance to herbicides. Where certain enzymes that metabolise xenobiotic substances are present in higher concentrations, either due to overexpression of specific genes or due to duplication of genes, then herbicides can be detoxified at a rate which is fast enough to allow for weed survival. Unlike TS resistance, where herbicide symptoms are often not observed, EM-resistant individuals may show some damage due to herbicide, but ultimately survive to complete their lifecycle and pass the resistance-conferring gene(s) to the next generation. The two enzyme families most commonly reported as being responsible for EM resistance in weeds are glutathione S–transferases (GSTs) and cytochrome P450 monooxygenases (CYPs).[109] The GSTs are a superfamily of enzymes which join the tripeptide glutathione to a number of molecules. This renders the resulting conjugate more soluble than the original molecule. In addition, the conjugate is often less toxic and conjugation may lead to enhanced compartmentalisation of the conjugate in the vacuole (see Ishikawa *et al.*[110]). CYPs are a very large family of enzymes that carry out a number of reactions that result in the oxidative metabolism of many substances, including the detoxification of a number of herbicides.[111] EM resistance due to other enzymes has been reported and it is undoubtedly likely that further examples will be reported as research further elucidates herbicide metabolism pathways.

Enhanced compartmentalisation involves movement of herbicides away from their site of action, often to within the vacuole. This has been reported in a few cases of resistance and may be linked to the conjugation of herbicides to glutathione as highlighted above.

3.2.3 Herbicide Resistance Case Study: Alopecurus myosuroides. *Alopecurus myosuroides* (black-grass) is an autumn-germinating annual grassweed of open habitats and disturbed ground, particularly suited to conditions associated with growth of winter-sown cereal and oilseed-rape crops.[112] The presence of *A. myosuroides* in cereal crops can result in yield reductions in excess of 50%.[113] It has the ability to produce high seed numbers, resulting in fast growth of population size from year to year. This also results in fast replication of resistant individuals within a population where selection pressure is applied. With the switch to autumn cropping, focus on cereal monoculture and heavy reliance on herbicides as a sole method of weed control, this species has become the dominant problem grassweed in the UK.[114] Falling control levels in the 1970s resulted in research that identified herbicide-resistant populations of *A. myosuroides*. The first of these populations was found in Peldon, Essex, in the early 1980s.[115] Currently there are in excess of 700 farms in 27 counties of the UK where ALS-resistant black-grass is present.[103] Resistance in this species is also reported in a number of other European countries. Resistance mechanisms in this species include TS-modified ACCase,[108] ALS[116] and EM, implicating GSTs,[117] CYPs[118] and possibly *O*-glucoyltransferases.[119]

3.3 Fungicide Resistance

3.3.1 Background. Fungicide resistance was first reported in the 1960s in *Penicillium digitatum* on lemons in storage.[120] Subsequently resistance was reported in bunt on wheat[121] and *Pyrenophora avenae* on oats.[122] Since these initial cases, fungicide resistance has risen to levels that, in some cases, severely threaten crop enterprises. Resistance to MBCs (methyl benzimidazole carbamates) was detected in the 1970s, to 2-aminopyrimidines in 1971, to phenylanides in 1980, to DMIs (demethylation inhibitors) in 1982, to QoIs (quinone outside inhibitors) in 1998 and to SDHIs (succinate dehydrogenase inhibitors) in 2007.[123] Worryingly, in some cases resistance developed very soon after commercial release of fungicides with new modes of action (two years in the case of QoI-type fungicides[124]). This probably represents the high genetic diversity and mutation rate in fungal pathogens.

3.3.2 Mechanisms of Fungicide Resistance. Major resistance mechanisms include altered target site (including resistance to MBC, azole, QoI and SDHI fungicides), overexpression of target site (DMI fungicides), efflux of fungicide from the cell (DMI fungicides), and metabolic resistance resulting from breakdown of the fungicide.[125,126] The latter is less-commonly reported than metabolic (EM) resistance in weeds and in insects.

3.3.3 Fungicide Resistance Case Study: Septoria tritici. *Septoria tritci* (*Mycosphaerella graminicola*; *Zymoseptoria tritici*) causes *Septoria tritici* leaf blotch, a commercially important foliar disease of wheat that occurs worldwide. In Northern Europe it is considered to be the most important wheat disease and its control is vital for commercially successful enterprises, as it can cause up to 50% yield loss. In the mid 1980s populations of *S. tritici* that showed reduced sensitivity to a range of MBC-type fungicides were reported, suggesting cross-resistance within the MBC group had developed. Target-site resistance in this case is due to a point mutation in the β-tubulin gene.[126] (E198A – indicating the position in the amino acid chain where a substitution due to the mutation in the gene has taken place (198) and the nature of the mutation, in this case the amino acid alanine [A] replacing glutamic acid [E]). Lack of fitness cost associated with this mutation means that high levels of the mutation in populations of *S. tritici* remain even after use of MBCs has ceased. Resistance to QoI fungicides was first reported in *S. tritici* in 2002, largely due to target-site mutation G143A in cytochrome b that is the target site for this fungicide group.[127] Another mutation (F129L) was reported, but was present at a much lower frequency.[128] In both the cases of resistance to MBCs and QoIs, resistant individuals showed a marked difference in sensitivity to fungicides of the respective types and quickly became the dominant members of *S. tritici* populations where these fungicides were used. In the case of resistance to azole-type fungicides, the change in sensitivity in populations was more gradual, possibly indicating presence of non-target site mechanisms and of more than one resistance mechanism. Indeed, many TS mutations have been identified that show different cross-resistance patterns to members of the azole group of fungicides. In addition, increased efflux is suggested as an additional mechanism for azole resistance, as has overexpression of the CYP51 target site for the azole fungicides.[129] SDHI fungicides are a group of fungicides recently developed for cereal crops, in part with the hope that they can successfully control pathogens that are resistant to other active ingredients. Their target site is the enzyme succinate dehydrogenase, laboratory-based studies have indicated that mutation in this target site will lead to reduced sensitivity to SDHIs. Isolated cases have been reported where this has been observed in Northern Europe in 2012. Monitoring did not detect these in 2013, although cases were reported in 2014 and 2015.[130] Although only a few cases have so far been confirmed, continued use of sequences and mixtures of fungicides with different modes of action is vital and should help to protect the utility of this important fungicide group in *S. tritici* control.

3.4 Insecticide Resistance

3.4.1 Background. Resistance to insecticides was first reported by Melander in 1914.[131] Populations of scale insect were observed that were not controlled by an inorganic insecticide that would usually control this species. Subsequent to this, other reports of resistance to inorganic insecticides were reported in a number of species. However, it was with the development of organic insecticides, with their single site of action, in the 1940s, that insecticide resistance really started to develop with pace. The first case of resistance to a synthetic organic insecticide was that of resistance to DDT in *Musca domestica*, reported in 1947.[132] Today, there are more than 580 arthropod species demonstrating resistance to one or more pesticides,[133] and this is undoubtedly an underestimate of the true scale of resistance. Although this includes species that are not responsible for crop damage (for instance, mosquito and housefly), it has been estimated that insecticide resistance adds in excess of $40 million annually in the USA to the already-high cost of crop protection. Resistance is reported against most modes of action (as classified by the Insecticide Resistance Action Committee, IRAC).[134] Some of the commercially important insect species demonstrating resistance include two-spotted spider mite, diamondback moth, peach-potato aphid, Colorado beetle, European red mite and the cotton bollworm.[133] From a UK perspective, the most-important crop pests showing insecticide resistance include the peach-potato aphid, European red mite, pea-leaf miner, cabbage-root fly, hop aphid, two-spotted spidermite and greenhouse white fly.[134]

3.4.2 Mechanisms of Insecticide Resistance. Insecticide resistance occurs due to the presence of one or more inheritable resistance mechanisms. Altered target site, where a single amino-acid change in the target-site protein reduces insecticide binding, confers resistance to a number of classes of insecticide. Metabolic resistance, where the insecticide is degraded to less- or non-toxic metabolites at a rate that is fast enough to allow survival, is also commonly reported. This is often due to higher levels of metabolism-related enzymes including GSTs and CYPs.[135] Penetration resistance has also been reported, where there is reduced absorption of the insecticide, often due to alterations in the composition of the cuticle of the target insect.[135] Increased rate of insecticide excretion has also been observed as a resistance mechanism. Behavioural resistance, where an inheritable behavioural trait means an insect is less likely to come into contact with the insecticide, is an additional mechanism.[136] There is often a fitness price to pay associated with insecticide resistance. This is in contrast to herbicide and fungicide resistance, where fitness price is either not present or has yet to be identified. The fitness price associated with insecticide resistance may become evident under stress conditions such as cold temperatures. For instance, slower movement away from predators (possibly related to the resistant individual's inability to detect aphid-produced alarm pheromones) and towards more beneficial feeding environments have been reported in resistant insects. Reduced larval survival, copulation rate, fecundity and fertility have all been reported in resistant individuals and these fitness prices will result in a reduction in the proportion of a population that is resistant in the absence of the selection pressure exerted by application of insecticide.[135] This can and should be exploited in any integrated pest management strategy.

3.4.3 Insecticide Resistance Case Study: Myzus persicae. The peach-potato aphid (*Myzus persicae*) is one of the most important crop pests worldwide. It has a very large host range and geographical distribution. *M. persicae* causes direct feeding damage which leads to reduced yield, quality and increased occurrence of disease. In addition, it acts as a vector in the spreading of a number of commercially important plant viruses. Resistance in this species was first detected in 1955 against the organophosphorus (OP) class of insecticides.[137] Currently, resistance in this species has been shown against a number of insecticides *via* a number of resistance mechanisms. Modified AChE (acetylcholinesterase or MACE) resistance is due to a modified target site and confers resistance to pirimicarb.[138] Knockdown resistance (kdr and super kdr) are also target-site-type resistance mechanisms, in this case due to modification of the sodium channel proteins, and confer resistance to DDT and pyrethroids.[139] Target-site resistance due to modification of the Rdl GABA ('Resistance to dieldrin' gamma-aminobutyric acid) receptor[140] and the nACh (nicotinic acetylcholine) receptor[141] have also been reported. Enhanced metabolism resistance has been reported *via* overproduction of esterases (both E4 and EF4 esterases), conferring resistance to OPs, carbamates and pyrethroids[142] and CYPs (cytochrome P450 monooxygenases), conferring resistance to neonicotinoids[143] *via* increased rate of insecticide detoxification by the aphid. Reduced penetration resistance has also been reported in this species. A recent report of behavioural resistance in *M. persicae* indicates that an inheritable trait causes some aphids to avoid neonicotinoid-treated areas of the leaf.[144]

3.5 Managing Resistance

Increased numbers of resistant populations of weeds, pests and diseases, combined with a steady decline in the availability of active ingredients to control them, create large-scale problems worldwide. Avoiding further resistance development, and managing it where it occurs, is vital for continued financially viable agricultural and horticultural productivity in many sectors and geographical regions. Practically speaking, resistance is a result of both selection pressure and increased weed, pest or disease population size. Both of these aspects need to be fully addressed. Managing resistance therefore needs to involve two separate but equally important strategies:

(1) Selection pressure favouring survival of resistant individuals over susceptible individuals must be reduced as much as possible. This involves the use of fully-recommended rates of pesticides (as lower-than-optimum rates may select for EM-type resistant individuals) in mixtures and in sequences, aiming to utilise as many different modes of action as is environmentally, practically and financially possible. This can often be enhanced by moving away from crop monoculture, as rotations can provide for a wider range of available pesticides. Over-reliance on a single mode of action must be avoided, even where resistance to that mode of action has not yet been reported.
(2) Populations of weeds, pests and diseases must be reduced in size using methods that do not exert a selection pressure favouring survival of a proportion of the population. Implementation of (where appropriate) manual, mechanical, cultural, biological and crop breeding controls will reduce weed, pest and disease populations without exerting unacceptable selection pressures. If populations are reduced in this way then even if individuals do survive agrochemical treatment, they are lower in number because the initial population was smaller. Although specific management strategies will differ for specific cropping situations, specific weeds, pests and diseases, and specific geographical regions, the rotation of crop species and type, of planting and harvesting dates, the use where appropriate of resistant crop varieties, and good crop husbandry and health resulting in competitive crops should all be considered. Methods to prevent weed, pest and disease problems occurring should underpin these integrated management strategies.

There is no doubt at all that further cases of pesticide resistance will occur. The evolutionary race mentioned at the beginning of this section continues apace and, from a cropping perspective, we are far from winning it. However, by using fully integrated approaches to pest management we can give ourselves the best chance we can of keeping up with Andy Dyer's Red Queen.[99]

4 Pesticides in Water

4.1 What Is the Issue?

The issue of pesticides in water grew to prominence in the 1980s and '90s. For example, Ongley,[145] writing for the Food and Agriculture Organisation

(FAO), refers to pesticide contamination of wells in the United States in 1992 and Canada in 1995 and serious contamination of surface waters around the Aral Sea in Russia, from the 1960s onward. The latter example had major impacts on human health and the ecosystem. In 1993, The World Health Organisation (WHO)[146] established drinking water guidelines for 33 pesticides. These guidelines have been periodically updated, with the fourth edition published in 2011.[147]

The principal concerns are the ecological impacts of pesticides in surface water and impacts on drinking water quality. Contamination of fish and shellfish in waters affected by pesticides can also be a concern. In the European Union (EU), the issue has attracted most attention, because the regulatory process sets limits for all pesticides. In contrast, EU ecological standards apply to a much-shorter list of pesticides.

4.1.1 *Minimising Ecological Impacts.*

In the EU, the Water Framework Directive (WFD)[148] establishes a strategy to protect the chemical and ecological status of water bodies. Environmental Quality Standards (EQSs) limit the concentrations in surface water of certain substances or groups that are considered priority pollutants, because of the substantial risk they pose to or *via* the aquatic environment. The EQS Directive[149] sets out the concentration and/or the annual-average concentration of 33 priority substances, plus eight other pollutants in water and, in some cases, sediment and/or biota (organisms). A further 12 priority substances are included in a later, amending directive,[150] both lists being combined into a total of 45 groups. 22 pesticides are included, most of which are approved in the EU. Table 1 shows the EQS values for the four which still have EU approval for agricultural use. Note that cypermethrin has also been used as a veterinary medicine (sheep dip), which has been the main cause of concern.

In addition, the WFD allows Member States to establish EQSs for Specific Pollutants (in the UK, "River Basin Specific Pollutants") that are discharged

Table 1 Environmental Quality Standards for currently approved EU pesticides (February 2016).

Pesticide	Annual average conc., inland surface waters (μg L^{-1})	Annual average conc., other surface waters (μg L^{-1})	Maximum allowable conc., inland surface waters (μg L^{-1})	Maximum allowable conc., other surface waters (μg L^{-1})	Biota if relevant (μg kg^{-1} wet weight)
chlorpyrifos (chlorpyrifos-ethyl)	0.03	0.03	0.1	0.1	—
quinoxyfen	0.15	0.015	2.7	0.54	—
bifenox	0.012	0.0012	0.04	0.004	—
cypermethrin	8×10^{-5}	8×10^{-6}	6×10^{-4}	6×10^{-5}	—

Table 2 Currently approved pesticides with proposed UK Specific EQSs (February 2016).

	Fresh water μg L^{-1}		Salt water μg L^{-1}	
Pesticide	Long-term (Mean)	Short-term (95 percentile)	Long-term (Mean)	Short-term (95 percentile)
Chlorothalonil	0.035	1.2	—	—
Cypermethrin[a]	0.1	0.4	0.1	0.4
2,4-Dichlorophenoxyacetic acid (2,4-D)	0.3	1.3	0.3	1.3
Dimethoate	0.48	4.0	0.48	4.0
Glyphosate	196	398	196	398
Linuron	0.5	0.9	0.5	0.9
Mecoprop	18	187	18	187
Methiocarb	0.01	0.77	—	—
Pendimethalin	0.3	0.58	—	—

[a] Cypermethrin is a Priority Substance under 2013/39/EU but there will be a transitional period before the Priority Substance standard applies.

to surface water in significant quantities. 29 UK specific pollutants are currently proposed, (February 2016), of which 12 are or have been agricultural pesticides.[151] Table 2 shows nine with current EU approvals. Note the different basis for reporting, compared to EU EQSs.

The 2013 amended EQS Directive[150] also establishes a mechanism to provide data on substances of possible concern in the aquatic environment, called the Watch List. Four out of the seven substances or groups currently on the list are pesticides, all with current EU approval for use in agriculture, namely oxadiazon, methiocarb (already a UK River Basin Specific Pollutant), tri-allate and the neonicotinoids imidacloprid, thiacloprid, thiamethoxam, clothianidin and acetamiprid.

Under the WFD, overall good status for a water body is reached if both ecological and chemical status are classified as good. Good chemical status is achieved where a surface water body complies with all the EU EQSs. However, Member State-specific pollutants are amongst the parameters used to assess ecological, not chemical, status. EQSs are also used to set discharge permits to water bodies. EQSs should protect freshwater and marine ecosystems from possible adverse effects of chemicals, as well as human health *via* drinking water or ingestion of food originating from aquatic environments.[152] Therefore, several types of receptor have to be considered: the pelagic (open water) and benthic (bottom) communities or biota in freshwater, brackish or saltwater ecosystems; the top predators of these ecosystems; and human health. Not all receptors need to be considered for every substance. This depends on the environmental fate and behaviour of the substance. For example, if a substance does not bioaccumulate, or does not have high intrinsic toxicity, there is no risk of secondary poisoning and so a biota standard is not required. However, where a possible risk is identified, quality standards need to be derived for that receptor, *i.e.* an EQS for biota or sediment.

In England in 2015, 11 water bodies failed on one or more EQS values, involving the banned pesticides HCH, cyclodienes (aldrin, dieldrin, endrin and isodrin), *para-para*-DDT, diazinon and the currently approved herbicide 2,4-D (Environment Agency, personal communication). The latter was found in two water bodies at mean concentrations 0.40 and 0.32 $\mu g\ L^{-1}$. The sources are not clear, but manufacture of 2,4-D has caused exceedances in the past and diazinon is a veterinary medicine used in some sheep dips. The remaining exceedances may reflect persistent residues from historic use or disposal.

4.1.2 Drinking Water. In contrast to the targeted setting of EQSs, all pesticides share common limits under the EU drinking Water Directive.[153] This Directive aims to protect human health from the adverse effects of any contamination of water intended for human consumption. It sets a maximum concentration, at the consumers' taps, of 0.1 $\mu g\ L^{-1}$ for individual pesticides (except for the banned pesticides aldrin, dieldrin, heptachlor and heptachlor epoxide, for each of which the limit is 0.03 $\mu g\ L^{-1}$). The limit for total pesticides is 0.5 $\mu g\ L^{-1}$. The 0.1 $\mu g\ L^{-1}$ limit was originally based on the limit of determination for analytical methods available at the time, although these have improved (*i.e.* reduced) substantially since the original Directive. However, the original limits remain. They are, in almost all cases, lower than the WHO guideline values for drinking water, where the latter have been established, in some cases by several orders of magnitude. In contrast, for those pesticides with an EQS in water, there are examples of some EQSs being higher and others lower than the EU drinking-water limit, (Tables 1 and 2). In the case of cypermethrin, the EU EQS is several orders of magnitude lower, reflecting its toxicity to aquatic organisms.

In England in 2015, pesticides were the largest cause of surface-water drinking-water sources, or surface-water Drinking Water Protected Areas being "at risk" of not meeting statutory objectives and the second largest contaminant group for groundwater sources.[154] Table 3 shows which pesticides caused most problems in surface water.

Most pesticides can be removed by appropriate treatment before putting into supply, although this can involve considerable cost. However, some pesticides are difficult to remove with current methodologies, or sometimes unexpected contamination of the source occurs, which risk assessment by the water undertaker fails to predict, or existing treatment fails to remove. In Central and Eastern England in 2014, out of 124 888 compliance tests for individual pesticides on water post-treatment works, 87 failed to meet the required standard.[155] 84 of these were due to metaldehyde, plus one each for clopyralid, oxadyxil and pendimethalin.

4.2 Pesticide Movement to Water

4.2.1 Processes in the Soil. In order to understand how pesticides reach water, some of the processes they undergo in the soil need to be

Table 3 Number of surface water DrWPAs at risk from currently approved pesticides (February 2016).

Pesticide	At risk DrWPAs	Pesticide	At risk DrWPAs
metaldeyhde	102	metazachlor	11
MCPA	38	isoproturon	6
propyzamide	35	bentazone	3
carbetamide	31	triclopyr	3
mecoprop	28	fluroxypyr	2
clopyralid	20	Total pesticides	1
chlorotoluron	17	asulam	1
2,4-D	14	cyromazine	1
glyphosate	14	linuron	1
quinmerac	14	pendimethalin	1
		terbuthylazine	1

considered. Unlike other potential pollutants, such as nitrate, each pesticide behaves in a unique way. There are many processes common to all pesticides, but the differences in individual pesticide properties produce different outcomes.

Two key processes affecting pesticide fate in soil are retention of the pesticide by soil (adsorption or sorption) and degradation of the pesticide in or on soil. Broadly, the more tightly a pesticide is retained by soil, the less likely it is to move away from the soil, although it may move with the soil. Similarly, the more rapidly a pesticide degrades in or on the soil, the less the potential to move away from or with the soil. Sorption is usually measured as a partition coefficient between the soil or a soil fraction (most commonly, the soil organic-carbon content) and soil water. Degradation (or persistence) is usually measured as the half-life, under specified conditions (*e.g.* temperature, soil moisture content).

4.2.1.1 Sorption

Sorption is affected by both soil properties and the characteristics of the pesticide, in particular the size, shape, molecular structure, functional groups, solubility, polarity and surface charge.[156] Various soil constituents are involved, including soil organic carbon, clay minerals and aluminium and/or iron oxides and hydroxides. Sorption mechanisms include ion exchange, hydrogen bonding, interactions with metallic cations, interactions as polar molecules, charge transfers and hydrophobic effects with van der Waals forces.[157] An understanding of these mechanisms helps with prediction of likely pesticide movement.

Ion exchange can occur between cations and a negatively charged surface, or anions and a positively charged surface. The former is the most common in temperate soils, which normally carry a permanent negative charge, balanced by exchangeable cations (although sites with positive charge may be exposed at the edges of soil minerals). There are relatively few ionic pesticides, but diquat and paraquat are examples.

Hydrogen bonds can form between a pesticide and the soil surface. These may be direct associations with functional groups on the soil surface, or indirect associations with water molecules of hydrated exchangeable-metal cations.

Cations in soil, present as exchangeable ions or as constituents of crystalline or amorphous minerals, provide opportunities for pesticide–metallic cation interactions. Depending on the electron-acceptor power of the cation, two types of attraction can occur: cation–pesticide dipole interactions (for pesticides with both negatively- and positively-charged groups) and coordination (electron sharing) bonds.

In charge transfer, it is thought that electron-donor and electron-acceptor molecules result in electron exchange. An example is believed to be the adsorption of triazine herbicides on humic acids.

Sorption of pesticides to soil is widely considered most often to involve soil organic matter interactions, especially for hydrophobic pesticides. Physical sorption onto soil organic matter is thought to occur, either by the hydrophobic pesticide being expelled from soil water (the "hydrophobic effect"), or attraction to soil surfaces through van der Waals forces (attraction through fluctuating polarisation of molecules in close proximity).

Ionisation of pesticides that are weak acids or bases is an important factor in their sorption and mobility. This may be affected significantly by soil pH, so the pK_a of these pesticides is important. In the common pH range of cultivated soils, weak acids or bases may be ionised in significant amounts. Some triazine herbicides and carbamate fungicides are weak bases with pK_a values (dissociation constant) between 3.0 and 8.0 that allow ionisation to positive species by protonation at normal soil pH values and attraction to the predominantly negative charge of temperate soils. In contrast, dissociated pesticide anions will be repelled by the soil surface. This is important in the movement of phenoxycarboxylic acid herbicides such as MCPA and mecoprop, which are commonly detected in drinking water sources at concentrations above $0.1\ \mu g\ L^{-1}$. Soil pH also affects pesticide sorption because of its effect on other soil properties, such as electric charge and ionic strength.[158]

Sorption mechanisms vary in the strength of interaction. Also, pesticides may contain groups involving one or more of the mechanisms above. This can make the description of sorption for a given pesticide very complex.[157]

Pesticide sorption in soil is often described by the K_{oc}, the partition of the pesticide between soil organic carbon and water. This assumes that pesticide sorption is primarily dependant on soil organic carbon. Certainly, the nature of soil organic matter is important in the sorption of non-ionic pesticides, with pesticides that have functional groups most similar to the components of organic matter most likely to bind covalently to organic matter.[158] However, the dependence on organic matter is not true for all pesticide sorption: K_{oc} is a poor predictor of sorption strength for pesticides that interact primarily with inorganic constituents, such as glyphosate, or for soils of low organic carbon content, such as subsurface soils and vadose zone (unsaturated zone) materials. The simple K_{oc} concept may be inadequate to describe sorption in soils with less than approximately 2% organic carbon.[156] Information on clay, iron and aluminium oxides and pH may be needed, in addition to organic carbon, for accurate prediction of pesticide mobility in soil.

Sorption, in principle, involves an equilibrium process: if the concentration of pesticide in solution declines, some will desorb from the soil. However, comparison of adsorption and desorption isotherms shows frequent hysteresis, *i.e.* sorption is not completely reversible. Also, sorption is often time-dependant: it frequently increases with time and may not reach an equilibrium.[159] Time-dependant sorption varies between soils as well as pesticides and there are some pesticide-soil combinations that show very little or no increase in sorption over time. Where it does occur, the processes involved are unclear, but it seems that diffusion into soil aggregates and increasing interaction with soil organic matter are likely to be involved,[158,159] in particular, intra-organic matter diffusion, in which the pesticide may become entangled with soil organic matter polymer chains.[160] Large increases in sorption have been reported, over periods of weeks. This has significance for predicting pesticide mobility and appropriate regulatory tests to assess time-dependant sorption are still being developed.[161]

4.2.1.2 Degradation

Pesticide dissipation involves physical, chemical and biological processes, including volatilisation, photodegradation, sorption, hydrolysis and biological degradation. Pesticide degradation in soil, *i.e.* post volatilisation and photodegradation, is considered to be the second-most important process in the prediction of pesticide fate[162] and microbial degradation is the primary route for loss.[163] Standard field and laboratory dissipation studies are conducted to determine the degradation rate. This is usually expressed as a first-order (*i.e.* rate of change is proportional to concentration) half-life or DT_{50}, the time required for 50% of the initial amount to disappear. Pesticide degradation rates are influenced by physico-chemical properties of the soil, such as pH and organic carbon content, biological properties such as species, activity and distribution of microorganisms, and environmental conditions such as soil temperature and moisture content.[164] Degradation rate and pathway also depend on pesticide properties. There is considerable variability in degradation rate between different environments, including field-to-field variation and between pesticides within a given environment. Generalisations on the effects of factors involved are difficult.

For many neutral pesticides, microbial degradation rate increases with pH, up to approximately 8–8.5.[162] Ionisable pesticides that show significant microbial degradation may be less sorbed and thus more available for degradation as pH increases, so both microbial and physical processes are involved. However, where abiotic degradation dominates, such as for most sulfonylurea herbicides (which are weak acids), pH and degradation rate are usually negatively correlated. Also, there is often no clear link between pesticide sorption and degradation rate. There are examples of pesticides for which degradation and sorption are positively correlated, for example as a result of catalysed hydrolysis after sorption onto soil organic matter. For other pesticides, activity of the soil biomass and/or pH appears more important than sorption. There is often a strong correlation between soil organic carbon content and degradation rate, reflecting greater bioactivity. This may be greater than any reduction in degradation rate resulting from increased sorption.[162]

The two parameters, K_{oc} and DT_{50}, are widely used for prediction of pesticide movement to water, either on their own or in models of varying complexity. This is necessary for risk assessment, but it is important to remember the variability they show and the limitations of their applicability.

4.2.2 Movement to Water. Movement of agricultural pesticides to water is often attributed to four main pathways: spray drift; surface runoff and erosion; leaching and movement to field drains; and point source losses, such as those from the yard.[164] Once a pesticide is on or in the soil, its movement is controlled in a large part by the movement of water. A full understanding of pesticide movement requires a thorough understanding of water movement.

Spray drift may cause short-lived concentrations of local significance in surface water, but total inputs are usually considered smaller than *via* the other routes[164] and of less significance,[165] at least at the catchment scale. Atmospheric deposition, following volatilisation and short- or long-distance atmospheric transport, plus aeolian deposition of pesticide-carrying soil particles, may also contribute to pesticides entering surface water. Some modelling evidence suggests that deposition of volatile pesticides may be as important as spray drift.[164] Atmospheric transport might not only be limited to volatile pesticides. Glyphosate, which is considered non-volatile, has been reported in precipitation samples in the US.[166] Wind-blown soil particles, washed out of the atmosphere by rain, might cause such an effect, but perhaps aerosols, produced during spraying, might also cause a form of longer-range drift; this requires further investigation.

The relative importance of runoff/erosion *versus* leaching/field-drains is not clear cut. However, in the UK modelling suggests drainage is likely to be more important at a national level, because although concentrations from drainage and surface runoff are similar, drainage is known to be a much more extensive process and with a greater volume of water moving from field to surface waters.[165]

4.2.2.1 Runoff and Erosion

Surface runoff may still be a significant (and even dominant) process in specific locations. Runoff and soil erosion can carry pesticides in solution, or sorbed to eroded soil: the former can include transport with dissolved soil organic matter; the latter may include suspended sediment, for example from dispersed clay. Pesticide losses to surface water *via* runoff are generally considered greater than losses *via* erosion, because the quantity of soil leaving the field is usually small compared to the runoff volume.[20] However, for strongly sorbing pesticides (K_{oc} greater than about 1000 L kg^{-1},[164] or 5000 L kg^{-1} [165]), erosion is considered to be the greater pathway. Also, pesticides with intermediate sorption are considered more susceptible to runoff losses than weakly sorbed pesticides, because the latter are more likely to move away from the soil surface quickly with infiltrating rainfall.

4.2.2.2 Leaching and Field Drainage

Leaching, the downward movement of substances through the porous matrix of the soil profile (theoretically, as a near-uniform front), is likely to be highest for weakly sorbing and/or more-persistent pesticides. It is increased by high rainfall and low temperatures (the latter reducing degradation rates and decreasing evapotranspiration losses). However, preferential flow of water through the soil profile has become recognised as an important and controlling process for pesticide movement down the profile.[160] Preferential flow involves water movement along specific pathways, bypassing part of the porous soil matrix. It can be divided into macropore flow (along cracks, fissures, root channels and earth-worm burrows) and finger flow, which occurs in sandy soils. Preferential flow can result in pesticides reaching field-underdrainage systems soon after application, if there is sufficient rainfall to cause a drainage event. Also, strongly sorbed, less-mobile pesticides may reach underdrainage systems at the same time as weakly sorbed, more-mobile pesticides, although the quantities lost are likely to be greater for more-mobile pesticides. Preferential flow can cause high pesticide concentrations in surface water. Pesticide-containing drainage water moves rapidly through only part of the available pore space, bypassing much of the soil matrix, so there is little time for sorption and degradation, or for equilibration with the slowly moving water held in soil aggregates.[167] The peaks in concentration will be transient but may re-occur with further drainage events. As a drainage event slows or ceases, pesticide desorption and migration from less-accessible parts of the soil matrix, within soil aggregates, replenish pesticide concentrations in the faster-responding drainage channels. However, as time progresses, degradation and time-dependant sorption continue and there is less pesticide available in the drainage channels. Hence with subsequent drainage events, the peaks in concentration typically decline in magnitude, if all other factors are equal (*e.g.* intensity and duration of rainfall, preceding soil moisture content, *etc.*).

Pesticide losses *via* preferential flow can be important on lighter-textured soils, as well as clayey soils and have even been reported on poorly structured sandy soils.[164] However, pesticide losses *via* drainflow are generally greater on heavier-textured, structured soils. Pesticide losses in drainflow often reflect rainfall and drainage events. In contrast, leaching is typically more continuous, being most associated with lighter-textured soils with more water movement through the soil matrix. Such soils are less likely to be underdrained, with pesticides moving to groundwater.

4.2.2.3 Point Sources

Point-source inputs of pesticides arise from practices such as sprayer filling, sprayer cleaning, pesticide or sprayer storage, poor equipment maintenance and accidents. Sprayer filling on a surface where spills are not contained, which may be hardcore, concrete or in the field too close to underdrainage, is a typical scenario. Careless storage or disposal of used containers, their foil seals, contaminated clothing and dirty sprayers (carrying contaminated soil and spray deposits) are all common point-source inputs. The total contribution of point sources to the surface-water pesticide load has been estimated at 40–90%.[164] The figure will vary with such factors as the hydrology of the catchment, farm size and type, and availability of training and information.

4.3 Regulatory Control

EU Regulation 1107/2009[168] controls the placing of plant-protection products, PPPs, on the market. It repeals previous Council Directives 79/117/EEC and 91/414/EEC. It aims to protect human and animal health and the environment and standardises rules on the sale of PPPs. The regulation has, in effect, two layers. The first is an EU-wide assessment and peer review of an active substance (a.s., the pesticide active ingredient, also referred to as a.i.), resulting in a positive list of such substances. This was previously sometimes referred to as "Annex 1 inclusion". However, the correct terminology is "active substance approval". The second is the authorisation by individual Members States (MSs) of PPPs, the formulated products that contain approved active substances. This was sometimes referred to as "Annex III listing". The Applicant (the organisation developing the pesticide or PPP) has to provide the data for both layers. The Regulatory Authorities evaluate the submission.

4.3.1 Active Substances. The first-layer a.s. review involves deriving a set of values or "endpoints" that describe the properties and behaviour of the substance and its metabolites. There is also a risk assessment of a representative use, or selection of uses, of the a.s. The set of endpoints comprises the results from a standard list of studies that must be submitted to the regulatory authorities. These are specified in Regulations 283/2013 (data requirements for active substances) and 284/2014 (data requirements for PPPs). These specify physical and chemical properties that must be submitted (*e.g.* melting and boiling point, vapour pressure, solubility in water and specified solvents), plus a considerable data package to describe properties such as toxicology and ecotoxicology, residues in food and feed, and environmental fate and behaviour. It is in this latter section that water contamination is considered. The key data requirements concern degradation in soil, water and sediment (speed; degradation pathway; identity of degradation products) and strength of sorption. Sorption and desorption studies are required for the active substance. They may also be required for metabolites, breakdown and reaction products, if these latter substances are present in specified amounts at specified points in the studies (*e.g.* if accounting for more than 10% of the a.s. at any time in the studies). The key results or endpoints and the risk assessment of the representative use are finally considered and presented in a European Food Safety Authority (EFSA) conclusion on the a.s., following a peer-review process by EFSA and the MSs.

4.3.2 Plant Protection Products. In the second layer of the regulatory process, individual MSs assess submissions for PPPs that contain approved active substances. Applicants submit the data to the MS(s) where they would like the PPP to be authorised for use. The proposed uses may be different from the representative use(s) considered for the a.s. approval, in which case the same endpoints are used to prepare risk assessments for the proposed uses.

4.3.3 Modelling. Modelling is an important part of assessing exposure of water. In the first pan-EU assessment, FOCUS[169] groundwater and FOCUS surface-water modelling frameworks are used. FOCUS, the FOrum for Co-ordination of pesticide fate models and their USe, provides simulation models and scenarios for calculation of Predicted Environmental Concentrations (PECs) of active substances in groundwater and surface water. The groundwater and surface water frameworks are similar in comprising a number of different models set up with standard scenarios, aiming to represent large geographical areas of the EU. They use vulnerable soil and climate combinations, to represent 90th percentile worst case (*i.e.* highest risk of reaching water) situations in the EU. Agreed endpoints from the EU peer-review procedure are used to represent substance properties, plus specific information on how the PPP will be used, such as crop, growth stage, application rate, number of treatments and time of year, to produce a PEC. FOCUS groundwater predicts annual average pesticide concentrations at 1 m depth and this is compared to the EU drinking-water standard of 0.1 μg L^{-1} for decision-making purposes. FOCUS surface water predicts concentrations in surface water and sediment for comparison against ecological data on aquatic species.

The applicant submits the FOCUS modelling outputs with the rest of the data package. The regulatory authority validates that the assessment has been conducted properly. They may require the modelling to be repeated, for example with more appropriate parameters, or they may decide to conduct further modelling themselves.

To authorise PPPs in individual MSs (the second layer), MS regulatory authorities can also use the FOCUS modelling framework. Some MSs do not do so, because they have had existing environmental exposure frameworks devised as representative of their water-exposure situation before the release of the FOCUS models, or they consider the standard FOCUS scenarios do not represent their national agricultural situations closely enough. Currently, the UK uses the FOCUS groundwater framework, because it is considered sufficiently representative for use in decision-making for UK national authorisations. However, following independent assessments of both frameworks, the FOCUS surface-water framework is not currently used for UK national authorisations. This may change in the future.

The criteria EU MSs must use for decision making, having followed the procedures above, are set out as the Uniform Principles.[170] Here there are limit values and qualifying criteria for end points in a.s. approval; for example, persistence and the risk assessment of PPPs. For groundwater, authorisation is linked to limits set out in the EU Groundwater Directive,[170] *i.e.* a maximum of 0.1 μg L^{-1} for individual pesticides, or to more severe toxicological limits set for an individual a.s. For surface water used for drinking water, the Uniform Principles are more open to interpretation, referring to concentrations above which compliance with drinking-water quality established in accordance with the WFD is compromised, or to impacts on non-target species. Pesticide regulation largely across the EU does not place emphasis on concentrations at surface-water drinking-water abstraction points, toxicity having been assessed earlier in the approval process, but considers the impacts on aquatic ecology and the wider consequences, for agriculture and society, of granting, refusing or withdrawing an authorisation.

4.4 Mitigation

There are many practices that have the potential to reduce pesticide losses to water and these have been widely reviewed.[164,165,171,172] They are listed in Table 4. Some practices have been used specifically for water protection, others are used primarily for other reasons, but may also reduce pesticide losses to water. The following discussion focuses on mitigation measures for runoff and erosion, leaching/drain-flow and point-source measures. It concentrates on those measures deployed specifically to reduce water contamination by pesticides and those considered to have most potential to do so. Spray drift is not discussed further; it has been recognised for longer than the other pathways. Its mitigation measures, which can be grouped into no-spray buffers, vegetation and artificial windbreaks and drift-reducing technology, have been available for many years, although often not deployed adequately. Sprayer and application technology are also not discussed further, but are developing rapidly, with drivers other than water protection, but again there are potentially many benefits for reducing water contamination.

4.4.1 Buffer Strips. Vegetated buffer strips, positioned along watercourses, have the potential to reduce pesticide losses by both runoff and erosion. The reduction is mainly due to sedimentation (as the flow velocity is reduced and the load-carrying capacity of water decreases) and infiltration in the buffer strip, although significant sorption to plant or soil may also occur. Grassed strips are generally more effective than cropped or bare strips,[164] at least for sediment and sediment-bound pesticides, and woodland strips more so than grass, because of greater infiltration under woodland. However, a riparian buffer (bank vegetation along a watercourse) is probably much less effective than an edge-of-field grass strip.[164] Load reduction is similar for weakly and moderately sorbing pesticides: the data for strongly sorbing pesticides are not clear, but will depend on the balance between sedimentation and infiltration. For buffers with shallow groundwater adjacent to a watercourse, there is the potential for pesticides in solution to infiltrate the buffer but still reach the watercourse. Generally, pesticide-reduction efficiency depends on the nature of the rainfall and runoff event and the antecedent soil-moisture conditions, because these affect runoff and infiltration; in a large rainfall event and/or steep slope generating high runoff velocities and/or with previously wet soil, there might be little or no sedimentation or infiltration and little pesticide reduction. Width of buffer will be important up to the width at which maximum infiltration occurs. However, as this will depend on the factors just described, the relationship to width is not simple.

Results in the literature are very variable, but average load reductions of approximately 50% for 5 m buffers strips and 90% for 10 m width have been suggested.[164] Vegetated strips can also reduce the velocity and volume of overland flow and soil, sediment and pesticide loss, if sited across slopes away from field margins, or along the bottom of gullies (forming swales).

4.4.2 Drain Flow. Buffer strips have little or no effect on pesticide losses in drainflow and currently there are very few mitigation measures for this pathway of loss. Cultivations could increase or reduce pesticide movement through the soil profile to field drains. Creation of a finer tilth may reduce preferential flow near the soil surface, but it might also increase the quantity of fine material able to carry soil-bound pesticides. Deep cultivations, such as sub-soiling, could increase preferential flow and current best-practice advice is to avoid sub-soiling unless there is an identified need, in catchments with pesticide problems.[173]

Measures to reduce the drainage efficiency in under drained fields, reducing the speed at which water moves to drains by impeding drainage and hence giving more time for sorption and degradation, have been reported to give a small reduction in pesticide loss.[171] However, a consequent increase in runoff losses has also been reported[164] and increased percolation to groundwater might also occur, so the measure would not be a simple one to deploy effectively. Placing pesticide-sorbing material into field drains has also been found to reduce losses of strongly but not weakly sorbing pesticides.[171] The material needs to have self-cleaning or pesticide-degrading properties if regular renewal is not to be required, which is impractical. Such a measure might be the bioreactor.[174] These wood-chip filled structures have been installed in field-drainage systems in the USA to reduce nitrate levels. They may have the potential to sorb and perhaps also degrade pesticides, after an effective microbial community has built up in the biofilm on the wood-chips, although the cost might be a barrier. Ongoing work in the USA suggests significant pesticide reductions can be achieved.[175]

Constructed wetlands are widely used for treating lightly contaminated wastewaters. They could provide mitigation for pesticides in both runoff and drainage; for example, if connected to the ditch network. They have been found effective at reducing pesticide levels,[164] probably largely through sorption to bed and suspended sediment and to plant material, plus settlement of pesticide-bearing sediment. However, their effectiveness with more-weakly sorbed pesticides is poorer and residence time is important,[176] so that large land areas may be required to achieve adequate mitigation; for example, a travel distance of up to 280 m. This might make them more appropriate to installation at the base of a sub-catchment, rather than at the farm scale.

Ponds, installed in ditches or to intercept runoff, might also help with mitigation through similar processes to constructed wetlands. Benefits of removal of sorbed rather than dissolved pesticides have been demonstrated,[177] but the limitations of constructed wetlands are likely to be even more severe with ponds, in view of their small size. There is also the risk that, under anaerobic conditions, bound pollutants can be re-released from sediment and that, if there is significant infiltration, contamination of groundwater by dissolved pesticides may occur.

4.4.3 *Timing.*

Time of pesticide application is important for several reasons. The higher the number of users of a pesticide at any given time within a catchment, the higher the risk of movement to water. Also, applying pesticides at a time of year when the likelihood of runoff and drainflow are greatest, usually autumn, winter and early spring, will present a greater risk than at drier times of the year. However, the presence of deep cracks in dry, early-autumn soils may justify delaying application until some re-wetting of the soil has occurred. Counter to this latter principle, the longer the time interval between pesticide application and a runoff or drainage event, the lower the risk of pesticide movement to water. This is because sorption, both rapid and time-dependent, and/or degradation will have reduced the amount of pesticide available for movement. There is some evidence that this applies more to more-strongly sorbed pesticides,[171] but it is nevertheless a key part of good practice advice that pesticides should not be applied shortly before rainfall or if the field drains are running.[173]

4.4.4 *Product Substitution.*

It is clear that there are few effective options for mitigating pesticide losses in drainage and for this reason rate reduction and product substitution are often included in a specific mitigation strategy. Often, the problem pesticides are older materials, many of which are used at relatively high rates. Many are soil-active herbicides, which depend on some mobility in soil for their activity and which are applied in autumn or winter (see Table 4), often with a restricted approved window for application. If the regulatory process focuses on ecological impact, not drinking-water compliance, exceedances of drinking-water standards may occur in drinking-water sources even when pesticides are applied according to good practice. If unsuitable weather results in an increasingly narrow window for application of a particular pesticide, then when that window opens there may be a significant proportion of a catchment being treated at around the same time. If a drainage or runoff event occurs sufficiently soon afterward, significant pesticide losses to water may occur, particularly if soil temperatures are low and degradation is slow. Reducing the application rate, perhaps maintaining efficacy by adding a different pesticide, or use of a different pesticide, at least on the highest-risk fields in a catchment, may be the only effective solutions. This is the case with the molluscicide metaldehyde in the UK.[172]

4.4.5 Point Sources. Point-source losses, at least those arising in the yard, are the most readily controlled, because near-total containment in the yard is feasible, available, and now considered best practice.[173] In the UK, government[178] and water-company grants are available in some areas for the installation of dedicated pesticide-handling areas and treatment systems for dilute pesticide wastes. Filling and washdown areas in the yard should be on an impervious surface, draining to a collection point. The collected spills and drips can then be treated through an on-farm treatment system, before ultimate disposal, usually also on farm. Biobeds and biofilters are increasingly being used for treatment. The most common UK design[173] uses a biomix of soil, straw and peat-free compost to achieve treatment through sorption and degradation, either in a lined pit (biobed) or in three stacked containers (biofilter). Removal levels of more than 99% of applied pesticides have been reported,[179] though this depends on good management and maintenance. A biobed mixture has been shown to have faster degradation than topsoil alone, with enhanced degradation following repeated applications[180] or priming.[181] The treated liquid is usually irrigated over grassland. In alternative systems, the Phytobac® uses evaporation to remove all drainage and discharge from the biomix[173] and the Heliosec® is based entirely on evaporation, with no biomix. Biobeds and biofilters are designed to treat dilute pesticide waste, not concentrates. It is recommended that the first sprayer washings are sprayed out onto the crop, rather than treated through a biobed.[173] Similarly, cleaning the outside of the sprayer or pellet/granule applicator may be better conducted in the field, provided the site selected presents no risk to water (*e.g. via* field drains or runoff) and the statutory maximum rate of application to the crop is not exceeded.

Table 4 Mitigation Measures and Target Pathways.

Measure	Principal target: Drift	Principal target: Runoff & erosion	Principal target: Leaching	Principal target: Drain-flow	Principal target: Point source	Comments
Band application	✓	✓	✓	✓		May reduce total application rate
Biobeds/biofilters					✓	
Buffers/riparian strips	✓	✓				
Container collection					✓	Depends how well rinsed and stored
Constructed wetlands		✓		✓		
Cropping change		✓	✓	✓		Could move the risk to another pesticide
Cultivations		✓		✓		May reduce or increase preferential flow pathways
Drift-reducing technology	✓					Many options: depends on uptake
Formulation			✓	✓		Conflicting evidence of benefit; see nanopesticides in section 4.5
Grassed waterways, swales		✓				Primarily for runoff/erosion control: similar mechanism to buffers
Land drainage reduction				✓		May increase runoff/erosion
Ponds		✓		✓		
Portable bunds & drip trays					✓	Contained pesticide requires appropriate disposal
Product substitution			✓	✓		Could move the risk to another pesticide
Rate reduction			✓	✓		Could move the risk to another pesticide
Soil organic matter increase			✓			May help reduce erosion
Sprayer filling/washdown containment					✓	
Sprayer technology	✓	✓	✓	✓	✓	Induction hoppers for filling; internal tank rinsing equipment; direct injection sprayers; spray nozzle control from cab; GPS guidance; precision application through target recognition
Stewardship	✓	✓	✓	✓	✓	
Storage/disposal practices					✓	
Timing	✓	✓	✓	✓		

Adoption of best practice, both in the yard and in the field, depends heavily on availability of training and information. Stewardship initiatives have been reported to achieve river-load pesticide reductions of 40–95%,[164] although not all have been successful and the result will depend on the balance between point-source and diffuse losses in the catchment. They also take time to have an effect, depending on the intensity of the campaign. For example, the Catchment Sensitive Farming initiative in England reported a three-year lag before pesticide reductions in rivers were observed.[182]

4.5 Looking Ahead: Do We Have All the Answers?

Our understanding of pesticide fate and behaviour and the assessment of risks to water have made great advances since the water issue grew to prominence in the 1980s. Risk assessment is not static and new tests continue to be devised, but are we now able to assess risk adequately, so that hazards are contained to manageable levels? The threat to drinking-water standards caused by apparently non-persistent herbicides such as 2,4-D, MCPA and mecoprop (Table 4) might reflect our lack of understanding of how these pesticides are used by operators, as much as how they behave in soil. New classes of pesticide are also constantly being sought. Often, these can be considered "conventional" organic molecules, for which our current risk assessments were developed. However, the need to increase food production, whilst reducing unwanted effects of pesticides, is also driving the discovery and development of new classes, very different from previous ones. Are current risk assessments adequate for these? Current monitoring methods may not be adequate for complex molecules, such as insecticidal proteins used as biopesticides.[183] Interest in nanopesticides has also increased greatly over the last decade.[184] Nanoemulsions, polymer-based nanopesticides and inorganic nanoparticles could offer advantages over conventional pesticides, including greater efficacy. Often the objective is to achieve slow release of an active ingredient, or to protect it from degradation. Clearly this could facilitate the transport in soil of a pesticide that would otherwise be considered immobile. Investigations into the environmental fate of nanopesticides are few and our current state of knowledge appears to be inadequate for a reliable assessment of risk.[184] Added to this, we do not have adequate mitigation measures for all currently known pathways of pesticide movement to water. In particular, pesticide loss through field drains continues to be a problem, with some of the oldest currently approved pesticides causing the biggest problems. The conclusion thus has to be that no, we do not have all the answers to prevent water contamination. Our understanding and the need for new tests and mitigation methods will continue to develop, for at least as long as there remains a need to increase food production and production efficiency.

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Agroecology and Organic Farming as Approaches to Reducing the Environmental Impacts of Agricultural Chemicals

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ABSTRACT

Agroecological approaches to food production, including organic farming, rely on improved understanding of ecological principles and their application to the management of agroecosystems in order to reduce agrochemical use and improve the environmental impact of the production systems. Agroecological approaches place increased reliance on biological processes such as symbiotic nitrogen fixation, biological control of pests and pathogens, species and habitat diversity, and closer integration of crop and livestock production, to achieve productivity, health, environmental and financial objectives. In most cases they are associated with positive environmental impacts in terms of biodiversity, resource use and emissions, but with potential trade-offs against productivity, particularly where certain inputs are avoided completely, as in the case of organic farming. In such cases, there are also potentially negative impacts on profitability, but these can be mitigated through the use of specialist markets for organic products and through agri-environmental support or payments for ecosystem services. In the longer term, there is potential for both the environmental benefits and productivity of such systems to be enhanced through research, education and

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knowledge exchange, engaging practitioners directly, with an increased emphasis on ecological innovation alongside the more traditional focus on technological innovation.

1 Introduction

The debate about the impact of agricultural chemicals on the environment, health and food quality goes back well over 100 years. It has been accompanied by intensive efforts on the part of different individuals and organisations to develop alternative approaches that are less reliant on chemical inputs, emphasising instead practices and systems that have a stronger emphasis on biological and ecological processes and principles. Organic farming is perhaps the best known, but others—including Integrated Pest Management (IPM), agroforestry and permaculture—also represent applications of similar ideas, which collectively can be grouped under the general term "agroecology".

In this chapter we consider the concepts, practices and principles underlying agroecological approaches such as organic farming, including the role of chemicals and chemistry in such systems, and we look at the impacts of these approaches on the environment as well as on the productivity and profitability of farming systems.

2 What are Agroecology and Organic Farming?

2.1 Agroecology

The term "agroecology" is becoming increasingly widely used to refer to a range of farming systems that emphasise a reduced role for agrochemicals and an increased role for management practices and system designs that utilise ecological principles. However, agroecology is used with a wide range of meanings in practice.[1] In one sense, all agricultural systems might be considered agroecological in nature, given that they rely on biological processes and are conducted in an ecosystem context. Agroecology can also be understood as an academic discipline, the study of the ecology of agricultural systems, and used to describe ecological processes that operate in agricultural systems and the farmed environment. However, in terms of recent agricultural policy debates, agroecology has been popularised more as an approach emphasising the application of ecological principles and practices to the design and management of agroecosystems, integrating the long-term protection of natural resources as an element of food, fuel and fibre production. The conceptualisation of this approach can be traced back to various authors in the late 20th century,[2–4] although it arguably has much earlier roots, including the literature on organic farming from the 1920s onwards (see Section 2.2). More recently, agroecology has also been associated with radical social, economic and political perspectives, in particular linked to peasant agriculture movements such as La Via Campesina, which originated in Latin America.[5,6]

Agroecology encompasses a wide variety of approaches, from integrated pest/crop management and conservation agriculture (where some chemical inputs continue to be used alongside an increased emphasis on biological controls and cultural practices) to organic farming, agroforestry and permaculture. Integrated Pest Management (IPM),[7,8] for example, requires a detailed understanding of the population ecology of the pest, as well as the monitoring of pest levels, in order to make decisions about what pest control measures are appropriate and when (at what threshold) to apply them to minimise the potential economic damage caused. Conservation agriculture[9] is used particularly in areas where soil is prone to erosion and emphasises the use of extended crop rotations, maximum soil cover, including catch crops and green manures, and minimum soil disturbance (reduced or zero tillage), but still permits the use of fertilisers and pesticides. Both IPM and conservation agriculture practices can be found in Integrated Crop Management (ICM)[10] as well as in organic farming.

At the other end of the spectrum, agroforestry[11] and permaculture[4] involve the integration of woody perennials into crop and livestock production. Agroforestry can be found in a wide range of different forms, from very complex forms in tropical, subsistence systems, to more-simplified alley-cropping examples where production systems are more mechanised, as in the UK. Along the spectrum are a range of intermediate approaches variously described as Low-Input Sustainable Agriculture (LISA), Low External-Input Sustainable Agriculture (LEISA), biodynamic agriculture, eco-agriculture, regenerative agriculture and many more.[1]

2.2 *Organic Farming*

Organic farming is used here as a specific example of an agroecological approach, because it has achieved widespread recognition in international policy and regulatory frameworks, as well as a significant global market presence.

Organic farming is commonly misconceived as being simply about the non-use of synthetic chemicals in agriculture. While this is (up to a point) a characteristic of the approach, it says nothing about what organic management involves instead and why certain technologies and practices are preferred over others. The result of simply not using synthetic inputs and doing nothing else (organic farming by default) is likely to be failure in terms of productivity, financial and environmental sustainability. The idea that organic farming is how all farming used to be, or at least agriculture before the mid-20th century, is also a long way from reality, given the adoption by organic farmers of many modern breeding and technological developments.

Organic farming can better be considered as an approach to agriculture where the aim is to create integrated, humane, environmentally and economically sustainable production systems.[12] This encompasses key objectives relating to achieving high levels of environmental protection; resource use sustainability; animal welfare; food security, safety and quality; social justice and financial viability. Maximum reliance is placed on locally, or farm-derived, renewable resources (working as far as possible within closed cycles) and the management of self-regulating ecological and biological processes and interactions (*e.g.* biological nitrogen fixation and biological pest control), in order to provide acceptable levels of crop, livestock and human nutrition, protection from pests and diseases, and an appropriate return on the human and other resources employed. Reliance on external inputs, whether chemical or organic, is reduced as far as possible in order to promote a self-reliant, self-sustaining system.

The term 'organic' refers not to the types of input used, but to the concept of the farm as an organism or system, in which all the component parts—the soil minerals, organic matter, microorganisms, insects, plants, animals and humans—interact to create a coherent and stable whole. In many European countries, organic agriculture is known as biological or ecological agriculture, reflecting the emphasis on biology and ecosystem management rather than external inputs.

The ideas and principles underpinning organic farming as a coherent concept go back over 100 years.[13,14] Since then, different issues have come to the fore at different times, from soil conservation and the dustbowls in the 1930s,[15,16] to pesticides following the publication of *Silent Spring*,[17] energy following the 1973 oil crisis,[18] and subsequently to current concerns about animal welfare, biodiversity loss, climate change, resource depletion and food security. These ideas and issues are also reflected in the four fundamental principles of organic farming—health, ecology, fairness and care—defined by the International Federation of Organic Agriculture Movements (IFOAM).[19]

The definition of organic farming and the debate surrounding it is further influenced by the development of the market for organic food since the 1970s, a relatively recent development in the history of organic farming.[14] In order to maintain the financial viability of organic systems in the absence of government policy support, producers looked to consumer willingness to pay higher prices for the perceived benefits of organic food. In some cases, this reflected more altruistic environmental, animal-welfare and social concerns; in others, more 'self-interested' concerns relating to food quality and safety, in particular issues relating to pesticide residues and health. To protect consumers and *bona fide* producers, the development of the organic market involved the development of production standards, initially by organic farming organisations. As the market developed and grew, many countries, including the USA and those in the EU, introduced legal regulations to define organic food, at least as far as the marketing of it is concerned. The original EU regulation[20] was substantially revised in 2007,[21] and a further major revision has been under discussion since 2014. For many, these regulations have become the standard definition of organic farming. However, the regulations often contain black-and-white distinctions when, in practice, shades of grey may be more appropriate to permit ideas and systems to evolve, and many issues debated within the organic movement, such as ethical trade and employment practices, are not addressed by them.

3 Typical Practices and Systems

A wide range of practices is commonly found in agroecological approaches, though none is exclusive to them, and all could be adopted by farmers in general.[1,22] Examples include:

- reliance on the symbiosis between legumes and nitrogen-fixing bacteria in preference to the use of industrially-fixed nitrogen to meet plant requirements;
- reliance on organic-matter sources, including plant residues, livestock manures and green manures to restore soil organic-matter reserves and build soil fertility;
- reliance on passive and active biological control of plant pests to reduce or eliminate pesticide use, including the use of deliberately sown habitats to encourage beneficial organisms, as well as the deliberate release of such organisms;
- supporting plant and animal health through strategies to reduce disease spread (*e.g.* variety/species mixtures), increase resistance (*e.g.* through breeding), and managing nutrition to avoid over-supply as well as deficiency situations;
- using extended rotations to restore soil fertility and break (in particular soil-borne) pest and disease cycles;
- using low-solubility mineral nutrient sources to compensate for removals in harvested crops, while at the same time relying on plant-root exudates and soil biological, chemical and physical processes to release soluble forms of nutrients for plant uptake;
- integrating livestock and crop production to ensure efficient utilisation of crop by-products.

These practices have a strong biological rather than technological focus, with reliance on knowledge, skills and experience for their effective management, emphasising diversity of system components and complex relations between components to deliver system resilience and stability, and reducing the need for agrochemical inputs.

3.1 What Role Does Chemistry Play in these Approaches?

Contrary to some popular opinion, the concept of organic food as 'chemical free' is a nonsense, as all foods consist of chemical elements and compounds, and (bio)chemical processes play a critical role both within organisms and within ecosystems. This includes moderating interactions between organisms, for example between plants of the same or different species (allelopathy),[23] or between crops and pests.

If this is the case, does it then matter if the active substances or compounds involved in these processes are extracted or synthesised and used directly to achieve desired ends such as crop nutrition, pest and disease control and animal health? Looked at from an ecological perspective, there is a risk that when using the active substances directly, the (self-) regulatory processes that control the availability and uptake of the substances by organisms can be by-passed, leading to excess uptake or losses, with implications for health, food quality and the environment. Eutrophication, greenhouse-gas emissions and nitrate leaching are all well-documented examples.

Some examples are, however, more subtle. This is most easily illustrated with respect to nitrogen inputs and the nitrogen cycle.[24] All plants (and, indirectly, animals) require nitrogen to build proteins. Nitrogen normally exists as nitrogen gas in the atmosphere, but cannot be taken up by plants in this form; plants take up virtually all their nitrogen in solution as either nitrate (NO_3^-) or ammonium (NH_4^+) ions (not larger molecules, with a few exceptions). Nitrogen can enter the soil ecosystem and become available for uptake in a variety of forms through a process of fixation, requiring significant energy inputs, which may happen atmospherically (*via* lightning, to a limited and uncontrollable extent), industrially (in the Haber process, typically but not exclusively using fossil energy), and biologically (often in a symbiotic relationship where the energy source is solar energy captured by plant photosynthesis). Biological fixation is preferred in agroecological approaches such as organic farming, as it is consistent with the ecosystem-management approach, and the use of non-renewable, fossil-energy inputs is reduced.

Pathways of fixed nitrogen through the soil ecosystem vary, depending on the form in which nitrogen has been fixed.[24,25] In particular, nitrate ions, often a form in which industrially fixed nitrogen is applied, are very prone to leaching, while biologically fixed nitrogen is initially bound in the protein of soil organisms and plants, eventually being broken down through mineralisation to form ammonium ions that can be taken up by plants. However, as a positive ion, ammonium may also be held by negatively charged clay particles and humic acids in the soil and therefore it is not leached to the same extent as nitrate, although it may be oxidised to nitrate form if not held in the soil or utilised by plants.

Surplus ammonium taken up by plants cannot be stored, whereas plants can store surplus nitrate ions in the sap. The stored nitrate can act as a nutrient reserve for pests (*e.g.* aphids) and pathogens, enabling faster growth and reproduction, potentially leading to the development of plant health problems.[26] Excess nitrate content of vegetables has been a significant focus for food safety standards too, owing to concerns about the potential impacts on human health.

It is also often claimed that there is no difference between nitrogen as plant food obtained from mineral fertiliser or from organic manures. While this is true in a strictly chemical sense, with organic manures nutrients are applied to the soil together with organic matter, providing a source of energy (stored in carbon compounds) for the soil ecosystem that is not available with mineral fertilisers. While soil organisms will seek to utilise the nutrients supplied by either source, they also need an energy source for respiration, growth and reproduction. In the mineral fertiliser case, soil organisms seeking to utilise the nutrients applied will need to break down existing soil organic matter, contributing to the decline in soil organic-matter levels and increased soil erosion that have been associated with intensive cropping systems.[27]

So, while all plants require nitrogen, whether provided organically or not, there are potentially significant environmental, resource-use, food-quality and health issues related to the way in which nitrogen is captured, and the form in which it is applied, that the organic approach seeks to address.

In the case of pesticide use, the concerns are not only about the direct toxic impacts on non-target organisms, but also on the indirect impacts; for example, the loss of food sources or hosts for beneficial organisms as well as wildlife. This has led in some contexts to the so-called boomerang effect,[28] where complete control of a pest deprives predators of the pest as a food source, leading to their disappearance, so that there is no longer a natural control present to suppress pests as they re-emerge, allowing them to reach much greater numbers than would have happened in the absence of pesticide use.

3.2 Restricting Inputs or Redesigning Systems?

A key consideration in agroecological approaches is the idea that restrictions on inputs are not in themselves enough to make a real difference. This may seem contradictory given the emphasis in organic standards and regulations on prohibiting certain inputs, but in this context the standards are being used to define a process for marketing purposes: the inputs are much easier to audit and control than the overall sustainability and environmental impact of the system, and a prohibition on inputs is much easier to communicate to consumers. The focus on inputs represents a means to an end, rather than the end in itself, although there are clear risks if ends and means get confused.

The adoption of agroecological concepts can be thought of in terms of a development pathway from input-intensive industrial systems through to highly sustainable, ecological systems, building on an efficiency, substitution and redesign framework.[29] Increased *efficiency* of input use, arguably the focus of much current commentary on sustainable intensification,[1] represents a first step on the road, but with limited potential to achieve significant change. Input *substitution*, where inputs causing concerns are replaced by more benign inputs, for example replacing soluble nutrients with organic sources, might take the situation a stage further. But, it is argued, the real potential of an ecological approach can only be realised if the whole system is *redesigned* and restructured, using a combination of different practices and components, to create a self-regulating whole, where synergies between components can be fully exploited.

Mollison[4] emphasises the importance of diversity and complexity in achieving this. He argues that each function (*e.g.* weed control) should be delivered by multiple components or practices (*e.g.* variety selection, timing of sowing/planting, rotations, *etc.*) and that each component or practice (*e.g.* green manures) has multiple functions (*e.g.* nutrient conservation, nitrogen fixation, soil protection, *etc.*). This approach builds on the ecological theory of niche differentiation: different species obtain resources from different parts of the environment, and the greater the number of trophic relationships (where one organism obtains resources from another), the more resilient a system is to shocks or disturbances that may impact seriously on a desired component. It is this use and integration of multiple practices and the possible synergies at a system level that really characterises an agroecological approach to agriculture.

4 Performance of Agroecological Approaches Relative to Conventional Intensive Systems

There is a very wide range of agroecological and organic farming systems in practice, reflecting global climatic, geographical, socio-economic and cultural contexts, and it is impossible here to do justice to the diversity of individual situations. In this assessment, we have focused on European literature primarily. However, even in a more narrowly defined context such as the UK, a wide range of farm types and intensities can be found, from intensive lowland horticulture to extensive hill cattle and sheep production. The actual performance of individual farms will also be affected by the skills, experience and objectives of the farmers involved. Therefore, in attempting to draw out some general conclusions, it is fully recognised that there will be examples of good and bad performance in all groups.

Any assessment of performance also requires the identification of relevant objectives, related outputs or indicators of performance, and criteria against which success or failure of different systems can be determined. In this context there is a very wide range of possible objectives, systems, metrics and indicators with variable data quality and comparability, so inevitably some constraint to the assessment, and reliance on judgement, is required. A further constraint on assessment is that some agroecological approaches, such as organic farming, have been better defined and recognised than others in research and statistical data collection, so that it is easier to identify relevant studies. In this section, we focus particularly on integrated crop management, organic farming and agroforestry as relevant agroecological approaches that are also well documented.

4.1 Biodiversity

There is now a strong body of evidence that agroecological approaches offer significant biodiversity benefits, with positive impacts on a wide range of species and habitats, including soil microbes, invertebrates, pollinators, plants, small mammals and farmland birds.[1,30–35] This is not only a direct consequence of the reduced use of pesticides and herbicides, although this is important.[36] It also reflects the emphasis on increasing spatial and temporal diversity as well as the provision of permanent habitats and areas with lower disturbance.[1,37] For example, spatial and temporal diversity within the farm can be enhanced:

- within species (*e.g.* composite cross-populations, variety mixtures);
- between species (*e.g.* cereal/legume mixtures, diverse fertility-building leys, polycultures);
- at the system level (*e.g.* crop rotations, mixed farming, agroforestry); and
- through the management of ecological-focus areas or non-cropped habitat (hedges, ditches, farm woodland, beetle banks, field margins).

Increasing the planned agricultural diversity within the farm leads to higher levels of associated biodiversity (*i.e.* wild species existing on the farmland). These species could be beneficial (*e.g.* pollinators, natural enemies), detrimental (pests) or neutral (*e.g.* some bird species). In turn, these contribute to the ecosystem services that underpin agroecological approaches. The greater diversity of components within the farming system, and of non-crop habitats (such as beetle banks, pollen and nectar mixes, diverse legume mixtures and wildlife seed mixes), is not only with the objective of supporting wildlife *per se*, but directly contributes to supporting the farming system, including soil-fertility building, crop protection and animal-health maintenance.

The need for species and habitat complexity and diversity in agroecosystems to support relevant ecosystem services makes it questionable whether land ‘sparing’ systems, that emphasise high-intensity production to the exclusion of non-agricultural biodiversity, are sustainable or desirable, given their dependence on synthetic inputs to substitute for the loss of ecosystem services in such contexts.[37]

4.2 Resource Use and Emissions

The consumption of non-renewable resources, such as fossil energy and minerals, is a key issue in the sustainability of food production systems. Even resources that are, in principle, renewable, thanks to natural cycling processes, such as those in soil and water, may be over-used or degraded to the extent that they become effectively non-renewable. In many cases, the consumption of these resources is also linked to emissions and other losses into the environment, including soil salinisation, nitrate leaching, pesticide residues, eutrophication and greenhouse-gas emissions linked to climate change.

As with biodiversity, there is good evidence that agroecological approaches can reduce both the consumption of non-renewable resources and the related emissions, although the extent of these benefits does vary according to the specific approach adopted and the specific resource or emission under consideration.

With respect to *soils,* the emphases on reduced or zero tillage and on the use of green manures, cover crops and fertility-building phases in rotations, all contribute to maintaining or enhancing soil organic-matter levels, soil biological activity and reducing soil erosion/degradation.[38,39] There is a continuing debate about whether the use of herbicides to enable zero-tillage systems in integrated crop management and conservation agriculture has more positive impacts on soils than is possible in organic farming, where some cultivations are required to kill vegetation in the absence of herbicides. However, this issue needs to be considered on a rotational, not an individual crop, basis, given the reliance of organic farms on extended rotations, including multi-year fertility-building phases with legumes.[40]

Agriculture accounts for a very high proportion of global water *consumption*, the significance of which depends on specific climatic conditions in different regions. Agroecological practices can contribute to reduced water consumption through shade and ground-cover reducing evaporation losses but, where irrigation is used, the question of which irrigation system is used to conserve water is more a technological than an ecological question. Excess water can also be a problem, particularly following severe weather events, and flood mitigation is also a relevant consideration. There is increasing evidence that soil-management practices, including cultivations, organic matter, vegetation and the use of fertilisers that might adversely affect soil pH and earthworm activity, all potentially impact on the ability of water to infiltrate the soil, so that agroecological approaches can make a positive contribution to flood mitigation.[41,42]

Protecting water *quality*, on the other hand, is a very different issue as this can be adversely affected by emissions such as nitrate leaching, eutrophication (resulting from phosphates attached to soil particles being lost into watercourses due to soil erosion) and pesticides. To the extent that agroecological approaches, in particular organic farming, severely restrict the use of synthetic nitrogen, soluble fertilisers, pesticides and herbicides, the beneficial impacts of these systems can be significant.[43] In some countries, such as Germany, water companies actively encourage organic management of catchments as a deliberate policy to improve water quality.[44]

Current methods for manufacturing nitrogen fertilisers and pesticides are heavily reliant on *fossil energy*, with consequent impacts on greenhouse-gas emissions, in particular CO_2 from the energy use and NO_x from the production process. While it is conceivable that technologies might adapt to be more reliant on renewable energy sources, there has been limited progress on this issue so far, despite continuing debates since the 1970s.[18] There is clear evidence that agroecological systems, such as organic farming and agroforestry, reduce fossil energy use per hectare, primarily as a consequence of the reductions in fertiliser and pesticide inputs.[45] While some additional energy might be required for cultivations to control weeds in the

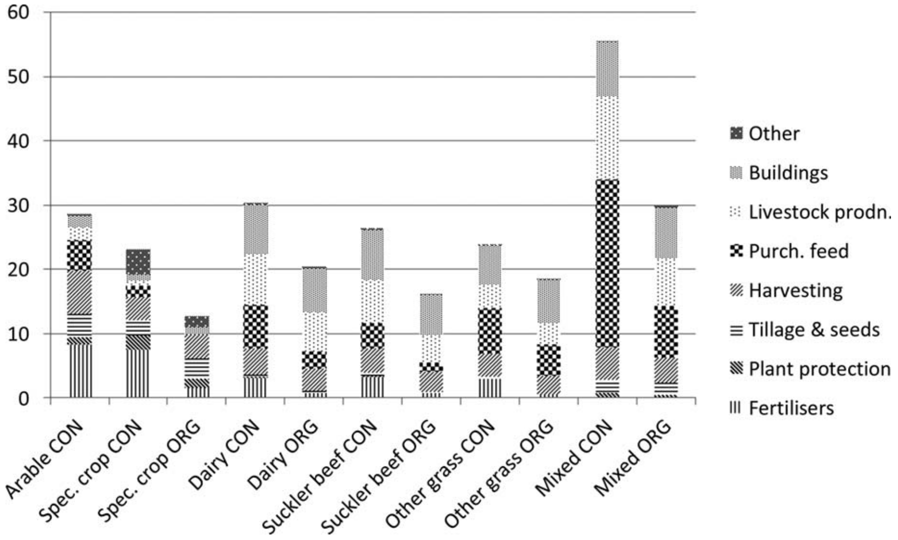

Figure 1 Energy use (GJ ha^{-1}) on organic and conventional farms in Switzerland, by farm type (adapted with permission from ref. 46).

absence of herbicides, this is minor in comparison. However, as an analysis of organic and conventional farms in Switzerland indicates,[46] the differences vary significantly according to farm type (Figure 1). This comparison illustrates not only the impacts of fossil energy use for fertilisers and plant protection (in the organic case this includes mechanical weed control), but also the significance of purchased livestock feeds, with organic farms generally showing a greater degree of reliance on home-produced feeds.

The direct reductions in fossil energy use in agroecological systems, as well as the reductions in emissions associated with input manufacture, contribute to reduced *greenhouse-gas emissions*, at least on a per-hectare basis.[47,48] These approaches can also contribute to climate-change mitigation through maintaining or enhancing soil organic-matter levels[49] and through the woody components of agroforestry systems.[50] However, the emphasis on the integration of livestock and on keeping livestock pasture-based in organic systems can lead to increased methane emissions, though these are frequently offset by reductions in CO_2 and NO_x.[51] There is also the potential for reductions in NH_3 emissions, particularly in agroforestry systems.[52]

Mineral nutrients such as phosphorus are also highly relevant in terms of sustainability and environmental impact. Nitrogen, due to its gaseous form and the nitrogen cycle can eventually be recycled, but this is not the case with phosphorus. Phosphorus suitable for agricultural use is only available in limited deposits in relatively few regions in the world, not all of which are politically stable. There is an ongoing debate about the extent of the reserves and for how long these might continue to be extracted.[53,54] Similar to the ‘peak oil’ debate, the discovery of new reserves and new extraction technologies might extend the lifetime of these reserves and address short-term supply constraints.

Phosphorus may be mined as rock phosphate, or extracted from guano deposits, and is then typically processed through acidification to increase its availability to plants. However, when applied to agricultural soils, much of the phosphate becomes bound to soil particles, increasing total soil-phosphorus levels, but with only a small proportion accessible by plants. Plants can extract phosphorus from the soil chemically as a result of acids in their root exudates, though different species vary in their capacity to do this. Plant uptake may also be influenced by mycorrhizal associations, where fungal hyphae penetrate the plant roots and provide a bridge to a much larger number of soil particles than plant roots alone could achieve. However, high soil-P levels reduce mycorrhizal activity,[55] which may take several years to recover once P applications have ceased.

The issue with phosphorus is not restricted to the plant-soil interactions. As indicated above with respect to water quality, the increased P attached to soil particles is a problem when soil erosion leads to soil particles entering watercourses, increasing phosphorus burdens and contributing to eutrophication. Potentially more significant is the linearity of P-flows in agriculture: mined sources are processed and applied to soils, with some P becoming bound to soil particles and lost to water sources. The P that is exported from the farm as harvested crops and livestock is then mostly transferred to urban areas, where it is lost to sewage and waste systems; in the UK case often to the sea following sewage processing.[53] There is a serious need to look at how such cycles can be closed,[54] by ensuring that waste food is composted and recycled, and by the development of sewage-treatment technologies, such as struvite (magnesium ammonium phosphate) production,[56] that allow phosphorus to be recovered in a form that is safe in terms of hygiene as well as biochemical (*e.g.* hormones), heavy metal and other contaminant effects.

Many of the positive impacts of agroecological approaches described in this section apply particularly on a land-area basis, but may not be as significant on a per-unit-food-produced basis, due to differences in productivity compared with intensive conventional systems. This is considered in more detail in the next section.

4.3 Productivity

While the biodiversity, resource use and emissions evidence with respect to the different agroecological approaches is relatively consistent, the evidence with respect to productivity is more mixed. Integrated and conservation agriculture systems, that still have recourse to agrochemical inputs, have the capacity to achieve yields per hectare similar to conventional intensive systems, but the potential to use these inputs more efficiently can lead to improved performance per unit of input.[57,58]

Agroforestry systems have demonstrated the potential to improve overall productivity compared to monocropping systems due to complementarity in resource-capture, *i.e.* trees acquire resources in space and time that the crops alone would not.[59] Tree roots generally extend deeper than crop roots and can access soil nutrients and water unavailable to crops, as well as absorbing nutrients leached from the crop rhizosphere. These nutrients are then recycled *via* leaf-fall onto the soil surface or fine root turnover. This should lead to greater nutrient capture and higher yields by the integrated tree-crop system compared to tree or crop monocultures.[60] The tree canopy also occupies space above surface crops, making better use of above-ground space for interception of sunlight and photosynthesis, with tree leaves continuing to harvest solar energy for longer periods than most annual crops.

The Land Equivalent Ratio (LER)[61] is a means of comparing productivity of polycultures and monocropping systems. It is calculated as the ratio of the area needed under sole cropping to the area of intercropping at the same management level to obtain a particular yield:

$$\text{LER} = \frac{(\text{Tree agroforestry yield})}{(\text{Tree monoculture yield})} + \frac{(\text{Crop or livestock agroforestry yield})}{(\text{Crop or livestock monoculture yield})}$$

If a rotation includes more than one crop, a weighted ratio for each crop can be used, based on its proportion in the rotation. An LER of 1 indicates that there is no yield advantage of the intercrop compared to the monocrop, while, for example, an LER of 1.1 would indicate a 10% yield advantage: under monocultures, 10% more land would be needed to match yields from intercropping. The LER reflects the ability of crops to partition resources in space and time, so that lower LER values are recorded from mixtures of grasses in pasture, intermediate values from dissimilar vegetables, cereals and legumes, and the highest values (1.2–2) in agroforestry systems.[62]

Lower yields are, however, perceived to be the key disadvantage of organic farming, although the reductions compared with conventional systems reported in different studies have been highly variable. In the UK, organic wheat yields are typically little more than half those of conventional systems (Table 1).[63,64]

However, this lower productivity is exacerbated due to the need for fertility-building crops in the rotation, so that organic farmers cannot grow

Table 1 Organic and non-organic (conventional) yields (t ha^{-1}) from Farm Business Survey data for England and Wales, 2011/2012.[63]

Product	Organic (farms)	Non-organic (farms)	Relative[a] %
Winter wheat	4.4 (37)	8.3 (272)	53
Spring barley	3.8 (44)	5.3 (136)	72
Winter oats	4.1 (17)	6.4 (37)	64
Field beans	2.8 (26)	3.9 (59)	72
Potatoes	29 (6)	44 (23)	66
Milk (L cow^{-1})	6315 (45)	7397 (145)	85
Stocking (cows ha^{-1})	1.4	1.7	82
Milk (L ha^{-1})	8841	12575	70

[a] Organic as a percentage of non-organic.

wheat every year. Therefore, the additional land area required to grow a tonne of wheat may be higher than a simple comparison of relative yields would suggest. Three recent meta-analysis studies have reviewed the global evidence on organic crop yields. Ponti *et al.*[65] analysed data from 362 studies, concluding that organic-crop yields are on average 80% of conventional yields, but finding significant regional and crop-type variations, with organic yields ranging from 20% to 177% of conventional. Seufert *et al.*[66] found average organic crop yields to be 75% of conventional, with only 5% differences for rain-fed legumes and perennials. Both studies make reference to an earlier much-debated review by Badgley *et al.*[67] which concluded that organic yields were 30% higher than conventional in a developing-country context.

Ponti *et al.*[65] and other studies have identified that the organic–conventional yield gap increases as conventional yields increase, but this relationship was not strong. They hypothesised that when conventional yields are high and relatively close to the potential or water-limited level, nutrient stress must, as per definition of the potential or water-limited yield levels, be low, and pests and diseases well controlled, which are conditions more difficult to attain in organic agriculture. Seufert *et al.*[66] suggested that, with good management practices, particular crop types and growing conditions, organic systems can nearly match conventional yields. It is clear from all these studies that yield differences found for specific crops in specific regions cannot be generalised globally. The most recent meta-analysis,[68] using data from 115 studies, found that organic yields were, on average across all crops, 19% lower than conventional. While most individual crop types showed an organic-yield reduction similar to the average, perennial fruit and nuts yielded closer to conventional, while root crops showed a bigger yield gap. It was also found that multi-cropping (polycultures) and crop rotations when applied only in organic systems could substantially reduce the yield gap.

These results are consistent with the long-term comparison between conventional/integrated, organic and biodynamic farming in Switzerland, which found organic yields on average 20% lower than conventional, ranging from up to 42% reduction for potatoes, 33% reduction for wheat, to 11% for forage crops and parity for soybeans.[69] The relatively larger differences for crops like wheat, compared with forage crops and grain legumes, are an indicator that a key factor is the intensity of nitrogen use in the conventional systems. This also applies to the same crop grown in different regions; for example, wheat yield differences are reported to be lower in the United States than in northern Europe, while conventional nitrogen use and yields are typically also lower in the US.[1]

4.4 Financial Viability

Where it is possible to achieve similar or only slightly reduced yields through more-efficient use of inputs, as in integrated crop management, cost savings can compensate for any losses and enable similar financial performance to be achieved compared with intensive conventional systems.[70] Agri-environmental support payments can also help cover the costs of field margins and habitats managed to encourage beneficial insects. For agroforestry systems, the financial performance depends both on the establishment costs and the time lag before the woody perennials become productive, for which some financial support may be available, and the nature of the tree species planted. Fruit species have the potential to enhance profitability, while timber or biofuel species may not be as profitable.[71] In both integrated and agroforestry cases, farms adopting these approaches tend not to be separately identified in farm financial-data surveys, and it is therefore difficult to present recent financial comparisons.

In the case of organic farms, the lower yields are not fully compensated by cost reductions. While there is potential for reducing input costs, particularly with respect to fertilisers and pesticides, other costs, including purchased organic seeds and feeds, are often higher. Labour and machinery costs may also be higher, though normally not on a per-hectare basis. However, when spread over reduced yields, the cost per unit product will be higher. Instead, the premium prices made possible through the development of specialist markets and/or support payments, in recognition of the environmental benefits of organic farming, are needed to achieve comparable incomes.[64,72] A summary of the recent financial performance of organic compared with conventional farms of different types is shown in Figure 2.[72] The longer-term trends[64] and the recent data indicate that, for most farm types, the profitability of organic farms has held up much better and shown less volatility than might have been expected following the recession, despite its impact on the UK retail market for organic food.

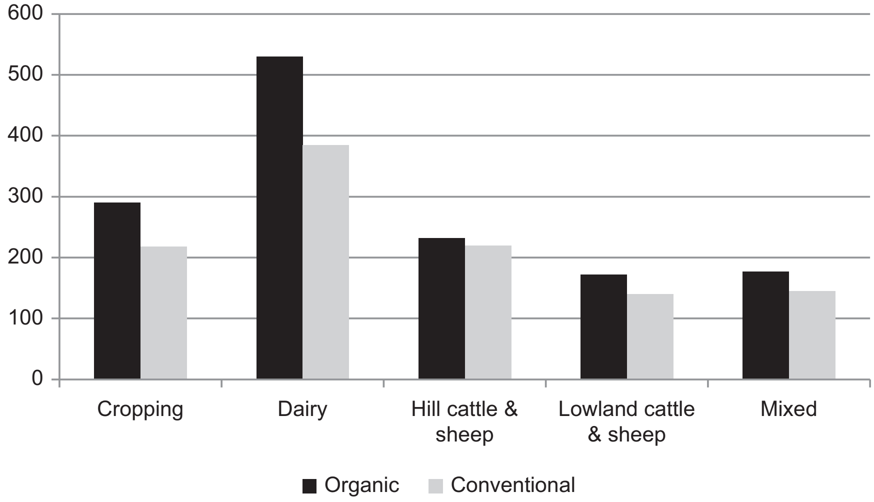

Figure 2 Organic and conventional Farm Business Income (£ ha^{-1}) by farm type, 2014/15.[72]

5 Conclusions

Agroecological approaches, such as integrated farming, organic farming and agroforestry, have consistently demonstrated their capacity to deliver environmental benefits in terms of enhanced biodiversity, reduced emissions and conservation of soil, water, energy and mineral resources. However, in some cases, such as organic farming, there are trade-offs to be made between higher environmental performance and reduced productivity; the right balance is a matter of policy judgement, given the wide variations in societal preferences on these issues.

To the extent that the benefits are judged to be of value to society, governments have put in place both regulations and support frameworks to encourage the adoption of agroecological practices and approaches. This is particularly so in the context of the European Rural Development Programme,[73] although there are significant differences in the way in which this has been implemented in different countries. In other developed countries the financial support for organic farming in particular may be less obvious, but most have implemented legislative definitions to support the organic market.[14] Policy support for agroecology is also increasingly common in other countries, including India, China, South Korea, as well as parts of Africa and Latin America.[74]

Despite this, the uptake of these approaches is still not widespread, with organic farming exceeding 5% of land area in only a few countries, such as Austria, Denmark, Estonia, Germany, Sweden and Switzerland.[75] More-widespread adoption requires significant investment in research and innovation, knowledge-exchange and education, across the spectrum of institutions from colleges and universities through to agricultural advisory services and research. There is also a need to continue improving the environmental, productivity and financial performance of these systems, in particular addressing weak points that have not yet been adequately resolved. Ecological innovation, in particular, needs to be given equivalent status to technological innovation in research programmes, both underpinned by high quality science, but also involving recognition of indigenous knowledge and active participation by practitioners.[1] The French government's *Action Plan for Agroecology*[76] and the German government's *Federal Programme for Ecological and Other Forms of Sustainable Agriculture* (BÖLN)[77] provide models for how this might be achieved.

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Crop Biotechnology for Weed and Insect Control

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ABSTRACT

The control of weeds and pests is a major challenge to farmers and the rapid uptake of GM crop varieties with tolerance to herbicides and resistance to insect pests is testament to their effectiveness. There have been no negative effects on human or animal health and environmental outcomes of the widespread adoption of GM crops have also been largely positive. However, the build-up of resistance in weeds and target insects to the respective active compounds in the GM plants is clear. Although the vast majority of the previously cultivated GM crops possess only a narrow range of herbicide-tolerant or insect-resistant traits, we are already seeing a wide range of new varieties possessing stacked genes as issues of resistance and traits for abiotic stressors and food quality become more significant. In addition, the use of new biotechnological breeding tools such as gene editing will make a step-change in crop breeding methodologies and reduce the time it takes to market a new product. However, this will be possible only if the regulatory landscape becomes proportionate, prompt and more globally unified.

1 Global Trends of GM Crop Adoption

The use of crop varieties generated using recombinant DNA technologies has grown phenomenally since they were first commercialised in 1992 and now accounts for some 12% of global arable land. According to James,[1] the years

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between 1996 and 2014 saw more than a 100-fold increase in the area of GM cultivation (see Figure 1), although this dipped a little in 2015.[2] Despite this rapid adoption rate, the number of crop types commercialised with biotech traits and the scope of those traits has remained low. Only three species, soya, maize and cotton, occupy 95% of the 181 million ha of total land cultivated with GM varieties in 2014 (each with 90.7, 55.2 and 25 million ha, respectively). The remaining area was occupied by canola/oil seed rape (9 million ha) and other minor crops such as sugar beet, alfalfa, papaya, squash and poplar (with about 1.5 million ha between them).[3]

The number of different countries in which GM varieties have been fully adopted has not changed markedly over recent years. The global value of GM seed was $15.7 billion in 2014 and 28 countries grew biotech crops, up one from 27 in 2013[1] (Table 1). However, the GM hectarage is not evenly distributed, with just five countries (USA, Argentina, Brazil, India and Canada) accounting for 90% of the global GM-cultivated area. GM cultivation remains a complex and highly contentious topic, particularly for food crops, even in areas that already accommodate some GM varieties. For example, in Mexico (which has cultivated GM cotton since 1996) there is considerable controversy over the production of GM soya and maize. Both crops have been subjected to a series of court orders, appeals and legal overturns regarding the commercial sale of GM seeds to farmers in recent years. This has created major rifts within the scientific, agriculture and environmental communities.[4] Despite already growing large areas of GM insect-resistant (Bt) cotton, similar arguments have taken place in India over the same insect-resistant trait in the food crop brinjal (eggplant) on which the Indian government imposed a moratorium on commercialisation. At the time of writing, the controversy in India still reigns over this and other GM food crops such as GM mustard.[5]

The EU allows the commercial cultivation of only one GM crop, one of the first insect-resistant Bt maize events (the word used to define a specific gene insertion in the context of the host genome) to be developed (Mon 810), which contains the Cry1Ab gene and was authorised in 1998 under an earlier adoption system. No further approvals have been made despite applications with positive risk assessments from the European Food Safety Authority (EFSA).[6] Despite the reluctance of the EC to authorise applications for cultivation, there are over fifty GM events authorised in the EU for import and processing, mostly for animal feed.[7]

Almost all the commercial GM crops cultivated today possess modifications in the agricultural input traits of insect resistance or herbicide tolerance (or, increasingly, both traits stacked together). These two traits made up 99% of the total global biotech area in 2014, with herbicide-tolerant crops dominant at 102.6 million ha, insect-resistant crops with 27.4 million ha and stacked traits 51.4 million ha.[1] The benefit of crops possessing herbicide tolerance and/or insect resistance lies in the time savings and reduced farming effort and these traits are described in more detail below. However, there are signs of a greater diversification of target traits in the near future,

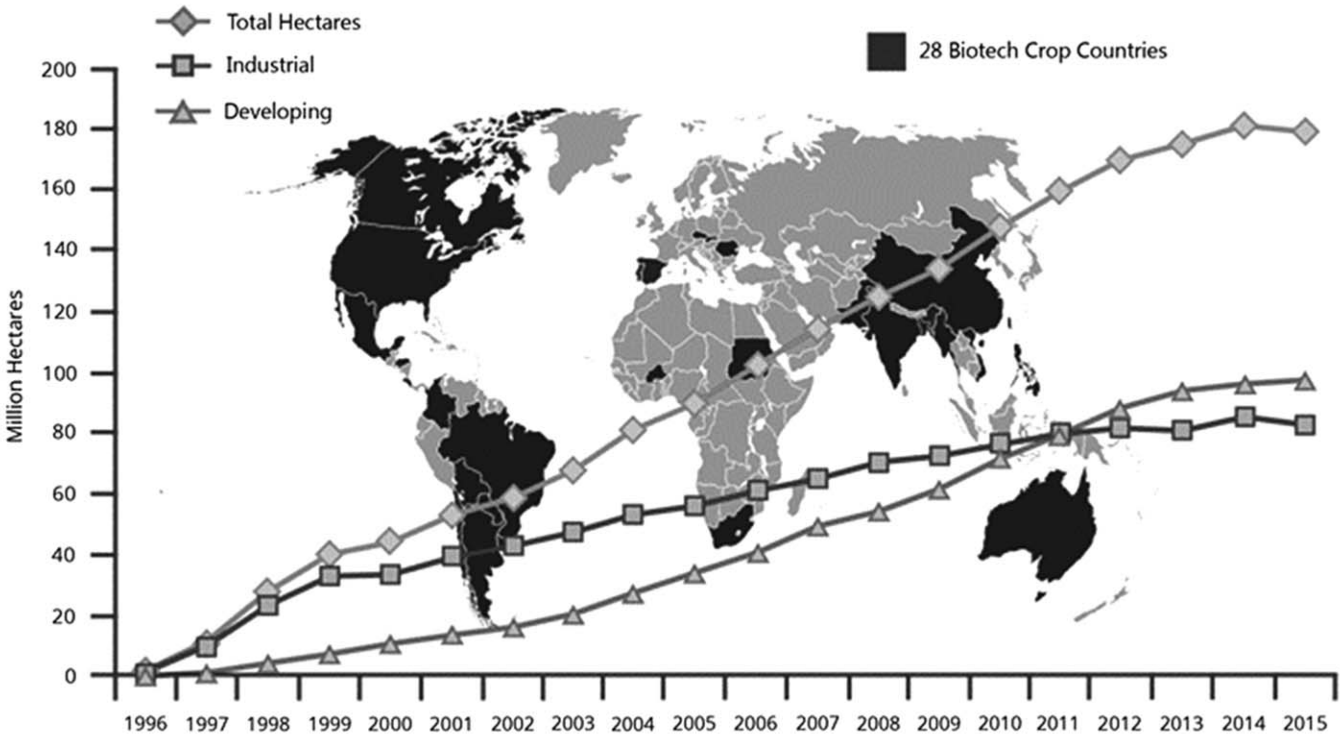

Figure 1 The global area of GM crop cultivation showed a year-on-year increase until 2015 when it declined slightly due to a drop in developed countries.[2]
[Reproduced with permission from C. James, Global Status of Commercialized Biotech/GM Crops: 2015, ISAAA Brief No. 51, ISAAA: Ithaca, NY, pp. 1–51].

Table 1 Area of GM crops cultivated globally.[2] In rank order by country.

Rank	Country	Area (million hectares)	Biotech crops
1	USA[a]	73.1	Maize, soybean, cotton, canola, sugarbeet, alfalfa, papaya, squash
2	Brazil[a]	42.2	Soybean, maize, cotton
3	Argentina[a]	24.3	Soybean, maize, cotton
4	India[a]	11.6	Cotton
5	Canada[a]	11.6	Canola, maize, soybean, sugar beet
6	China[a]	3.9	Cotton, papaya, poplar, tomato, sweet pepper
7	Paraguay[a]	3.9	Soybean, maize, cotton
8	Pakistan[a]	2.9	Cotton
9	South Africa[a]	2.7	Maize, soybean, cotton
10	Uruguay[a]	1.6	Soybean, maize
11	Bolivia[a]	1.0	Soybean
12	Philippines[a]	0.8	Maize
13	Australia[a]	0.5	Cotton, canola
14	Burkina Faso[a]	0.5	Cotton
15	Myanmar[a]	0.3	Cotton
16	Mexico[a]	0.2	Cotton, soybean
17	Spain[a]	0.1	Maize
18	Colombia[a]	0.1	Cotton, maize
19	Sudan[a]	0.1	Cotton
20	Honduras	<0.1	Maize
21	Chile	<0.1	Maize, soybean, canola
22	Portugal	<0.1	Maize
23	Cuba	<0.1	Maize
24	Czech Republic	<0.1	Maize
25	Romania	<0.1	Maize
26	Slovakia	<0.1	Maize
27	Costa Rica	<0.1	Cotton, soybean
28	Bangladesh	<0.1	Brinjal/eggplant
Total		81.5	

[a] 19 biotech mega-countries growing 50 000 hectares, or more, of biotech crops. [Reproduced with permission from C. James, Global Status of Commercialized Biotech/GM Crops: 2015, ISAAA Brief No. 51, ISAAA: Ithaca, NY, pp. 1–51].

with several new varieties that are either close to commercialisation or are already being cultivated that possess traits such as drought tolerance, end-use quality or nutritional enhancements.[7] For example, GM varieties with altered oil profiles have been, or will imminently be, commercialised in the USA. Soya varieties (Monsanto's Vistive® Gold and DuPont-Pioneer's Plenish™) which have high oleic/low linolenic oil, giving better heat stability for frying, longer fry life and improved flavour of fried products, have received approval from the US regulatory authorities. In addition, a Monsanto soya variety producing higher than normal levels of the omega-3 fatty acid SDA (stearidonic acid) is expected to be cultivated under close stewardship protocols for identity preservation within the next few years. Potatoes (Innate™) engineered for low-acrylamide potential and reduced black-spot bruising by the J. R. Simplot Company were deemed by the USDA to be a non-regulated product and will soon be commercialised.[8] Another end-quality GM product close to market is the Arctic Apple (Okanagan Specialty Fruits)[9] which has fewer of the enzymes that cause browning when apples are cut.

2 Herbicide Tolerance

2.1 A Driver for Changing Agronomic Practices

Weeds are a major problem for farmers. Traditional methods of control include the use of ploughing and tilling, crop rotation, and the application of selective and broad-spectrum herbicides at appropriate times in the cropping cycle. The invention of a crop plant that could withstand the application of an effective, broad-spectrum, systemic weed killer was seen by farmers as a major benefit and was rapidly adopted by certain sectors of the industry. Herbicide tolerant (HT) crops have seen massive take-up rates and have made significant changes in agricultural practice where they have been adopted. In the USA in 2013, GM HT traits accounted for 90% of soya plantings, 85% of corn, 82% of cotton, 93% of canola and 98% of sugar beet.[10] The speed of uptake of GM HT sugar beet by farmers was especially fast. While it took 15 years for the previously most-successful GM crop in the USA to reach an adoption rate of 95%, GM HT sugar beet achieved this figure after only 2 years.[11]

The main effect of switching to HT crops has been a predictable change in the profile of herbicides used: from a wide range of selective weed killers used previously to a much narrower set of products with glyphosate and, to a lesser extent, glufosinate and 2,4-D as the active ingredients. Analysis of the amount of herbicide used under HT regimes shows variations between crops and years, but there is an overall pattern of lower total units of active-ingredient application. For example, data generated by Brookes and Barfoot[12] showed that cultivation of GM HT maize has resulted in a significant reduction in both the volume of herbicide-active ingredient usage and the associated Environmental Impact Quotient (EIQ). The EIQ is described by Kniss[13] and integrates the various environmental impacts of individual pesticides into a single value. For 2011 specifically, the reduction in herbicide usage was just over 23 million kg of active ingredient (−12.7%), with a larger reduction in the EIQ indicator of 23%.[12] However, for GM HT soya there was a less-dramatic reduction of only 0.6% (about 12.6 million kg less active ingredient). The environmental impact, as measured by the EIQ indicator, nevertheless improved by a more-significant 15.5% due to the increased usage of more environmentally benign herbicides.[12]

2.2 Conservation Tillage Agriculture

Agriculture is considered as a significant producer of carbon dioxide and other greenhouse gases,[14] with approximately 20% of global CO_2 emissions originating from soils.[15] The HT trait has facilitated a move away from annual ploughing to zero- or minimum-tillage (also known as conservation tillage) production systems which bring significant economic and environmental benefits. Non-GM HT farming relies on the use of selective herbicides integrated with crop rotation and various forms of tillage to manage weeds. Some farmers quickly realised that the levels of weed control provided by GM HT varieties allowed them to stop or reduce post-harvest tilling and, instead, direct drill into the stubble of the previous crop. This has several economic and environmental benefits, including reduced tractor fuel use, reduced carbon emissions and soil erosion, and increased soil–water conservation.[10] Although precise estimates are difficult to make for the changes resulting from conventional to no-till agriculture, the same authors judged the move from conventional tillage to zero-till in Canadian canola production generated fuel savings of 6.4 L ha^{-1} $year^{-1}$ in 2010.[16] Further, VandenBygaart *et al.*[17] estimated that between 0.06 and 0.16 t ha^{-1} $year^{-1}$ of additional carbon is sequestered in Canada under zero-till compared to conventional tillage.

2.3 Managing Resistance

Resistance to many classes of herbicide has been seen in different weed species over several decades, pre-dating the introduction of GM crops. However, the widespread cultivation of GM HT crops first commercialised in 1996 has undoubtedly contributed to the evolution of weeds with tolerance to glyphosate (Figure 2). The first glyphosate-resistant weeds were found in orchards (*Lolium rigidum* in 1996 and *Eleusine indica* in 1997), after repeated applications (5 to 10) per year for more than 15 years.[18] Unlike the ALS inhibitors, ACCase inhibitors or triazines, there are few target-site mutations that confer resistance to glyphosate and it is considered a low-risk herbicide for selecting resistance. However, Ian Heap, director of the International Survey of Herbicide Resistant Weeds, has confirmed that glyphosate-resistant weeds have now been found in 18 countries worldwide, with significant impacts in Brazil, Australia, Argentina and Paraguay.[18,19] Of particular concern to the southern states of the USA is herbicide-resistant amaranth, which is a weed that grows in cotton crops. In 2004 it was found in one county in Georgia, but by 2011 it had spread to 76 counties and was significantly reducing cotton yields.[19] The reaction of the companies that market the HT GM seeds was to stack two or more tolerance mechanisms into the same seed. In addition to glyphosate tolerance conferred by the EPSPS gene, there are also many GM crops that possess the *bar* or *pat* genes, providing tolerance to glufosinate ammonium-based herbicides. Clearly, adopting weed-management strategies by alternating or mixing different modes of action will significantly prolong the useful life of the herbicides involved.

Amongst more-recent efforts to deal with herbicide resistance, Dow AgroSciences have developed double-action GM HT maize and soybean

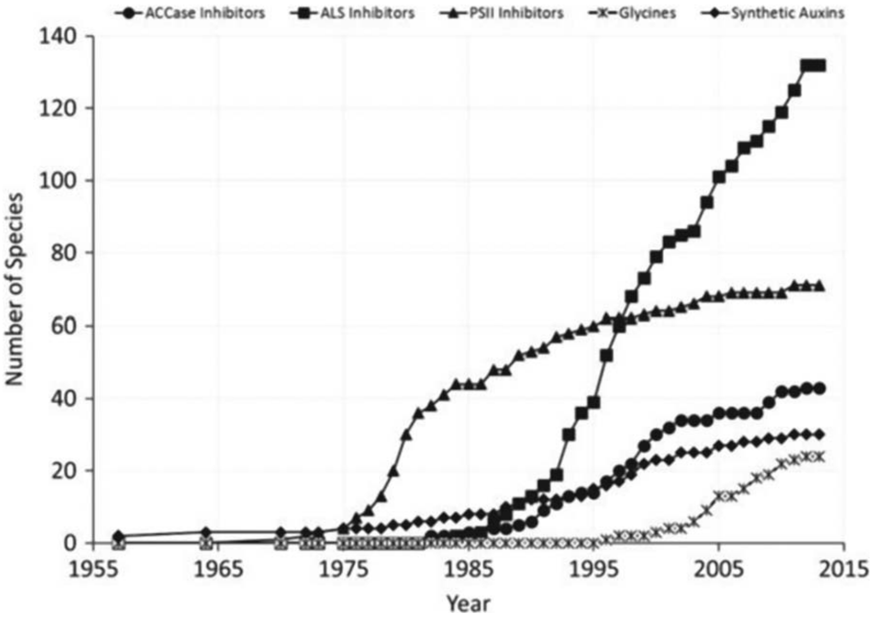

Figure 2 Change in the number of herbicide-resistant weeds for several herbicide classes (the Glycine class includes glyphosate).[18]
[Reproduced from I. Heap, Global perspective of herbicide-resistant weeds, *Pest Manage. Sci.*, 2014, **70**, 1306–1315 with permission from John Wiley and Sons. © 2013 Society of Chemical Industry].

products called 'Enlist™', which they have been marketing in the USA and Canada since 2014. These seeds are designed to be used in conjunction with the Enlist™ Duo herbicide with two active agents, 2,4-dichlorophenoxyacetic acid (2,4-D) and glyphosate. Using a similar strategy to deal with resistant weeds, Monsanto have stacked a dicamba-tolerant gene with EPSPS in their new glyphosate- and dicamba-tolerant "Xtend" soybeans. Assuming approval is forthcoming in the key importing countries, these seeds will be cultivated in the USA and Canada from 2016.

3 Pest/Disease Resistance

3.1 Bt Genes and Toxins

Bacillus thuringiensis (Bt) is a Gram-positive, soil-dwelling bacterium that produces insecticidal Cry toxins. However, these Cry toxins are remarkably non-toxic to humans as well as other mammals and non-target insects, making them a useful alternative to synthetic insecticides for the management of crop pests. Preparations of dried Bt spores and/or the toxins have been used commercially as an insecticide since the 1930s, although it was not until the 1960s that their use became more widespread, particularly amongst organic growers, after various highly pathogenic strains of Bt were discovered with particular activity against different types of insects.[20] In 2008 the non-GM biopesticide market accounted for 2% of the worldwide crop-protection market of about 600 million US dollars, with about 90% of all biopesticide sales involving products based on Bt.[21] Cloning and sequencing of the Cry gene family has resulted in the publication of more than 300 Cry gene nucleotide sequences.[20] The various endotoxins they encode have been grouped into classes (Cry 1, 2, 3, 4, *etc.*) on the basis of amino-acid sequence similarities. These classes are, in turn, composed of several subclasses (Cry1A, Cry1B, Cry1C, *etc.*), which are themselves subdivided into subfamilies or variants (Cry1Aa, Cry1Ab, Cry1Ac, *etc.*).[21] However, only a few of these have been used in GM crops designed for insect resistance. Some of the more prominent commercial ones are: Cry3Bb1 and Cry34Ab1/35Ab1 for resistance to Western corn rootworm; Cry1Ab for resistance to European corn borer; Cry1F for resistance to Western bean cutworm; Cry3A for resistance to Colorado potato beetle and Cry1Ac/Cry2Ab for resistance to cotton bollworms and budworms. Of the 181 million ha of GM crops currently cultivated worldwide, 43% possess a Cry gene, either singly or, increasingly, combined with other Cry or VIP variants or a different GM trait altogether.[1] Vegetative insecticidal proteins (VIP) are a distinct family but, like Cry, also possess potent and highly specific insecticidal properties (reviewed by Chakroun *et al.*[22]). The Vip1 and Vip2 proteins are toxic to some members of the Coleoptera and Hemiptera insect orders. The Vip3A protein possesses insecticidal activity against a wide spectrum of lepidopteran insects and displays acute bioactivity towards the black cutworm, with 260-fold higher insecticidal activity than some Cry1A proteins.[23] Interestingly, the European corn borer (*Ostrinia nubilalis*) is not susceptible to Vip3A, with the insect host range determined by its ability to bind insect gut cells.[22] There are commercially grown varieties of Bt cotton and Bt maize that express the Vip3Aa protein in combination with Cry proteins.

3.2 Reduction in Insecticide Use

GM insect-resistant crops have increased yields and farm incomes, particularly in developing countries, and have reduced the volume of chemical insecticides used to control insect crop pests. This is particularly evident in cotton, which traditionally has been a crop where the intensive use of insecticides was commonplace to control bollworm and budworm. For example, farm survey data from the two major cotton-growing provinces of Argentina (Chaco and Santiago del Estero), which together account for almost 90% of the Argentine cotton area, showed that the technology reduced application rates of chemical insecticides by 50%, while significantly increasing yields.[24] On a global scale, the average farm income from 1996 to 2012 for cultivation of GM insect-resistant cotton (after the cost of adopting the technology was deducted) benefitted by \$230 ha^{-1}.[25] If this is calculated cumulatively since 1996, the gains have been \$36.3 billion.[25] Between 1996 and 2014 there was a global reduction of 249 million kg in the use of active ingredient for insect control in cotton, which represents 28% fewer active chemicals sprayed over a 16-year period.[26] In addition to the reduction in application of insecticides, there is also good evidence that Bt crops can promote biocontrol services in agricultural landscapes. Twenty years of data from 36 sites in northern China, with widespread adoption of Bt cotton and reduced insecticide sprays, showed a marked increase in beneficial arthropod predators (ladybirds, lacewings and spiders) and a decrease in aphid pests.[27] The same authors also found evidence that the predators might even provide additional biocontrol services spilling over from Bt cotton fields onto neighbouring crops.[27]

3.3 Evolution of Insect Resistance to Cry Toxins

Although highly effective, the widespread adoption of Bt strategies increases the chances of insects developing resistance and, in 1998, Gould[28] predicted there to be a high risk of rapid insect adaptation to the Bt toxin unless significant mitigation measures were put into place. Resistance development is also one of the main concerns of the organic grower movement because it would not only affect insect-resistance GM technology but would also imply loss of Bt-based bioinsecticides which are widely used in organic agriculture. Several examples of Bt-resistance have been demonstrated in laboratory studies and have been discovered naturally in the field.[29] Tabashnik[30] analysed results of studies from five continents reporting field-monitoring data for resistance to Bt crops. Although most pest populations remained susceptible, reduced efficacy of Bt crops caused by field-evolved resistance has been now reported for 5 of the 13 major pest species examined. The specific pests for which field-evolved resistance has been reported and which is associated with reduced efficacy of the relevant Bt event are: the corn earworm (*Helicoverpa zea*), the fall armyworm (*Spodoptera frugiperda*), the African maize-stalk borer (*Busseola fusca*), the pink bollworm (*Pectinophora gossypiella*) and the Western corn rootworm (*Diabrotica virgifera virgifera*) (Figure 3).

However, in addition to genetic resistance to high toxin concentrations based on target site mutations, exposure of insect larvae to lower than optimal levels of toxin also induces immunity and metabolic responses, resulting in low-level resistance (inducible tolerance).[31,32] To slow the development of insect resistance, the biotechnology industry and regulatory authorities encourage a two-pronged approach involving a high-dose of active Cry protein in the crop parts attacked by pests, coupled with the use of non-GM refuge areas in the field. The concept of 'refugia' in resistance management strategies is now well accepted and works by deliberately maintaining populations of insects that are not exposed to Bt plants. Progeny from the untreated insects feeding within the refugia provide a source of wild-type/unselected susceptible individuals which dilute any resistant alleles evolving within the Bt crop and hence reduce the rate of resistance development.[33,34] Both the US Environmental Protection Agency

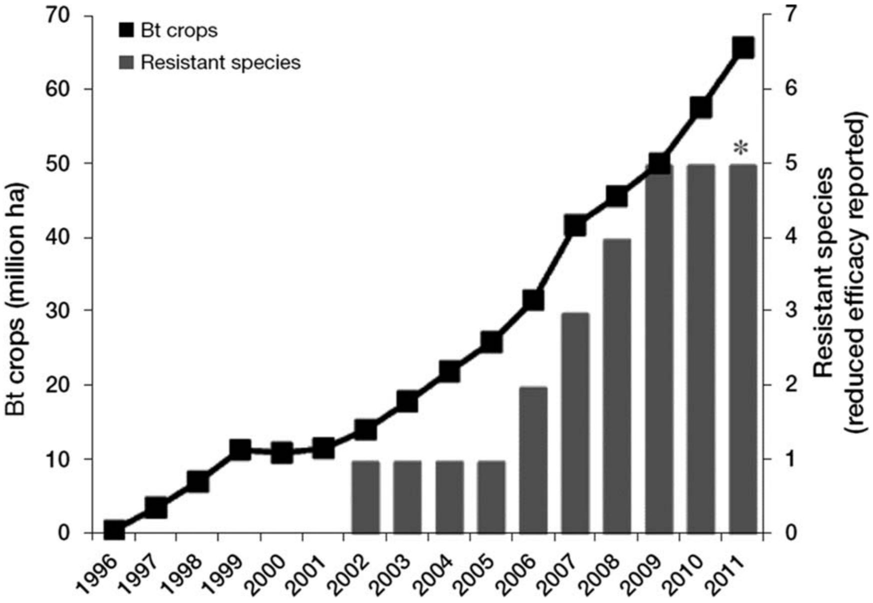

Figure 3 Global area of GM Bt crops and field-evolved resistance resulting in reduced efficacy in target insects (* For 2011, the number of species with resistant populations may be underestimated).[30]
[Reproduced by permission from Macmillan Publishers Ltd: *Nat. Biotechnol.*,[30] Copyright 2013].

and the European Food Safety Authority (EFSA) recommend the planting of non-Bt refugia as part of the approval of Bt crops. The major biotechnology companies selling Bt seeds have now developed the 'refuge in a bag' idea whereby the GM Bt seed also contains some non-Bt seed, typically at a rate of 10%. Another strategy adopted by the seed companies is to stack genes for different insecticidal toxins into the same plant. For example, recent cotton products in this category are Monsanto's Bollgard® III which possesses Cry1Ac, Cry2Ab and Vip3A and Dow AgroScience's WideStrike™ which contains Cry1Ac, Cry1F and Vip3A.

While these various technological and management strategies will inevitably slow the evolution of insect resistance, a fundamental problem is that the currently used Cry and Vip proteins target relatively few receptors in the insect gut. With the aim of expanding the range of insect gut target sites, Badran *et al.*[35] identified a cell-membrane receptor (TnCAD) that is not normally targeted by Cry1Ac. They then used a system of 'phage-assisted continuous evolution' to rapidly evolve Bt toxins through more than 500 generations of mutation and selection. They identified several new Cry1Ac variants that bound to the TnCAD with high affinity and killed insects up to 335-fold more-potently than wild-type Cry1Ac.[35] This type of research is needed to identify both novel insect cell receptors and new compounds with highly specific toxicity for development either as sprayable products or *via* biotechnology.

4 What Does the Future Hold?

4.1 Regulatory Hurdles and Asynchronous Approvals

The current markets for GM crop cultivation are becoming saturated. In the USA in 2015, 94% of cotton, 92% of maize and 94% of soybean cultivation was GM.[36] However, for the first time since they were initially commercialised in 1996, the global area of GM sowings in 2015 did not show an increase. 28 countries planted GM crops in 2015 over a total area of 179.7 million hectares, a decrease of 1% (1.8 million hectares) from the 181.5 million hectares in 2014.[2] A significant factor is thought to be the current low price of commodity crops soybean, corn, cotton and canola, which are likely to revert to higher hectarage levels when crop prices improve.[2] Another significant factor determining the adoption of GM crops is the regulatory situation in some countries, both in terms of cultivation but also where it impacts on the trade of commodities. For instance, China and the EU are major importers of maize and soybeans but have strict, zero-tolerance policies for non-approved GM varieties. However, in the countries that cultivate bulk commodity crops, the storage and transportation systems mean that total segregation of different GM varieties is impossible. Thus, unless all the varieties sown in any specific season are approved in all the target export markets, there is a significant risk that a shipment arriving at the port of an importing nation is refused entry because it contains a trace amount of a variety not yet approved in that nation. These are not hypothetical situations. There are examples from 2013 in China where more than 665 000 tonnes of corn shipments were rejected from the USA due of the presence of Syngenta's MIR162, an insect-resistant GM maize that is permitted in the USA, Japan and Europe, but not in China.[37] Approximately 180 000 tonnes of GM soybean from the USA were also turned away from European ports in 2009. In this case, it was not the intended soya cargo *per se* that was the problem, but the ships also contained a barely detectable residue of an unapproved GM maize from a previous shipment.[38] The problem underlying this issue is the different time-scales taken by various regulatory bodies to approve the same new GM variety. It is not easy to get good comparative data, but a recent opinion-piece by Mark Wagoner,[39] a guest author in Agri Pulse, a US farming journal, states that since 2010 the Brazilian system has taken an average of just more than a year between first application and final approval. Regulators in the USA have typically needed almost three years to approve new products. In Japan, since 2011, the average time duration for registration and regulatory affairs is 5.5 years.[40] In the EU, applications for import of GM food/feed products between 2011 and 2013 took, on average, 4 years to approve, of which just more than 3 years was spent on risk assessment by the EFSA and 9 months on processing and voting-related procedures after an EFSA positive opinion.[41] However, the recent discussions over the Member State opt-out clause resulted in longer delays, with no European Commission (EC) decisions being made between

November 2013 and April 2015 when, finally, 10 pending applications with positive EFSA opinions were approved in one go. These time-scales for approval also apply only to imports. Applications for cultivation seem to be blocked completely. Only one GM variety is currently approved for cultivation in the EU: the insect-resistant maize MON810, which was authorised in 1998 under an earlier adoption system. No further approvals have been made despite applications with positive risk assessments from EFSA. This problem of asynchronous approval was highlighted in a report by the Joint Research Council of the EC who wrote ‘asynchronous approval is of growing concern for its potential impact on international trade, especially if countries operate a “zero tolerance” policy that may result in rejections of imports that contain only traces of such GMOs’.[42] Currently there is no solution in sight to this problem which may even get worse before it gets better.

4.2 What is the Future for Crop Biotechnology?

To ensure food security over the next 10 to 20 years will be challenging; to ensure it over the next 50–100 years without permanently degrading the natural resources of our planet will need step-changes in agricultural systems. Various august bodies predict that to sustain future needs, agricultural output will need to increase by between 70 and 100%. At the same time, agricultural production will need to become more resilient to biotic and abiotic stresses, utilise no more land or energy than it does now, consume less water for irrigation and, ideally, have less reliance on synthetic-chemical inputs for nutrient supply and pest control. Plant breeding will play a key role in this challenge and, as one facet of modern plant breeding, biotechnology must be fully integrated into that process. However, as discussed above, the global regulatory oversight of modern plant breeding will itself play a significant part in determining when, where and how these tools will be utilised. Although twenty years of cultivating and consuming the current limited range of GM crop traits have not given rise to any significant harm, either to human or animal health or to the environment, there seems to be no immediate prospect of a reduction in the data requirements for GM risk assessment in the major importing or exporting countries.

A relatively new, highly specific and powerful technology for making minor edits to the DNA of plants (called gene editing) is now finding commercial applications. However, the future of this technology also lies in the hands of the global biotechnology regulators.[6] Gene editing tools, such as CRISPR Cas9, TALENS and Oligonucleotide Directed Mutation, are capable of making targeted and simple edits in the DNA of a crop plant. This is fundamentally different from the transfer of foreign DNA from another organism and utilises the natural DNA-repair mechanisms present in all cells. Some of the regulatory agencies (such as those in Argentina, USA and Brazil) have already indicated that they do not consider new crop varieties made using gene editing technologies as GM and this has stimulated research and development in the commercialisation of this technology in those countries. However, even after several years of deliberation, the EU has not yet formalised its regulatory procedures for gene editing.[43] This uncertainty is a major disincentive to innovation and biotechnological investment in the EU. Many scientists and other commentators are calling for a global framework for the proportionate regulation of gene editing and other biotechnologies. If this becomes a reality, I am confident that the significant challenges facing the agricultural sector over the next 50 years will be met.

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Aquaculture

COLIN F. MOFFAT

ABSTRACT

In 2013, aquaculture produced 97.2 million tonnes (live weight) of fish, shellfish, aquatic plants and other aquatic animals. Valued at $157 billion (138 billion euros), a total of 575 aquatic species and species groups were cultivated in freshwater, seawater and brackish water. Although aquaculture production is dominated by the fish and shellfish cultivated in Asia, both mariculture and inland aquaculture are global. Moreover, aquaculture will have a major role to play in meeting future food supply and resource challenges and will need to produce a greater proportion of the required high quality protein, with improved sustainability. Further expansion of aquaculture will have significant consequences for the management of aquatic habitats and for the supply of fertiliser and feed resources. The prevalence of disease, specifically in the intensive production environment, will require the continued use of a wide range of pesticides. In the current climate, total replacement of pesticides through new technologies and improved husbandry is unlikely. This means that there must be an understanding of how best to apply those pesticides that are currently available, their wider environmental impact and the use of alternative, future pesticides. This must, however, be part of a fully integrated management system for both mariculture and inland aquaculture that facilitates the production of high quality food while minimising any detrimental impacts on the environment.

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1 Aquaculture – A Modern Food Industry with a Long History

1.1 Our Seas and Oceans as a Source of Food

Humans have always made use of lakes, rivers, seas and oceans as a source of food. Initially focused on aquatic systems that could be readily accessed, especially at low tide, the process was very much a 'hunter-gatherer' activity, with fish being trapped, speared or netted and shellfish being collected from the rocks and natural shellfish beds. As time progressed, humans took to the sea and accessed the large offshore resources that include fish, shellfish, cephalopods (Table 1), pinnipeds (seals, sea lions and walruses) and cetaceans (whales and dolphins). Exploitation of such resources continues today and, for many communities, represents one of the few continuing 'hunter-gatherer' activities (Table 1).

Table 1 A selection of commonly harvested fish, shellfish and cephalopods from the seas adjacent to the United Kingdom.

Category	Common name	Scientific name
Fish		
Demersal fish[a]	Atlantic cod	*Gadus morhua*
	Haddock	*Melanogrammus aeglefinus*
	Whiting	*Merlangius merlangus*
	Monkfish (Angler)	*Lophius piscatorius*
	Saithe (Coley)	*Pollachius virens*
	Common dab	*Limanda limanda*
	Atlantic halibut	*Hippoglossus hippoglossus*
Pelagic fish[b]	Atlantic herring	*Clupea harengus*
	Atlantic mackerel	*Scomber scombrus*
	Blue whiting	*Micromesistius poutassou*
	European sprat	*Sprattus sprattus*
Mixed[c]	Pollock	*Pollachius pollachius*
Crustaceans		
Crabs	Edible carb	*Cancer pagurus*
	Velvet swimming crab	*Necora puber*
	Shore crab	*Carcinus maenas*
Lobsters	European lobster	*Homarus gammarus*
	Norway lobster	*Nephrops norvegicus*
Molluscs		
Scallops	King scallop	*Pecten maximus*
	Queen scallop	*Aequipectin opercularis*
Mussels	Blue mussels	*Mytilus edulis*
Cephalopods		
Squid	Long-finned squid	*Loligo forbesi*
	European squid	*Loligo vulgaris*
Octopus	Common octopus	*Octopus vulgaris*

[a] Demersal fish live and feed close to or on the bottom of the sea.
[b] Pelagic fish live and feed in mid-water.
[c] Pollock are unusual in that they feed at all water levels.

It is interesting to note that palaeolithic humans enjoyed many of the seafood products that are still eaten in 2016; in Europe this included salmon, tuna, eels, sea bass, crustaceans and molluscs.[1,2] Trout and carp (*e.g. Cyprinus* spp.) were the most popular freshwater fish in their diet.[2] Trade in marine fish and shellfish is recognised as taking place from the end of the Bronze Age onwards.[2,3] Furthermore, there is evidence of transport or trade of dried cod in medieval Europe.[4] This illustrates the economic value of marine resources to communities, something which continues to be the case today.[5]

Although probably not directly recognised by early societies, seafood is highly nutritious, being a rich source of protein, vitamins, minerals and trace elements.[1] Marine lipids are also important for the human diet. The lipid in marine products originates from the phytoplankton, the small flagellates, cyanobacteria, diatoms and dinoflagellates that are abundant in our seas and play a fundamental role in marine food webs and global biogeochemical cycles. Marine lipids are characterised by long-chain, polyunsaturated fatty acids. This includes *all-cis*-5,8,11,14,17-eicosapentaenoic acid (EPA, timnodonic acid)[6] and *all-cis*-4,7,10,13,16,19-docosahexaenoic acid (DHA, cervonic acid).[7] These n-3 (or omega-3), methylene-interrupted fatty acids[6] contrast with the n-6, methylene-interrupted polyunsaturated fatty acids in terrestrial-based animals. Critically, from a physiological perspective, the n-3 fatty acids give rise to a specific group of eicosanoids (prostaglandin E3 (PGE_3),[8] thromboxane A3 (TxA_3), and leukotriene B5 (LTB_5))[9] in the human body which are distinct from those derived from the n-6 fatty acids (prostaglandin E2 (PGE_2), thromboxane A2 (TxA_2) and leukotriene E4 (LTE_4)).[10–12] The benefits of these n-3 lipids in the diet are now widely recognised; the United Kingdom Food Standards Agency and National Health Service recommend the consumption by adults of at least two portions (140 g per portion when cooked) of fish each week,[13] including one oily fish (*e.g.* salmon (*Salmo salar*), Atlantic herring (*Clupea harengus*), Atlantic mackerel (*Scomber scombrus*), European anchovy (*Engraulis encrasicolus*) and fresh tuna (*Thunnus* spp.)).

White (demersal) fish (Table 1), including Atlantic cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*), dab (*Limanda limanda*) and Nile tilapia (*Oreochromis niloticus*), are low-fat alternatives to red meat. They also contain the n-3 fatty acids, although the flesh of the white fish contains far less lipid than that of the oily (often pelagic) fish.

Shellfish (prawns (*e.g.* the whiteleg shrimp (*Penaeus vannamei*)), blue mussels (*Mytilus edulis*), king scallops (*Pecten maximus*), Pacific oysters (*Crassostrea* gigas), edible crabs (*Cancer pagurus*), European lobster (*Homarus gammarus*) and Norwegian lobster (*Nephrops norvegicus*)) also are nutritious. They are low in fat and are a good source of trace elements, including selenium, zinc, copper and iodine. As with white fish, shellfish are a good source of n-3 fatty acids, but again, they do not contain as much as the oily fish.

Seaweed was used as long ago as 3000 BC in China for medicinal purposes. Seaweed was also the basis of popular drinks in China. However, the Japanese are credited with discovering the many uses for its gels in foods such as noodles and soups.[14] They also realised that many could be eaten raw as part of a salad, or preserved in brines. In Wales, the Celts used a red seaweed called laver to produce a black bread. Seaweeds are rich in alginates, carrageenan and agar,[15,16] which are not digested in the gut to any great extent and so can help increase feelings of satiety. In addition, seaweeds contain high concentrations of iron, calcium and iodine, with some varieties rich in protein. There are very small amounts of fat in seaweed, while vitamins A, C and E are found in seaweed in useful amounts. Seaweed is also one of few vegetable sources of vitamin B_{12}, making it a useful adjunct to a vegetarian or vegan diet.

Although the benefits of consuming marine-based foods in the diet are well established, as with any wild food products there are potential risks. Shellfish can concentrate phycotoxins, including saxitoxins and derivatives, okadaic acid, azaspiracids and domoic acid. These compounds are responsible for specific forms of shellfish poisoning in humans.[17] The reasons why phytoplankton produce these complex chemicals remain unclear. However, over the years, people have learnt to avoid consuming shellfish at certain times of year so as to avoid the risk of being poisoned. Today, food-safety authorities operate comprehensive monitoring programmes to ensure the safety of the shellfish that is sold in shops.

Finfish can be toxic; the best examples are the pufferfish (Family – *Tetraodontidae*) which contain tetrodotoxin (TTX). This toxin is produced primarily by marine bacteria,[18] and the pufferfish become toxic *via* the food chain which starts with the toxin-producing bacteria. The presence of TTX in these fish makes them highly toxic; a blood TTX concentration of $9\ \text{ng mL}^{-1}$ (a total of 45 μg in 5 L of blood, the typical blood volume for an adult) or greater may be considered as potentially lethal for human beings.[19] However, in Japan the consumption of such fish is a delicacy associated with highly trained, specialist chefs.

Ultimately, the seas provide a vast array of nutritional riches. However, it has become increasingly clear that the natural capacity of our seas and oceans is not limitless. Stocks of fish show significant natural variations, and during the twentieth century many wild species went into decline due to overfishing. Additional sources of fish and shellfish are required.

1.2 A Changing Landscape

The human population is projected to reach 9.2 billion by 2050. This represents an increase of approximately 2.0 billion (27.8%) on the estimated global population in 2012.[20] At the same time, many people will probably be wealthier. These two factors will result in an increased demand for a more varied, high-quality diet across the various continents. To produce such a diet will require additional resources.[21] On the production side, competition for land, water and energy is likely to become more intense. Furthermore, the effects of climate change will become increasingly apparent.[22] This means that there will be an ever-growing pressure for governments and individuals to reduce greenhouse gas emissions (GHGEs); adaptation to a changing climate will become an imperative. Globalisation will continue, exposing the food system to novel economic and political pressures. These multi-faceted pressures are unprecedented and will bring new and significant challenges to the food-producing industries.

Depending on circumstance, consumer choice, and being able to influence such choice, is an option. In the United Kingdom (UK), recent research from the Food Standards Agency has revealed that people in the UK want to be educated about the challenges that face the food system, in order to enable them to make more informed decisions about food.[23] Consumer choice alone (when there is such an option) will not yield the required global response. There is a need to critically review how and where humans produce food, ensuring that the methodologies are appropriate. Moreover, consideration must be given to seasonality returning to our food consumption, while waste at all stages of production, transportation, place of sale and location of consumption must be minimised.

The oceans cover 70% of the Earth's surface, contain 97% of its surface water and support 50% of global primary production. Given that the Earth's land produces 98% of all food, and that the ceiling for increased food production appears more severe on land than in the ocean, increased utilisation of marine living organisms is an obvious option. There is a need to increase the ocean harvest and, in this context, aquaculture is a clear option.[24]

1.3 A Long History

The 'farming' of aquatic plants and animals has a long history that dates back to 3500 BC in China.[2,25] Common carp (*Cyprinus carpio*) culture flourished. This was replaced by silver carp, bighead carp, the mud carp and the grass carp around 600 AD, all four being cultured in the same pond due to the fact that the four species have different dominant behavioural habits with regard to their own nutrition.[26] Both fish and shellfish were cultured by the Romans in 'piscinae' or simple fishponds.[27] There is evidence that the Romans spread the practice of keeping fish and shellfish in 'piscinae' throughout their Empire. During the Middle Ages (5th to 15th Century), there continued to be examples of the rearing of fish for food in ponds in both Europe and Asia. The fish in the European stew ponds (ponds used to store live fish where they were purged of muddy water before cooking) included native freshwater species, such as bream, perch, common carp, barbell and roach, with crucian carp (*Carassius carassius*) being favoured in Northern Europe, including Scandinavia, the Baltic region and Poland.[28] At the same time, beds of sessile (anchored to a substrate) shellfish were crudely maintained and harvested in western European countries.

During the Renaissance (1300–1600), the construction and management of fishponds improved, especially in Central and Eastern Europe. Small ponds were constructed for holding broodstock fish and for spawning. Ultimately, management of the ponds became more intensive and yields steadily improved. Ponds three hundred hectares in area and ten metres deep were constructed in Europe; techniques for intensified fish culture were now being readily recognised, some being published in the mid-1500s, with consideration also being given to economics and disease.[2,26] At the same time, the Japanese were improving their management of clams and oysters, with the oysters being cultured on bamboo poles placed upright in sand and mud. Books were being written on good husbandry,[26] particularly of carp. This included the drying of ponds to allow terrestrial animals to graze on the vegetation. They would deposit their manure, which ensured rapid growth of aquatic vegetation when the ponds were refilled.[2]

Overfishing of the natural resource is not just a modern-day problem, but has been a consequence of human activities for centuries. Striped bass (*Morone saxatilis*) and sturgeon (most likely the Atlantic sturgeon, *Acipenser oxyrinchus*) were both totally removed from the Exeter River in New Hampshire, USA, around the 1760s. The changing habitat exacerbated the impact of fishing activity. A consequence of this was the development of fish culturing in the USA; the culturing of common carp started around 1831.[29] Artificial propagation of salmon and trout was also investigated in the USA during the second half of the 19th Century with improving results as the 19th Century progressed, capitalising on the completion of the first *trans*-continental railway.[29]

With the development of the steam engine and the increasing availability of ice to preserve the fish, marine fisheries in Europe became practical and economically viable. Towards the end of the 19th Century, steam trawlers, coupled with the use of the otter trawl, resulted in the industrialisation of fishing, which saw uncontrolled harvesting of the continental shelves of Europe and North America.[2] This provided large quantities of nutritious fish as food. At the same time, however, water extraction, the damming of rivers and significant pollution of inland waters from industrial developments had a very negative impact on the inland fisheries and also had a detrimental effect on coastal shellfisheries. The draining of land also saw less water available for the traditional fishponds and many were drained. However, the artificial culture of fish to replenish falling fish stocks, devastated by the industrial revolution in Europe, was one small part of the regulatory response for the management of both marine and inland fisheries. Fish hatcheries developed across North America as well as Western and Eastern Europe throughout the second half of the 19th Century, with France providing the lead in Europe. Scotland contributed to the developments through W. C. McIntosh at the University of St Andrews and J. Cossar Ewart at the University of Edinburgh who hatched the eggs of cod, haddock, whiting, gurnard, flounder, turbot, lemon sole, dab and long rough dab.[30]

The salmon (both Pacific, of which there are seven North American species, and Atlantic (*Salmo salar*)) has been a key aspect of aquaculture in North America and parts of Western Europe for the last 150 years.[31] Initial focus remained on hatcheries, ultimately for release into rivers. In the late 19th Century to the very early 20th Century this included the export of eggs from

North America to New Zealand (salmon) and Japan (rainbow and brown trout), illustrating the potential for international trade.[30] Hatcheries extracting water from the marine environment experienced natural marine biofouling, which required various filtration and technical solutions to ensure delivery of the water to the rearing tanks. Metal toxicity was also an early problem. This was a result of salt corrosion of the metal pipes and valves.[2] Much of the marine-based aquaculture in Europe and North America in the early part of the 20th Century continued to focus on replenishing stocks, rather than providing fish for the table. In America this included pollock (*Pollachius virens*), flounder (*Bothidae* and *Pleuronectidae*)[25] and Atlantic cod (*Gadus morhua*). However, disease of both the fish and shellfish was a recognised issue; a build-up of infectious agents can occur in susceptible stocks, especially where the general health status of the population is poor.[32] Interestingly, in the early 20th Century, the concept was mooted of culturing fish from Europe such that insect-eating fish could be used to clear mosquitos from African water bodies, thereby reducing the risk of malaria. Around the same time, attempts were made to relocate some of the marine species to the saline inland lakes of Egypt, while fish culture also developed in India and Japan. Thus the development of aquaculture was continuing to be a truly global activity.[2]

In the last 50 years or so, aquaculture for direct human food consumption has increased markedly in some countries, including Scotland (Figure 1). One of the developments which contributed to this was the availability, initially for trout in the United States of America (USA), of pelleted feed.[29] These pellets were supplemented with vitamins and minerals and are also used as a method for the administration of medication, including antibiotics.[33] The pelleted food, which was pasteurised and could be stored for months, resulted in the increased survival and fitness of the juvenile fish as well as reducing the costs of producing salmon smolts.[2]

In the mid-1960s, an experimental flatfish farm was built at Ardtoe on the west coast of Scotland. This experimental site became a hub for scientists and ultimately led to the establishment of an aquaculture complex at the University of Stirling, Scotland. In the late 1960s, two farms were built in Scotland for the production of trout solely for human consumption, while Unilever Research took forward salmon production in Aberdeen and Loch Ailort.[34] In the USA, the catfish industry began to develop (Figure 1), as did the cultivation of salmon.[25] The decline in wild fish spurred the Norwegians to investigate Atlantic salmon culture in the fjords. Scandinavian countries, together with Ireland and Scotland, were all interested in the commercial farming of salmon and rainbow trout; this included the use of floating cages.[34] On a global basis, the quantity of fish, shellfish and seaweed being cultivated for direct human consumption continued to increase.

Between 1975 and 1990 production of Atlantic salmon in Scotland, catfish in the USA and Nile tilapia in the Philippines showed similar, increasing trends. Post-1990, production of these three fish in the three locations varied, Nile tilapia in the Philippines ultimately showing the largest increase in production during the 2000s (Figure 1). Expansion of aquaculture on land

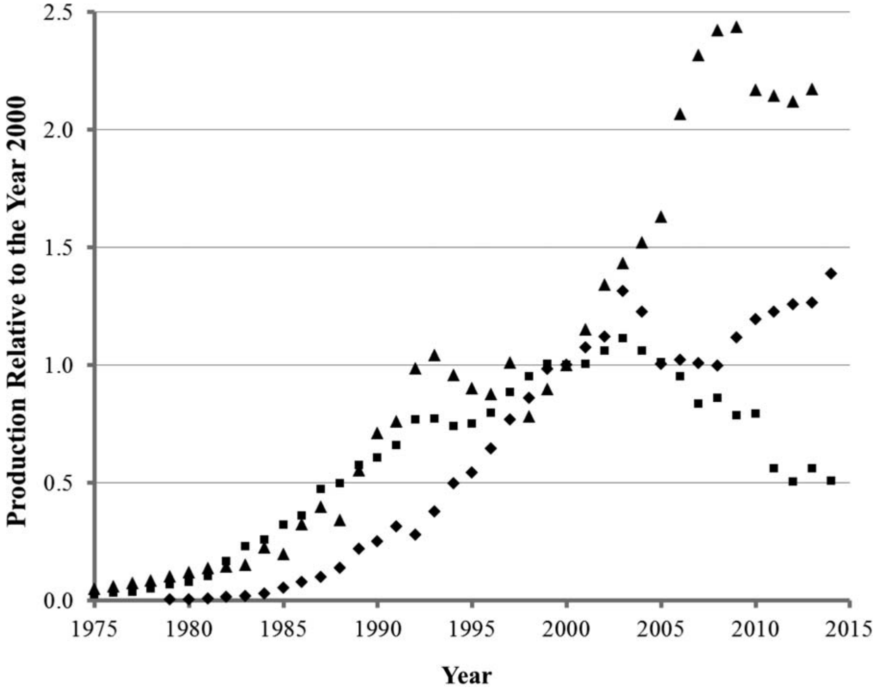

Figure 1 Atlantic salmon (*Salmo salar*) production in Scotland (closed diamonds), United States of America (USA) farm-raised round channel catfish (*Ictalurus punctatus*) processed (closed squares) and Nile tilapia (*Oreochromis niloticus*) production in the Philippines (closed triangle) from the 1970s to 2014 (2013 for Nile tilapia). The data are normalised to production in year 2000 which was 128 959 tonnes for Scottish Atlantic salmon, 593.603 million pounds for catfish in the USA and 77 642 tonnes of Nile tilapia in the Philippines. Both Atlantic salmon and catfish showed a steady increase in production until 2003 after which production was more variable. Atlantic salmon production in Scotland recorded an all-time high in 2014 of 179 022 tonnes. There was little growth in the production of Nile tilapia in the Philippines during the 1990s. However, there was a significant increase in production during the 2000s to a maximum, in 2009, of 189 363 tonnes. However, global production of Nile tilapia has continued to grow to a total of 3 436 508 tonnes in 2013, which was worth $5772 million. Atlantic Salmon data from the Scottish Government Scottish Fish Farm Production Surveys: 1979 onwards (accessed at www.gov.scot/Topics/marine/Publications/stats/FishfarmProductionSurveys/OlderSurveys). Catfish data from several sources including Hanson, T. and Sites, D. (2015) US Farm-Raised Catfish Industry 2014 Review and 2015 Outlook. (accessed at www.agecon.msstate.edu/whatwedo/budgets/docs/catfish2014.pdf). Tilapia data sourced by Helen McGregor, Marine Scotland Science.

and at sea was significant during this period. Salmon was farmed in North America, South America (Chile), Japan and various European countries. As expansion continued, so large losses were experienced as a result of disease. Despite advances in prophylaxis and vaccines, disease outbreaks were, and remain, one of the major limiting factors for the production of farmed fish worldwide.[32]

1.4 The Present Day

Today, the term '*aquaculture*' is as readily recognised as that of '*agriculture*'. It is used here to refer to the managed production of marine or freshwater animals and aquatic plants, usually with controlled seed stocks, water management and feeding or nutrient input.[21] Aquaculture is the world's fastest-growing food-production system, growing 7% annually.[35] The range of species being cultivated is extensive, with about 567 species being farmed across the world. By way of example, the Food and Agricultural Organisation of the United Nations (FAO) provides extensive information on 68 cultured aquatic species (Table 2). Although finfish dominate in terms of taxonomic groups, eels, shellfish and seaweed are also cultured, together with a few specialist animals (Table 2).

Between 2004 and 2013, there was a steady increase in both inland aquaculture and mariculture production, with the proportion from inland aquaculture being consistently greater than from mariculture (Figure 2). In 2013, 70 189 847 tonnes (live weight) of food fish (Figure 2) were produced through aquaculture globally. This comprised 44 684 866 tonnes live weight from inland aquaculture (value, $84 857 million) and 25 504 981 tonnes live weight from mariculture (value, $65 490 million; Figure 2). The top three most-valuable species produced in 2013 were the whiteleg shrimp (*Penaeus vannamei*), which was worth $16 515 million, Atlantic salmon (*Salmo salar*), worth $12 904 million, and the grass carp (*Ctenopharyngodon idellus*), which came in at $6690 million. The production of fish and shellfish was augmented by the production of approximately 27 million tonnes of aquatic plants (value, $6701 million), the bulk (99.7%) of which was produced through mariculture, with much of this activity taking place in Asia (Figure 3).

Although aquaculture remains a global activity, food fish production in 2013 was greatest in Asia (89.1%), followed by the Americas (4.4%), Europe (4.0%), Africa (2.1%) and Oceania (0.3%) (Figure 4).[36] Inland aquaculture

Table 2 Cultured aquatic species by category. Factsheets on 68 cultured aquatic species are available from the Food and Agriculture Organisation of the United Nations website (http://www.fao.org/fishery/culturedspecies/search/en).

Cultured aquatic species	Number of species
Fish	35
Shellfish	22
Seaweed	5
Eels	2
Other	4[a]

[a] Tiger tail seahorse (*Hippocampus comes* (Cantor, 1849)), American bull frog (*Rana catesbeiana*), Japanese sea cucumber (*Stichopus japonicus*) and soft-shell turtle (*Trionyx sinensis*).

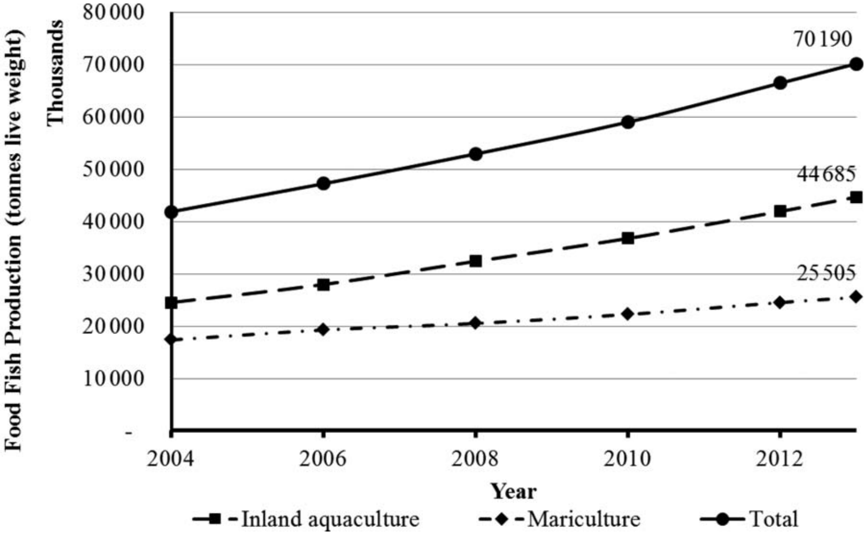

Figure 2 World food fish (food fish includes finfish, crustaceans, molluscs, amphibians, reptiles (excluding crocodiles) and other aquatic animals, such as sea cucumbers and seas urchins, for human consumption) production between 2004 and 2013 inclusive from both inland aquaculture and mariculture. The inset values are the global production figures for 2013 (1000 tonnes live weight).

dominates in Asia and Africa, while mariculture dominates in the Americas, Europe and Oceania. Examining the top ten producers, it is evident that China dominates the production for 5 of the 6 assessed categories (finfish – inland aquaculture (Figure 4), crustaceans – inland aquaculture, crustaceans – mariculture, molluscs – mariculture (Figure 5) and seaweed – mariculture (Figure 3)). Norway has the largest production of finfish – mariculture, this being dominated by Atlantic salmon (Figure 4). Across Europe finfish – mariculture and molluscs – mariculture dominate, primary countries being Norway, UK and Greece (finfish), Spain, France and Italy (molluscs) (Figure 4).

2 Challenges

Capture fisheries and aquaculture are important in terms of both nutrition and providing livelihoods, especially for the poor. Approximately one billion people rely on fish as their main source of animal protein. Aquaculture is considered to be one of the ways of providing the future protein needs of the growing, global human population, especially in east and south Asia.

A range of fish and shellfish are cultured; this is generally geographically determined. That said, the main producers of Atlantic salmon, which is both one of the highest value products and most intensively farmed fish, are Norway, Chile, Scotland, Canada, Faroe Islands, Australia, USA, Ireland, France and Iceland. It has also been produced in Turkey, the Russian

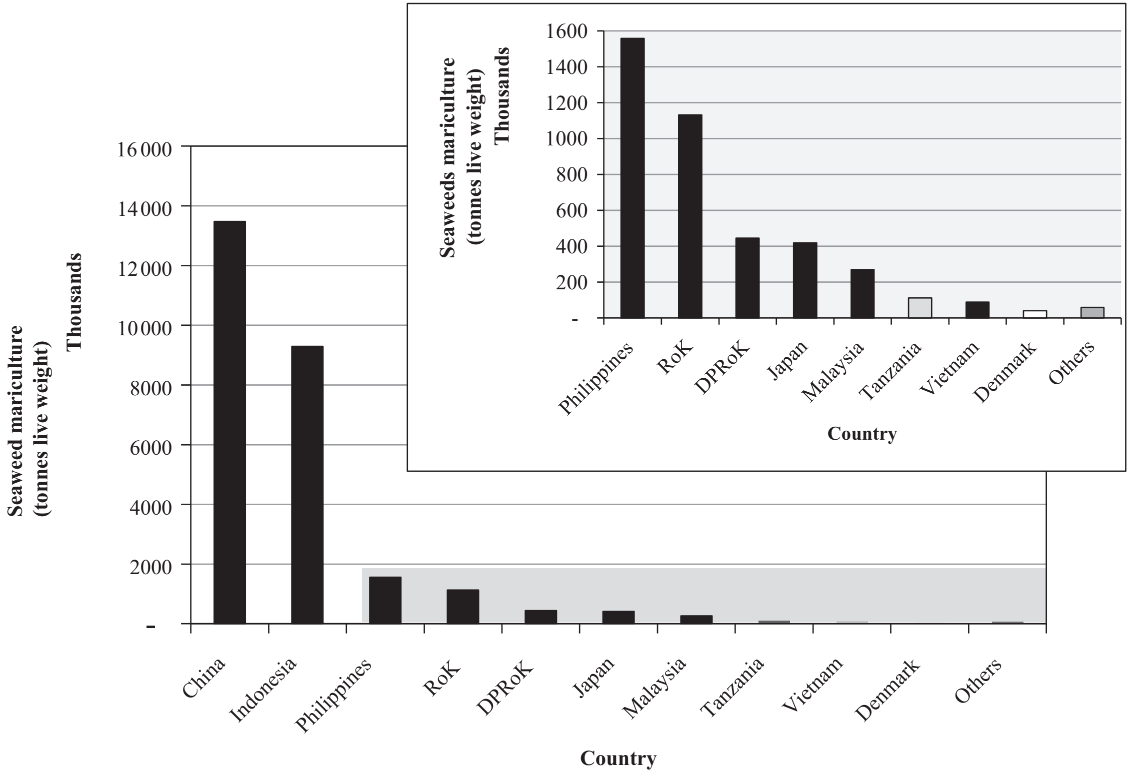

Figure 3 Top 10 seaweed producers (aquatic plant production) by mariculture.[36] RoK: Republic of Korea; DPRoK: Democratic People's Republic of Korea. Black bars—Asia, Light grey bar—Africa, White bar—Europe, Dark grey bar—other countries not in the top 10, any continent.

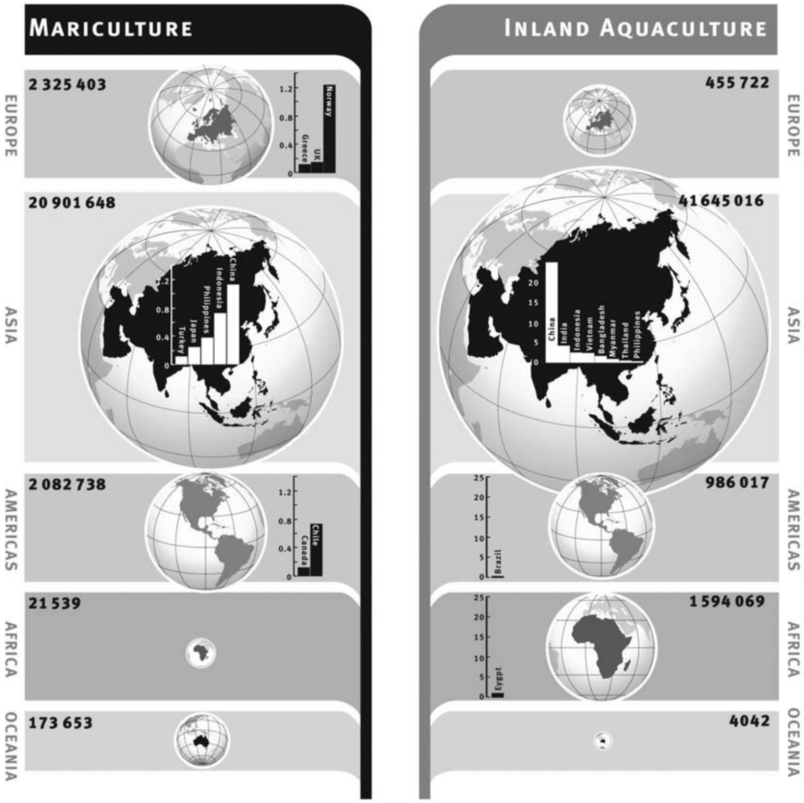

Figure 4 Global food fish (inland aquaculture and mariculture) total production. (Figures based on data from the FAO Global Aquaculture Production 1950–2013 statistics database (http://www.fao.org/fishery/statistics/global-aquaculture-production/query/en).[36] The values in each box are the total production (tonnes live weight) of food fish produced for each continent through either mariculture or inland aquaculture. The vertical axes of the plots within mariculture and inland aquaculture are million tonnes live weight of finfish production which are presented on the basis of the top ten world producers. Countries in Asia make up 5 and 8 of the top ten for mariculture and inland aquaculture, respectively.

Federation, Greece and Finland.[37] In Norway, Atlantic salmon production in 2014 was 1 258 365 tonnes (Figure 6A). This resulted in Norwegian salmon exports for the first half of 2013 being valued at 17.4 billion Norwegian Krones (~2.1 billion euros).[38] In Scotland there are currently 262 marine finfish farms. They produced 180 997 tonnes of finfish in 2014, the bulk of which was Atlantic salmon. The strategy in Scotland is to further grow finfish production by 16% by 2020 (Table 3). However, within the wider salmon aquaculture industry, there is approximately one new significant disease identified every year. In addition, approximately one third of the biomass can be lost to disease in salmon aquaculture.

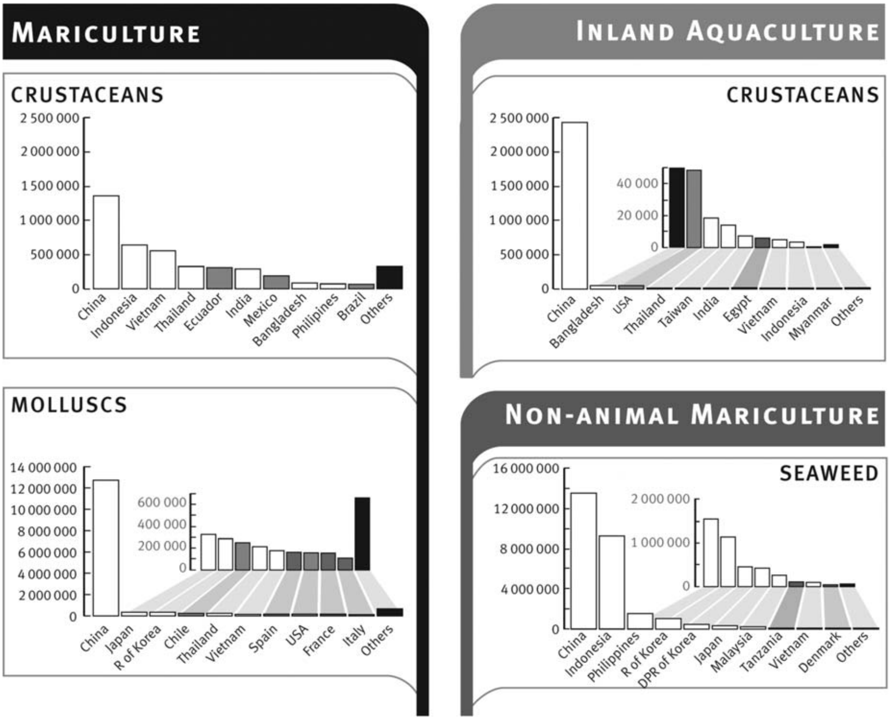

Figure 5 Top ten countries producing crustaceans by mariculture, crustaceans through inland aquaculture and molluscs by mariculture. The units for the vertical axis are tonnes live weight. China dominates production in each case, but especially for the inland aquaculture production of crustaceans and mollusc mariculture.

The world's largest producer of farmed Atlantic salmon, Norway, lost an average of 34 589 600 individuals per year to mortality over the period 2010–2014. This was by far the largest single reason for losses.[39] There are many viral and bacterial infections which can thrive in an intensive aquaculture environment that is typical of Atlantic salmon production (Table 4). Parasites are also a problem, especially for the Atlantic salmon industry where sea lice, specifically *Lepeophtheirus salmonis* and *Caligus* spp.,[38] remain a significant and continuing concern (Table 4). Although treatment of these copepod ectoparasites with various products has been efficacious, drug resistant parasites are now present on farmed salmonids.[43]

Amoebic gill disease (AGD) is one of the main problems for salmonid aquaculture in Tasmania and Australia, resulting in severe economic losses. Outbreaks have also been reported from New Zealand, United States, Canada, France, Spain, Ireland, Chile, Norway and the UK. The clinical signs and mortality depend on the level of infection and subsequent severity of the gill pathology; therefore, low or early infections may remain unnoticed. In severe cases, the proliferated gill tissue impairs the respiratory capacity of

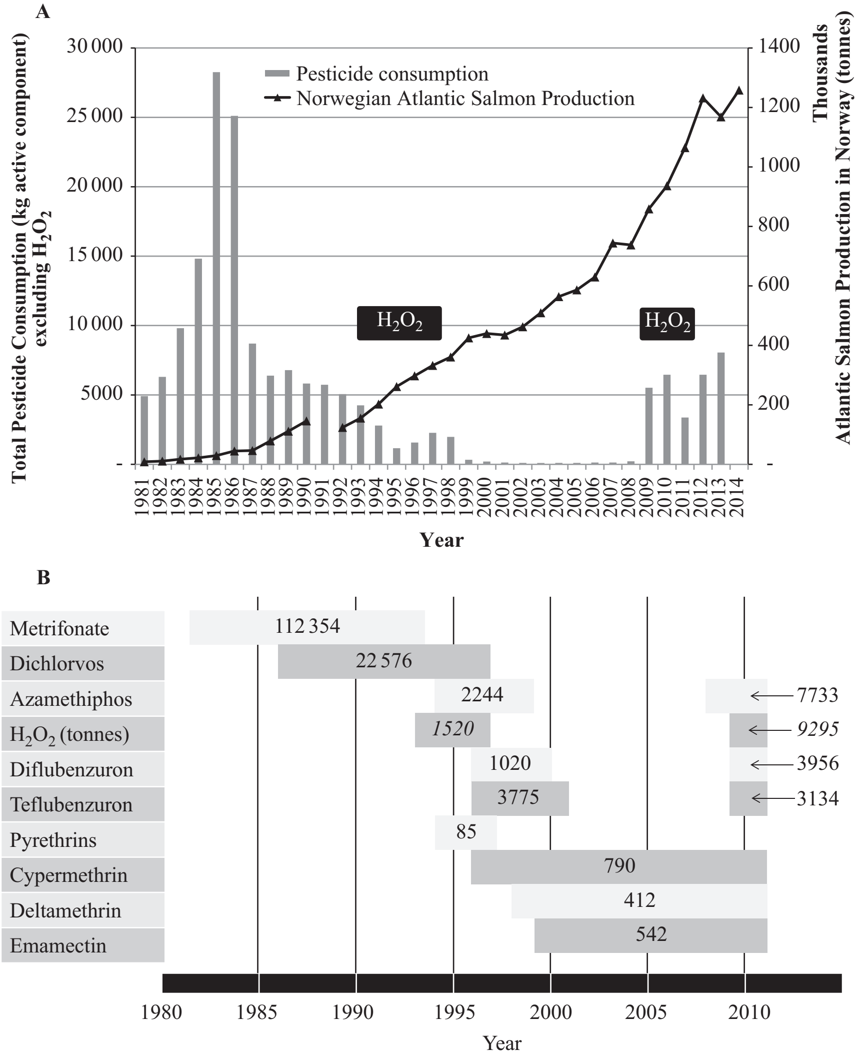

Figure 6 (**A**) Growth of the Norwegian Atlantic salmon (*Salmo salar*) industry (1981–2014) compared to the total pesticide consumption (kilograms active weight, excluding hydrogen peroxide (H_2O_2); 1991 data unreliable and not published). H_2O_2 was used during the period 1993–1997 and 2009–2011 (black horizontal bars). (**B**) The period of application for the different compounds used in the treatment of sea lice. The numbers are the total used (kg active weight for all but H_2O_2 which is tonnes active weight) during that period. For azamethiphos, H_2O_2, diflubenzuron and teflubenzuron there were two distinct periods of use; the amount for each period is shown separately. (Based on data from ref. 38, 53, FAO[54] and Fish Farming 1996[55]).

the fish, leading to asphyxia and death. Affected fish may be weakened and are more susceptible to other infections; but conversely, fish suffering from other diseases may also be more susceptible to AGD. Experience in Scotland

Table 3 Projected growth in aquaculture (both finfish and shellfish) in Scotland. By 2020, the Scottish industry could be worth £2 billion *per annum*, providing 10 000 jobs, mainly on the west coast, Na h-Eileanan Siar (Western Isles) and the Northern Isles (Orkney and Shetland).

	Year		
Aquaculture production	Production in 2014 (tonnes)	Projected production in 2020 (tonnes)	Percentage growth 2014–2020
Finfish production	180 997	210 000	16%
Shellfish production	7980	13 000	63%

suggests mortalities are typically 10–20%, but losses as high as 70% have occasionally been reported. In chronic cases low, but ongoing, mortalities can persist for up to three months.[44]

Other species experience their own particular disease problems (Table 5). Viral, bacterial and parasitic diseases continue to be an issue in the global production of fish and shellfish. Indeed, new diseases are being reported on a relatively frequent basis. There are a number of new or newly emerging diseases amongst the cultivated penaeid shrimp in Asia. For example, outbreaks of acute hepatopancreatic necrosis disease (AHPND) of shrimp began in China in 2009, reaching Mexico in 2013.[51] Also in 2013, a new type of yellow-head virus (YHV) was suspected in China. Tilapia (*Oreochromis* spp.) hatcheries in Thailand have been impacted by a novel disease called *Hahellosis* or 'red egg disease'. The bacterium *Hahella chejuensis* has very recently been proposed as the likely causative organism of this disease.[52] As diseases continue to emerge, a key way forward is good disinfection and high quality husbandry. At the same time, pesticides will remain part of the armoury.

3 The Use of Chemicals for Pest/Disease/Parasite Control

3.1 The Requirement to Use Pesticides

There is little doubt that aquaculture, be it mariculture or inland aquaculture, will continue to expand in its intensive format. Technological developments will provide enhancements to production processes, while new strategies for dealing with disease and pests, including the use of cleaner fish, should reduce losses. However, there will continue to be a need for pesticides in the foreseeable future. Indeed, the development of new medicines, due to parasite resistance, is required. This will be the case even though the use of pesticides should be as part of integrated pest management which aims to prevent disease rather than using medicine treatments as the only response when dealing with, for example, sea lice.[43,53] Vaccine development continues to be slow, but the lack of an adaptive immune response in shellfish means that an alternative way of dealing with shellfish diseases must be sought.[40] Clearing ponds of predators or weeds in advance of stocking has also been achieved using various

Table 4 Disease problems affecting salmonids.[32,37,40–43]

Disease	Agent	Type	Region/syndrome	Impact/measures
Viruses				
Infectious salmon anaemia (ISA)	*Orthomyxovirus* Enveloped virus consisting of 8 single-stranded RNA segments	Virus	Canada, Faroe Islands, Scotland, USA, Ireland, Chile Lethargy, appetite loss, gasping at water surface, pale gills and heart, fluid in body cavity, dark liver, haemorrhages in internal organs	Mortality No treatment Statutory controls, biosecurity, bloodwater treatment
Viral haemorrhagic septicaemia (VHS)	*Novirhabdovirus* within the *Rhabdoviridae* family	Virus	Holarctic Bulging eyes and, in some cases, bleeding eyes, pale gills, swollen abdomen, lethargy	Mortality No treatment Statutory controls, vaccines being developed
Infectious pancreatic necrosis (IPN)	*Aquabirnavirus* containing double stranded RNA	Virus	Worldwide Erratic swimming, eventually to bottom of tank where death occurs	Mortality No treatment Statutory controls, biosecurity, broodstock screening, vaccination possible
Salmon pancreas disease virus (SPD)	*Alphavirus* of the family *Togaviridae*	Virus	Europe (UK, Ireland, Norway) Weight loss, emaciation, mortalities	Mortality No treatment Withholding feed, vaccination
Oncorhynchus masou virus disease (OMVD)	Salmonid *herpesvirus 2* (SalHV-2)	Virus	Asia, Middle East Fish are dark, severe exophthalmia[a] and petechial haemorrhage[b] under the lower jaw Oncogenic potential	Mortality Avoidance and hygiene practices, thorough disinfection of fertilised eggs
Heart and skeletal muscle inflammation (HSMI)	*Piscine reovirus*	Virus	Norway, Scotland Slow disease development	Morbidity and mortality No treatment or vaccines

Table 4 Continued

Disease	Agent	Type	Region/syndrome	Impact/measures
Infectious hematopoietic necrosis (IHN)	*Rhabdovirus* containing single stranded RNA	Virus	United States, Europe, Japan Lethargy, abnormal swimming, darkening of the skin, pale gills, ascities[c], distended abdomen, exophthalmia and petechial haemorrhage	Mortality
Bacteria				
Furunculosis	*Aeromonas salmonicida* Gram-negative, non-motile, facultatively anaerobic bacillus	Bacterium	Holarctic Inflammation of intestine, reddening of fins, boils on body, pectoral fins infected, tissues die back	Mortality Antibiotics, vaccination
Bacterial kidney disease (BKD)	*Renibacterium salmoninarum*	Bacterium	Worldwide Whitish lesions in the kidney, bleeding from kidneys and liver, some fish may lose appetite and swim close to surface, appear dark in colour	Morbidity Statutory controls, biosecurity, broodstock screening
Winter ulcer disease	*Moritella viscosa* (multifactorial)	Bacterium	Norway, Iceland, Scotland, Ireland Ulcers, diffuse or petechial haemorrhage in internal organs	Antibiotics, vaccination
Enteric redmouth (ERM) disease	*Yersinia ruckeri* Gram-negative, facultatively anaerobic bacillus	Bacterium	Europe, Chile, Canada/USA Black, lethargic fish ‘hanging’ in areas of low flow, bilateral exophthalmia, abdominal distension as result of fluid accumulation, haemorrhages of mouth and gills	Mortality Antibiotics, vaccination in freshwater
Salmonid rickettsial septicaemia (SRS)	*Piscirickettsia salmonis* Gram-negative, facultatively intracellular, bacterium	Bacterium	Chile, Canada, Norway, Ireland, Scotland, Greece Increased mortality, anorexia, pale gills and lowered haematocrits, swollen abdomens, affected fish appear dark and lethargic, swimming at the sides of enclosures	Antibiotics, vaccination

Fungus				
Saprolegnia	*Saprolegnia*	Fungus	Europe White or grey patches of filamentous threads on surface, cotton-like appearance radiating in circular, crescent-shaped or whorled pattern, usually begins on head or fins, lethargy and loss of equilibrium	Bronopol/formalin bath
Parasites				
Sea lice	*Lepeophtheirus salmonis*; *Caligus* spp.	Ectoparasites	Holartic (*L. salmonis*) Global (*Caligus* spp.) Reduced growth, loss of scales, haemorrhaging of eyes and fins	Mortality Parasiticides 1. Bath treatment: azamethiphos, cypermethrin, hydrogen peroxide 2. In-feed treatment: emamectin benzoate, teflubenzuron
Amoebic gill disease (AGD)	Protozoan parasite *Neoparamoeba perurans*	Ectoparasite	Tasmania, Australia (severe economic losses) Outbreaks in New Zealand, United States, Canada, France, Spain, Ireland, Chile, UK and Norway Gill infestation	Freshwater baths, hydrogen peroxide
Tapeworms	*Eubothrium* spp.	Endoparasites	Europe Reduced growth, reduced condition factor, aesthetically unacceptable to consumers	Morbidity, occasional mortality Fenbendazole/ praziquantel in feed, avoidance of early hosts

[a] Exophthalmia: bulging or protruding eyeball.
[b] Petechial haemorrhage: a subcutaneous, mild haemorrhage that causes distinctive markings (red or purple spots) called petechiae.
[c] Ascities: a condition when fluid fills the space between the lining of the abdomen and the organs.

Table 5 Examples of diseases affecting aquaculture species other than the salmonids (see Table 4 for salmonids).[32,40,41,45–50]

Disease	Agent	Type	Region/syndrome	Impact/measures
Viruses				
Lymphocystis disease (LCD)	Icosahedral DNA virus of the *Iridoviridae* family	Virus	Worldwide Described in more than 125 species of fish Small cream-coloured nodular lesions on skin and fins, low growth rates	Morbidity No commercial vaccine Scrupulous disinfection, bath treatment with formalin, H_2O_2 and Jenoclean
Channel catfish virus disease (CCV)	—	Virus	USA Channel catfish Reduced feeding activity; erratic swimming behaviour, sometimes spiral; alternating hyperactivity and lethargy; swollen abdomen; distended vent area; bulging eyes; haemorrhage	No treatment; good management practices
Iridoviral disease (RSIV)	*Iridoviridae* family – 5 genera Icosahedral deoxyriboviruses with a large double-stranded DNA genome	Virus	Asia Affects red sea bream, rock bream, amberjack/yellowtail Darkness of the body color, congested eyes, congested internal organs, enlarged spleen	Implementation of hygiene practices at the farm
Spring viraemia of carp virus (SVCV)	Rhabdovirus – a single stranded RNA virus in the family *Rhabdoviridae*	Virus	Europe Mostly carp species Clinical signs include darkening of the skin, swollen eyes, abdominal swelling, pale gills, and trailing faecal casts	Appropriate hygiene measures Currently there are no licensed vaccines against SVC.

Haemorrhagic disease	Reovirus (GCRV)	Virus	Asia, South America, south-east Europe Affects grass carp (*Ctenopharyngodon idellus*) Red muscle caused by haemorrhage, red fin, red operculum and enteritis, high mortality (30–50% of infected fish)	Vaccination Disinfection – fish seed, culture environment with chlorine compounds, quicklime and potassium permanganate, Chinese Rhubarb (*Rheum officinale*), sweet gum leaves (*Liquidambar taiwaniana*), cork tree bark (Genus *Phellodendron*) and skullcap root (*Scutellaria baicalensis*)
Infectious hypodermal and haematopoietic necrosis virus (IHHNV), causing Runt deformity syndrome (RDS)	Systemic parvovirus	Virus	Asia, Americas Whiteleg shrimp (*Penaeus vannamei*) Low mortality for resistant *P. vannamei*, however, reduced feeding, growth and feed efficiency, cuticular deformities (bent rostrum – RDS) occurs in <30% of infected populations, increasing variance of final harvest weight, reducing market value	Wash and disinfect eggs and nauplii An infected, culture facility must be completely disinfected
White spot disease (WSD)	Part of the white spot syndrome baculovirus complex	Virus	Worldwide (first identified in Asia) *e.g.* Giant tiger prawn (*Penaeus monodon*), whiteleg shrimp (*Penaeus vannamei*) Red discoloration and white spots beneath cuticle, stop feeding, very lethargic, gather around edges of ponds	Mortality No available treatments Good husbandry, avoid shrimp stress, treat infected ponds and hatcheries with 30 ppm chlorine to kill infected shrimp and carriers

Table 5 Continued

Disease	Agent	Type	Region/syndrome	Impact/measures
Bacteria				
Columnaris disease	*Flavobacterium columnare*	Bacterium	Channel catfish White spots on mouth, edges of scales and fins, cottony growth around mouth, fins disintegrate at edges, 'saddleback' lesion near dorsal fin, fungal invasion of gills and skin	Antibiotics: oxytetracycline, sulfadimethoxine, ormetoprim
Nocardiosis	*Nocardia crassostreae*	Bacterium	Americas, Asia, Europe, Australia, South Africa Pacific cupped oyster (*Crassostrea gigas*)	Modified culture practices
Parasites				
Proliferative gill disease	*Aurantiactinomyxon* sp., *Dero digitata*	*Myxozoans*	Channel catfish Swelling and red and white mottling of gills gives raw minced meat appearance	Formalin
Copepod parasites	*Ergasilus* sp., *Argulus* sp., *Lernaea cyprinacae*	Copepods	Channel catfish Visible parasites on gills	Formalin
Trichodinidosis	*Trichodina* spp.	Ciliates	North-East Atlantic Cod (*Gadus morhua*) Respiratory problems; mucus secretion; itching	Bath treatment (formaldehyde)
Denman Island Disease	*Mikrocytos mackini*	Protozoan parasite	Americas, Asia, Europe, Australia, South Africa Oysters (various)	Restricted modified culture practices

chemical treatments. Fouling of sea cages is a further challenge facing the mariculturist and, as for the other highlighted challenges, the use of various chemical-based antifoulants has been a primary method of dealing with this specific issue.

3.2 Sea Lice Treatments in Salmon Aquaculture

The coastline of Norway is well suited to the marine aquaculture of salmonids, specifically Atlantic salmon (*Salmo salar*). As the world's largest producer of Atlantic salmon, this industry has grown from producing 418 tonnes in 1981 to 1 258 356 tonnes in 2014 (Figure 6A). Cultured salmon are susceptible to epidemics of bacterial, viral and parasitic diseases as detailed earlier (Table 4). This includes the sea louse, *Lepeophtheirus salmonis,* in the northern hemisphere and *Caligus teres* and *Caligus rogercresseyi* in Chile. Although sea lice do not generally cause direct mortality, their impact is significant as they result in skin lesions and sub-epidermal haemorrhage. This increases a salmon's susceptibility to secondary infections and osmotic stress. In addition, treatment is expensive and represents part of the global cost of sea lice to marine salmonid production of 300 million euros. Control of sea lice has been achieved largely through the use of pesticides. During the early, developmental years in Norway, significant quantities of the pesticide metrifonate (Neguvon) were used. Consumption of this pesticide peaked in 1985 at 28 260 kg active substance (Figure 6A).[53] Other organophosphates were introduced (*e.g.* dichlorvos (Nuvan) in 1986). However, it became apparent that alternatives to these compounds were required and hydrogen peroxide was given its first period of use in 1993 (Figure 6A and B). Over the years, in addition to the organophosphates and H_2O_2, Norway utilised pyrethroids, benzoylureas and avermectins (Table 6 and Figure 6) to treat sea lice. As production increased, there were significant improvements in husbandry, since the use of pesticides decreased markedly in Norway, such that, between 1999 and 2008, only relatively small quantities of pesticides were used. For example, in 2007, when production was 744 222 tonnes, 30 kg active ingredient of cypermethrin and 73 kg active ingredient of emamectin benzoate were used.[56] The compounds used to treat sea lice are applied under veterinary prescription.

Diflubenzuron and teflubenzuron both were used in Norway in the 1990s (Figure 6B). However a voluntary ban, due to suspected adverse environmental impacts of these products, meant that their use ceased around 2000. In recent years, both diflubenzuron and teflubenzuron have been reintroduced as a replacement for emamectin benzoate due to the sea lice developing a resistance to this product; reports of resistance to emamectin benzoate emerged from both Norway and Scotland during 2008.[43]

Other salmon-producing countries have used a variety of treatments for sea lice (Figure 7). Canada, Chile, the Faroe Islands, Norway and Scotland all

Table 6 Pesticides used in the control of sea lice. An early product, used in Norway from 1974 and Chile from 1981, contained metrifonate,[43] but this was phased out while other pesticides (*e.g.* emamectin benzoate, used since 1998), have a more recent history of use in controlling sea lice (see Figure 6 and ref. 43).

Active ingredient (treatment)	Type of pesticide/action	Product[a]
Cypermethrin (Bath treatment)	Type II pyrethroid	Excis, Betamax
Deltamethrin (Bath treatment)	Voltage-dependent sodium channel modulator, leading to excitation and subsequent paralysis	Alphamax Vet
Pyrethrins[b]	Pyrethrum-derived Sodium channel modulators, leading to excitation and subsequent paralysis	Py-Sal
Dichlorvos	Organophosphate	Nuvan, Aquaguard
Azamethiphos (Bath treatment)	Acetylcholinesterase inhibitor in cholinergic synapses leading to excitation and, subsequently, paralysis[c]	Salmosan
Metrifonate (Historical use)		Neguvon
Diflubenzuron (Oral treatment)	Benzoylurea – inhibits chitin biosynthesis, rendering the parasite unable to detach from their exuviae during molting	Lepsidon, Releeze vet,
Teflubenzuron (Oral treatment)		Ektoban, Calicide
Emamectin benzoate (Oral treatment)	Avermectin group of macrocyclic lactones	SLICE
Ivermectin[d]	Glutamate-gated chloride channel allosteric modulator – reduces the cell's excitability	Ivomec
Hydrogen peroxide (Bath treatment)	Disinfectant with insecticidal and ovicidal properties. Gas bubbles in body rendering the parasites unable to hold on to a surface	Paramove 35 and 50, Salartect 350 and 500

[a] Inclusion of brand names is for illustrative purposes only and does not imply endorsement by the author or any organisation with which the author is associated. Other products may be equally efficacious.

[b] Pyrethrum is found in the Chrysanthemum plant, *Chrysanthemum cinerariaefolium.*[57]

[c] The enzyme cholinesterase (ChE) facilitates the transmission of nerve impulses. ChE-inhibiting pesticides disable this enzyme, resulting in symptoms of neurotoxicity and, at a high enough dose, death.

[d] Ivermectin has not been licensed for fish, but was used in some countries up to 2000.[58]

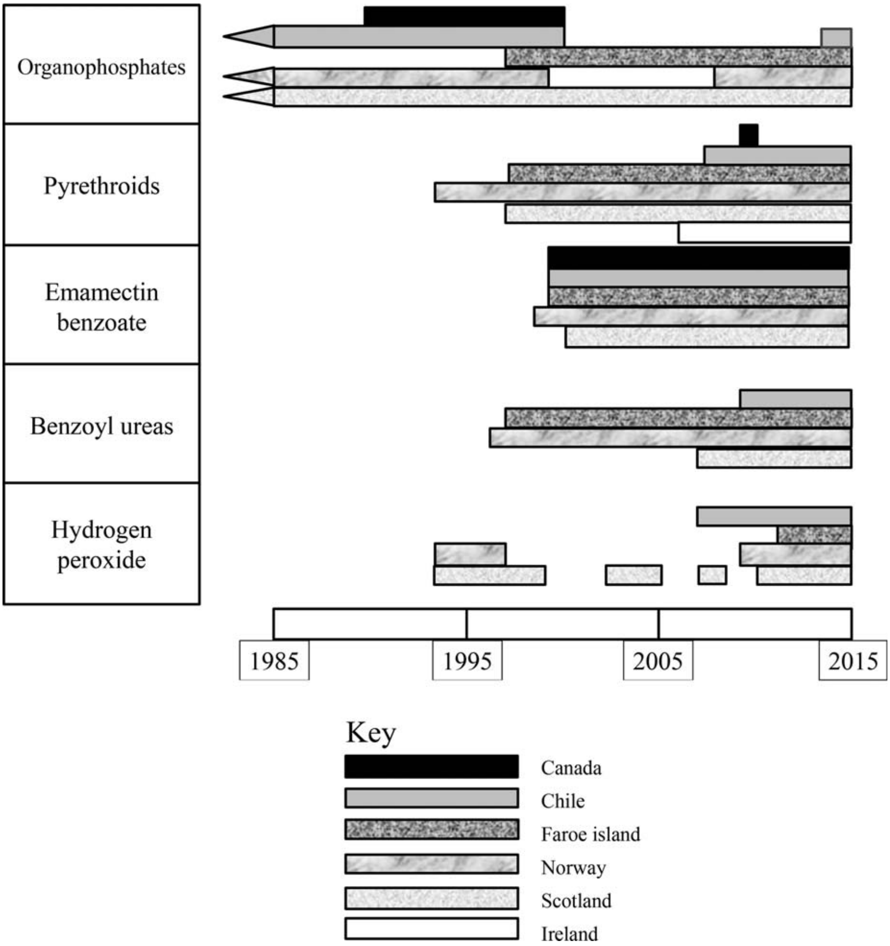

Figure 7 Use of various pesticides (presented by group other than for emamectin benzoate and hydrogen peroxide) in salmon aquaculture by country between 1985 and 2015. Ireland has made use of a range of compounds with the exception of hydrogen peroxide. However, dates were only available for the pyrethroids. (Based on Table 2 in Aaen *et al.* (2015)[43] and Murray (2016)[59]).

started to use emamectin benzoate in the late 1990s (Figure 7). Hydrogen peroxide was introduced (Chile, Faroe Islands) or reintroduced (Scotland, Norway; Figure 7) in the 2000s.

The majority of treatments in Scotland in more recent years have been through the use of a single compound. However, there has been an increasing trend towards the use of multiple medicines.[59] Pairings include deltamethrin with azamethiphos and cypermethrin with emamectin benzoate. Treatments with three or four compounds have been undertaken. Furthermore, in Scotland, although the use of in-feed treatments (*e.g.* emamectin benzoate and teflubenzuron) was relatively small over the period 2005–2011, a large increase in bath treatments† (including cypermethrin) was observed. Treatment rates tend to be seasonal in Scotland, with a peak in March and another in August; the treatment rate in August is greater than that in March and continues at the elevated level until the end of the year.[59] Of importance is the fact that the pattern of sea lice treatment observed in Scotland has changed substantially: there has been an increase in the number of treatments per month, the use of bath treatments has increased quicker than the use of in-feed treatments, and treatments involving more than one medicine in a single month also has increased. However, the diversification of treatment towards the use of more agents is in accordance with good management practice since such integrated pest management aids in the reduction of the emergence of lice that are resistant to current treatments.[59]

In 2016, there remains a need to utilise pesticides against sea lice. However, potential impacts on non-target organisms of these pesticides (see Section 4) means that alternatives continue to be sought.

3.3 Non-salmonid Aquaculture

Salmonid aquaculture is extremely important in both Norway and Scotland as well as several other countries, providing these countries with a premium commodity for both internal consumption and export. However, in terms of tonnage live weight, it represents only 24% of the total global finfish production through aquaculture in 2013 (Figure 4). At the same time, finfish comprise a relatively small proportion (<10%) of total global aquaculture production as measured by the tonnage live weight. As such, it is critical to consider the conditions that might arise in non-salmonid aquaculture that are dealt with through the use of pesticides.

Pond-reared fish can become infested with the Asian tapeworm (*Bothriocephalus achelognathii*). Although not native to the southwestern USA, this intestinal fish parasite, which is responsible for reduced survival, growth, condition and fecundity, has been associated with mass mortalities. Cyprinid fish are most susceptible to this parasite and are treated with praziquantel (Biltricide; Table 7). Administered as a bath treatment, which reduces handling stress, all fish are exposed and the process generally is extremely effective in eliminating the tapeworm.[60] Praziquantel is also used against monogeneans (parasitic flatworms) in grass carp (*Ctenopharyngodon idellus*) in China.[61]

The management of monogeneans in the production of silver perch (*Bidyanus bidyanus*) can be up to 22% of the total production cost.

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† A bath treatment is where a topical application of an anti-parasitic chemical is made by reducing the depth of the cage and enclosing the cage with a tarpaulin, thereby restricting the movement of water between the cage and the surrounding sea. The water in the cage is dosed with the chemical and the tarpaulin maintained *in situ* for a period of time. After that time the tarpaulin is removed and water exchange takes place, flushing the cage.

Lepidotrema bidyana infects the gills and results in gill epithelial hyperplasia and can increase the occurrence of secondary infections. This has traditionally been managed using a bath treatment of formalin or trichlorfon (Table 7), the effectiveness of both being temperature dependent.[62]

A range of organophosphates is used in inland aquaculture (Table 7). There are a variety of reasons for the use of these compounds, including the removal of molluscs from shrimp ponds. In southeast Asia, the tin compounds, triphenyl tin acetate and tripehnyl tin chloride, were both historically used for this purpose, especially in advance of stocking the ponds. The shrimp culture process has used a range of compounds; for example, malachite green has been used as an antifungal and antiprotozoal bath treatment in shrimp hatcheries.

Herbicides are used to control aquatic weeds, algal blooms and organisms that foul the aquaculture structures.[63] This includes their use in shrimp ponds. In Egypt, rice and fish may be cultivated together. Although this has many advantages, one of the drawbacks is the application of the herbicides used in rice culture. These include thiobencarb ($C_{12}H_{16}ClNOS$, a thiocarbamate cholinesterase inhibitor) and dithiopyr ($C_{15}H_{16}F_5NO_2S_2$, S,S′-dimethyl-2-(difluoromethyl)-4-(2-methylpropyl)-6-(trifluoro-methyl)-3,5pyridinedicarbothioate) (Table 7).[64]

The removal of fish prior to stocking of ponds is not unusual since undesirable fish species present in culture ponds may prey on the cultured species, compete for food and spawning habitat, make harvest more difficult, or contribute to a deterioration in water quality. Although ammonia, administered as a combination of urea and bleaching powder, or bleaching powder on its own, has been used as a piscicide, other compounds are available. Rotenone (Table 7), a fish toxicant of botanical origin, is derived from the roots of plants such as *Lonchocarpus* spp. and *Derris trifoliate*, and has long been used as a piscicide in many countries. Other products of plant origin include mahua oil cake and tea seed cakes. These contain saponins (there are over 2000 known saponins; Table 7), also known as ‘triterpene glycosides’.[67] Such compounds are often more specific in their action, degrade faster and do not result in any residue. As such they may be favoured by aquaculturists.[66,68]

3.4 Anti-fouling Compounds

Any aquaculture system which uses a cage or resident structure has the potential to be impacted by biofouling: the growth of unwanted organisms on the surfaces of artificial structures immersed in an aquatic environment. With marine cages this can be a particular concern since biofouling can add significantly to the weight of the structure as well as increasing the drag from currents. In Atlantic salmon cages there can be a reduced flow of water through the cage. This results in decreased nutrient exchange and a reduction in oxygen supplies to the fish.[69] Many of the biocides used in the aquaculture industry came from agriculture or were used in anti-fouling

Table 7 Compounds currently or previously used during the process of culturing fish, shellfish or aquatic plants (excluding those in Table 6 and antibiotics).

Name	Use	Product[a]
Fenbendazole	Treatment of *Eubothrium* (a stomach cestode (parasitic flatworm)) Binds to tubulin subunit and interferes with microtubule formation	Panacur
Praziquantel	Treatment of the Asian tapeworm *Bothriocephalus achelognathii*, *e.g.* in pond-reared fish in the USA	Biltricide
Niclosamide	Anthelmintic in fish culture including turbot Mollusicide used on a large scale in China[65]	Niclocide
Trichlorfon	Treatment of sinergasiliasis in grass carp (*Ctenopharyngodon idellus*) Used against monogenean ectoparasites in Mediterranean sea bass and sea bream Organophosphate – Acetylcholine esterase inhibition	Dipterex, Neguvon
Azinphos ethyl	Removal of molluscs from shrimp ponds Organophosphate – Acetylcholine esterase inhibition	Gusathion A
Diethyl 2-[(dimethoxyphosphorothioyl)sulfanyl]butanedioate	Control of sea lice and trematode infections in shrimp hatcheries Organothiophosphate	Malathion
Chlorpyrifos	Control of ectoparasitic crustaceans in freshwater fish and monogenetic trematode infection in shrimp hatcheries Organothiophosphate	Dursban, Lorsban
Diazinon	Removal of mysids from shrimp ponds in Indonesia Organophosphate	Dimpylat
Malachite green oxalate	Antifungal and antiprotozoal bath treatment, primarily in shrimp hatcheries Organonitrogen compound	Malachite green, Basic Green 4, Diamond Green
Trifluralin	Prophylactic fungicide in shrimp hatcheries Herbicide As a herbicide – affects the tubulin protein involved in cell division	Treflan

Dimethyl 2-(difluoromethyl)-4-(2-methylpropyl)-6-(trifluoromethyl)pyridine-3,5-dicarbothioate	Herbicide used in rice fields where tilapia is frequently farmed Inhibits mitosis (blocks cell division)	Dithiopyr 40 WSB
S-(4-Chlorobenzyl) diethylcarbamothioate	Herbicide used in rice fields where tilapia is frequently farmed Cholinesterase inhibitor	Thiobencard
Triphenyl tin acetate	Previously used in south east Asia for elimination of molluscs prior to stocking shrimp ponds Organotin compound	Fentin acetate, Brestan
Triphenyl tin chloride	Previously used in south east Asia for elimination of molluscs prior to stocking shrimp ponds Organotin compound	Fentin chloride, Aquatin
Copper compounds	Used against external protozoans and filamentous bacterial diseases in post-larval shrimp farms	Aquatrine
Ammonia	A piscicide added prior to pond stocking in shrimp culture Interferes with osmoregulation at the gills and disrupts the blood chemistry	Ammonium sulfate plus hydrated lime Urea and bleaching powder
Antimycin	Piscicide Cellular respiration inhibitor	Fintrol (USA) Antimycin A_1 Antimycin A_3
Rotenone	Used to remove fish from ponds[66] Interferes with the electron transport chain in mitochondria (stops the oxidation of nicotinamide adenine dinucleotide)	Fish Tox Nox-Fish Prentox Nusyn Nox Fish[66]
Saponins (plant-derived compounds also known as 'triterpene glycosides')	Piscicide used in ponds prior to stocking of shrimps in Southeast Asia Destroy red blood cells (haemolysis) and therefore reduce oxygen uptake and alter haemoglobin concentrations May damage the gills of aquatic organisms	Tea seed cake Mahua oil cake

[a] Inclusion of brand names is for illustrative purposes only and does not imply endorsement by the author or any organisation with which the author is associated. Other products may be equally efficacious.

paints. This means that much of the original work on consequences of the use of these materials was based upon their original primary use. Organotin compounds (*e.g.* tributyl tin (TBT) and tributyltin oxide (TBTO)) were used extensively in ship paints as a biocide against hull fouling and were initially used in aquaculture as a means of preventing biofouling. However, when it became clear that TBT causes disruption of the endocrine system of marine snails, including the dogwhelk (*Nucella lapillus*), leading to the development of male sexual characteristics in female snails, the use of TBT was phased out. Another reason for no longer using TBT was that this biocide was found to impair the immune system of organisms and produce malformations of the shells of oysters. As a consequence of this, metallic copper and various copper(I) derivatives are now used extensively as antifoulants due to their biocidal activity towards a range of animals and seaweeds (Table 8).[70] Zinc-based compounds and various organic compounds are also used (Table 8). Some are the principal active ingredient, while a number of the compounds in use today act as boosters to increase the efficacy of

Table 8 Antifoulant biocides used to inhibit growth on structures in the aquatic environment.[71,72]

Product[a]	Active ingredient(s)
Tin-based	
Bioclean	Tributyltin (use now banned)
Copper-based	
Amercoat 70E3	copper
Flexgard VI	13.6% cuprous oxide, 2,4,5,6-tetrachloro-isophthalonitrile
Netrex AF	17% cuprous oxide
Aquanet/copper Net	Copper oxide and dichlofluanid
Copper pyrithione	bis-{1-hydroxy-2[*H*]-pyridine thionate-*O,S*}-Cu
Zinc-based	
Zineb	Zinc ethylenebis(dithiocarbamate)
Zinc pyrithione	bis-{1-hydroxy-2[*H*]-pyridine thionate-*O,S*}-Zn
Organic compounds	
Sea-Nine 211	4,5-Dichloro-2-*n*-octyl-4-isothiazolin-3-one
Diuron	3-[3,4-Dichlorophenyl]-1,1-dimethylurea
Irgarol-1050	2-Methylthio-4-*tertiary*-butylamino-6-cyclopropylamino-*s*-triazine
DENSIL100	TCMS pyridine (2,3,5,6-tetrachloro-4-(metylsulfonyl)pyridine)
Clorothalonil	2,4-Dicyanotetrachlorobenzene
Flexgard X-CFR	Dichlofuanid
	N-{[Dichloro(fluoro)methyl]sulfanyl}-*N′*,*N′*-dimethyl-*N*-phenylsulfuric diamide
Mixed metals and organic	
Net-Guard	Copper oxide, zinc oxide, dichlofluanid

[a] Inclusion of brand names is for illustrative purposes only and does not imply endorsement by the author or any organisation with which the author is associated. Other products may be equally efficacious.

the treatment. These include Irgarol 1051, Sea Nine 211, dichlofluanid, chlorothalonil, zinc pyrithione and Zineb. Many of the organic compounds, *e.g.* chlorothalonil, dichlofluanid, diuron, TCMS pyridine and Irgarol 1051, function by inhibiting Photosystem II (PS II) electron transport or mitochondrial electron transport. Those containing metals act as a multi-site inhibitor.

3.5 Disinfectants

For a number of infectious diseases there are no specific vaccines or medications available (Table 5). The best way of avoiding the consequence of the infection is to ensure that the infection does not develop within the aquaculture environment. This requires excellent husbandry and biosecurity, which includes scrupulous disinfection with appropriate chemicals. Disinfection can also be used as a mortality-mitigation and disease-management tool in hatcheries. This is important because fish eggs may harbour pathogenic microorganisms, which means that they are considered a potential route of disease transmission. Typical disinfectants include hydrogen peroxide, ozone, glutaraldehyde, iodophors (compounds that act as a source of active 'free' iodine), formaldehyde, peracetic acid (based on a mixture of ethanoic acid, hydrogen peroxide and water), tannic acid, bronopol, sodium chloride (used as an anti-fungal agent) and copper sulfate (mainly used as an algicide and to treat parasites in aquaculture) (Table 9).[73,74]

The range of disinfectants available can be used across a number of applications (*e.g.* foot baths, cages, processing plant effluent, *etc.*) and are effective against a number of viral (*e.g.* infectious salmon anaemia virus, ISAV) and bacterial (*e.g. Renibacterium salmoninarum,* which causes bacterial kidney disease, BKD) agents (Table 9). It is important to use the correct disinfectant such that an appropriate balance is obtained between disinfection and any possible negative effect, such as on larval health. In a study comparing the use of formalin and the iodophor povidone iodine as disinfectants on the eggs of California yellowtail (*Seriola lalandi*), white seabass (*Atractoscion nobillis*) and California halibut (*Paralichthys californicus*), treatment with 100 mg L^{-1} formalin for an hour gave the best balance of disinfection and larval health.[75]

4 Potential Impacts on the Environment and Non-target Species

Chemicals used to remove pests, unwanted fish or plants, and viruses or bacteria, may have an impact on non-target species. Furthermore, the compounds may accumulate in marine sediments or enter the edible tissue of the cultured product. Chemical resistance can also develop in the pest. Some of these issues have already been highlighted. In identifying further

Table 9 Disinfectants, doses and applications. Abbreviations in the 'Comments' column (*e.g.* ISA) are detailed in Table 4. Based on Table 1 in ref. 74. (Crown Copyright).

Disinfectant	Example[a]	Dose	Application	Comments[b]
Sodium hypochlorite	Klorsept (Jencons Scientific UK)	100 ppm, 10 minutes	Boats, cages, tanks, hand nets, harvest equipment	Reported effective against ISA and IPN
		1000 ppm, 10 minutes	Processing plant effluent	
		1000 ppm, 6 hours	Cage nets	Ensure an active free chlorine level of at least 5 ppm after treatment
Chloramine T	Halamid (Axcentive, France)	1% (w/v), 5 minutes	Foot bath, non-porous surfaces	Reported effective against ISA and AGD (www.halamid.com)
Chlorine dioxide	Zydox AD-05 activated by DRA-2 (Zychem Technologies, Norway)	100 ppm, 5 minutes	Processing plan effluent	Effective against ISA
Iodophor	Buffodine, FAM30 (Evans Vanodine, UK) or Tegodyne (Diversey Johnson, UK)	100 ppm, 10 minutes	Foot bath, clothing, diving gear, hand nets, salmonid ova, non-porous surfaces	Reported effective against ISA Fading colour from brown to yellow indicates inadequate concentration. Not suitable for nets treated with antifoulant.
Peroxy compounds	Virkon S (Antec International, UK)	1% (w/v), 10 minutes (IPN)	Foot bath, non-porous surface	Reported effective against IPN, ERM and BKD
		0.5% (w/v), 30 minutes (ISA)		Reported effective against ISA and furunculosis (www.antecint.co.uk)
Peracetic acid, hydrogen peroxide and acetic acid mix	Proxitane 5 (Solvay Interox, UK)	0.4% (v/v), 5 minutes	Non-porous surfaces	Reported effective against ISA

Quaternary ammonium compounds	Cetrimide (FeF Chemicals A/S, Denmark)	125 ppm, 5 minutes	Plastic surfaces	Reported effective against VHS and furunculosis Not effective against IPN at 12 500 ppm
Formic acid		$\mathrm{pH} < 4$, 24 hours	Ensiling fish waste	Reported effective against ISA Also effective against BKD and furunculosis, but not against IPN
Ozone		8 mg $\mathrm{L^{-1}\,min^{-1}}$, 3 minutes (Corresponding to redox potential 600–700 mV)	Water – intake and effluent	Reported effective against IPN, furunculosis, ERM and *Vibrio anguillarum* Filtration, pre-treatment is recommended
Heat		70 °C, 2 hours 60 °C, 2 minutes 37 °C, 4 days	Cage nets, diving gear, steam cleaning non-porous surfaces	Reported effective against IPN Reported effective against ISA Reported effective against nodavirus Heat treatment above 71 °C may reduce nylon net breaking strain
UV		122 $\mathrm{mJ\,cm^{-2}\,s^{-1}}$ 290 $\mathrm{mJ\,cm^{-2}\,s^{-1}}$	Freshwater intake supply	Reported effective against IPN Reported effective against nodavirus Efficacy compromised by organic loading. May be combined with ozone for treating effluent from processing plants

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[a] Inclusion of brand names is for illustrative purposes only and does not imply endorsement by the author or any organisation with which the author is associated. Other products may be equally efficacious.

[b] For full literature associated with this Table see ref. 74. Abbreviations as in Table 4.

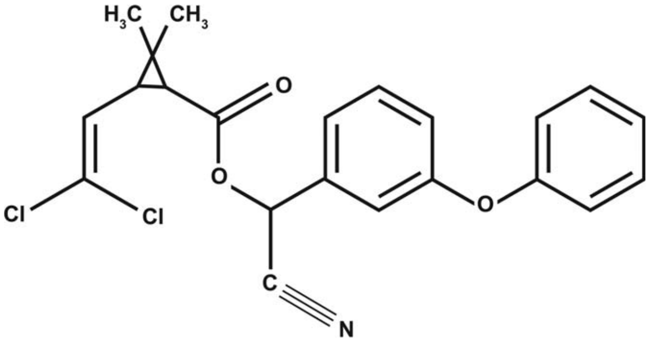

Figure 8 The structure of cypermethrin, a sea lice treatment used in Atlantic salmon aquaculture.

issues, however, there is a need to understand why intensive aquaculture is practised – there is a need to provide a nutritious food product, but of course such food must be safe to eat. There have been two studies where the concentrations of organophosphates in aquaculture fish were shown to be higher than in wild-caught fish.[63] However, it has to be said that pesticide residues in aquaculture products are often below the limits of detection and certainly below relevant EU maximum residue limits.[76]

The interaction of various treatments with non-target organisms is of considerable interest, not least because there is a need to understand whether or not an interaction is positive, neutral or negative. As an example of this, farmed mussels (*Mytilus edulis*) were found to contain an altered *cis:trans* isomer ratio of cypermethrin (Figure 8) to that which they were originally exposed. In addition, there was a pronounced behavioural effect of shell closure, where mussels exposed experimentally to 1.0 mg L^{-1} cypermethrin shut their shells within an hour of exposure. However, even at 1.0 mg L^{-1} cypermethrin, neutral-red retention time and aerial survival were not affected, suggesting that these responses of the mussels were unlikely to occur in the field.[77]

The shore crab (*Carcinus maenus*) is found in the vicinity of fish farms in Scotland. Glutathione *S*-transferase (GST) activity was significantly increased in *Carcinus* exposed to nominal concentrations of 50 and 500 ng L^{-1} of water-borne cypermethrin. However, the absence of a clear dose-response relationship between cypermethrin and GST activity suggested that GST activity in *Carcinus* may be of limited use as a biomarker. However, the fact that there was an observable short-term effect is of interest in respect of the response of a non-target crustacean to this sea lice treatment.[78]

The potential impact of other sea lice treatments on non-target organisms has been studied. Acute exposure of the polychaete worm *Nereis virens* to deltamethrin (the active ingredient in Alphamax, Table 6) was negligible when current aquaculture scenarios were used. However, chronic exposure through the sediment did result in sub-lethal effects relating to burrowing activity and worm condition/mobility.[79] The 10-day LC_{50} (average concentration of the chemical capable of causing death to half of the test organism sample population) of the same compound, in the form of both deltamethrin, and cypermethrin (active ingredient in Excis, Table 6) in spiked sediment to the amphipod *Echinogammarus finmarchicus*, were 16 and 80 ng g^{-1} dry weight, respectively. These results are consistent with there being a low risk from sediment exposure to this species of amphipod.[80]

Crustaceans are potentially one of the high-risk groups in terms of sea lice treatments. With bath treatments (as compared with in-feed treatments) there are recommended dosages in Canada for hydrogen peroxide (1.2–1.8 g L^{-1} for 40 minutes), azamethiphos (an organophosphate; 100 µg L^{-1} in wellboats[‡] and 150 µg L^{-1} for skirted cages for 30–60 minutes), and deltamethrin (a pyrethroid; 2.0 µg L^{-1} for 40 minutes). Although the recommended dosage for hydrogen peroxide has been found to be appropriate for sea lice control, potential impacts on American lobster (*Homarus americanus*, adult and larvae) and the sand shrimp (*Crangon septemspinosa*) were observed for the other two compounds. Deltamethrin was found to be lethal in a range of <1 to 27 ng L^{-1} for the various life stages of *H. americanus* and for *C. septemspinosa*, with the sand shrimp being the least sensitive. Life stages I and II of *H. americanus* were the most sensitive. The LC_{50} values are such that the recommended treatment concentration of deltamethrin should be diluted at least 500 times to avoid impact on the most sensitive non-target species.[81] In another study comparing deltamethrin and azamethiphos, this time examining the toxicity of plume water using *Eohaustorius estuarius*, the plume from deltamethrin bath treatments was found to be more toxic than the azamethiphos treatments.[82]

The specific mode of action of sea lice medicines will influence which organisms may be affected. The benzoylurea pesticides teflubenzuron and diflubenzuron inhibit chitin biosynthesis (Table 6). They are not very toxic to fish or algae, but their mode of action suggests that they are likely to have an adverse effect on crustaceans and amphipods, including the non-target marine copepod *Tisbe battagliai*. The use of both teflubenzuron and diflubenzuron increased in Norway in 2012 and 2013 relative to 2011.[38] This was partly due to the fact that the two compounds were administered together in Norway, *via* the feed. When tested, developmental effects were seen in *T. battagliai* in the ng L^{-1} range. This reflects environmentally relevant concentrations.[38]

Pesticides, especially in the case of inland aquaculture, can be present both as a result of direct use and from diffuse pollution. Often pesticides will find their way into natural water courses though industrial and agricultural drainage, runoff following either flooding or rain, and leaching through the soil profile surrounding a fish farm. Furthermore, co-culture involving both plants and fish can expose the fish to herbicides used in the agricultural side of the co-culture. As highlighted earlier, the co-culture of fish and rice is

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[‡] A wellboat is a vessel that contains a tank or well for holding water (including sea water) into which live farmed fish may be taken and subsequently kept for a number of reasons, including transportation and the treatment of farmed fish in connection with health, parasites, pathogens or disease.

common in Egypt, where both thiobencard and dithiopyr are heavily used. Exposure (both chronic and acute) of Nile tilapia to these pesticides resulted in physiological changes to the fish. Long-term exposure to both agents produced severe degenerative changes in the parenchymatous organs, widespread necrosis and activation of melanocytes, suggesting that these two pesticides can combine to have cytotoxic effects on Nile tilapia.[83] Ultimately, fish or shellfish can be exposed to many pesticides not directly applied to mitigate the effects of various pests on the actual aquaculture product. In addition, there is the risk of exposure to a range of persistent organic pollutants (POPs), including polychlorinated biphenyls (PCBs) and polybrominated diphenyl ethers (PBDEs).

In attempting to remove 'nuisance species' there is a risk of impacting on the cultured product. A piscicide approved in the USA is Antimycin A, a cellular respiration inhibitor. Antimycin is particularly toxic to scaled fish, is less toxic to channel catfish (*Ictalurus punctatus*), and has low toxicity to other aquatic organisms. Juvenile life-stages are more susceptible to Antimycin A than are adult fish.

There is currently a need to use both antifoulants and disinfectants. However, both can present issues for non-target organisms. In the case of copper-based net coatings, the main antifoulants used in marine salmonid operations, species vulnerable to copper can be impacted and the ecological balance can change. High concentrations of copper can inhibit growth, reduce photosynthesis and decrease enzyme activity. The lethal concentration required to kill 50% of the population (LC_{50}) for copper varies from 5 to 100 000 $\mu g\ L^{-1}$.[70] In terms of the organic antifoulants, dichlofluanid shows embryotoxicity in the sea urchin *Glyptocidaris crenularis*, which is found off the coast of Japan. Diuron reduces the chlorophyll *a* levels in phytoplankton and is very toxic against the reproduction of the green freshwater alga *Scenedesmus vacuolatus*. Disinfectant formulations contain surfactants. Some of these compounds are known to be endocrine disruptors and, accordingly, the surfactants in disinfectant formulations should be clearly identified.[73] Negative impacts of the disinfectants themselves are recognised. Ozone residues are highly toxic, as is free iodine, the latter causing irritation of the skin and mucous membranes of fish. The use of formalin can also cause unwanted effects such as inhibition of growth and mortality of phytoplankton.[84] Such impacts point to the need for judicious use of disinfectants in the aquaculture industry.

Disinfectants, pesticides and antifoulants are all part of the aquaculture process. The need to make high-quality protein available requires that there is continued development of mariculture and inland aquaculture. Although chemical residues in the cultured product are often less than maximum residue limits (Table 10) or below limits of detection,[85–87] chemical resistance and impact on non-target organisms mean that alternative compounds are required. However, the use of synthetic or natural products which exhibit toxicity and thus limit the impact of a pest or fouling organism should not be automatic, and alternatives to chemicals should be sought.

Table 10 Maximum residues limits (MRLs) for assessing compliance with European Commission Regulation No 37/2010 on pharmacologically active substances and their classification regarding maximum residues in foodstuff of animal origin.[86]

Chemical	Maximum residue limit (ng g^{-1} wet weight)
Sea lice treatments	
Ivermectin	0.4[a]
Emamectin benzoate	100
Cypermethrin	50
Deltramethrin	10
Teflubenzuron	500
Diflubenzuron	1000
Antifungal/antiprotozoal agent	
Malachite Green	1.0[a]

[a] Decision Limit. European Commission Regulation (EU) No 37/2010 (Table 1) and Directive 2008/97/EC: Substance banned and should not be detected.

5 Strategies to Reduce Chemical Usage

5.1 Testing the Products

Although not a strategy that will reduce chemical usage, assessing edible products for the absence (or otherwise) of contaminants does give some assurance that the product is safe to eat, even though at some stage in the process pesticides have been used. The European Union (EU) is the world's largest market for imported seafood.[88] Countries exporting to the EU are required to guarantee that monitoring is undertaken to provide assurance that unacceptable residues above certain limits are not present. In addition, EU countries conduct non-statutory sampling of imports based on experience, risk analysis and intelligence. Within the UK, there is a statutory monitoring programme, undertaken by the UK Veterinary Medicines Directorate, covering UK salmon and trout production. In 2015 this included the analysis of 83 samples for avermectins. Although one sample was found to be over the reference point, further examination found that the sample was taken during a treatment period and was not valid in the context of residue testing.[89]

5.2 Changes to Husbandry

Advances in nutrition and related sciences offer substantial prospects for improving the efficiency and sustainability of aquaculture. At the same time, avoidance of stress on the fish is probably the most effective means of avoiding disease. Thus, maintenance of optimal oxygen levels, stocking densities, feed and water quality are essential. Site placement of cages in mariculture is crucial, as is understanding the possible interactions between fish farms in a given geographic location (see Section 5.3). Across inland aquaculture and mariculture there are varying changes that can be introduced to the production process that ultimately lead to the improved availability of a good protein source without recourse to pesticides. As an example, in upland areas of Vietnam the production of carp and tilapia in freshwater is crucial in supplying animal protein to the Vietnamese population. Using a local, traditional pond-management system, yields were low and mortality due to unknown pathogens and/or exogenic factors was high. The aquaculture process was part of an integrated agriculture-aquaculture system, with farmers using weeds (*e.g.* barnyard grass (*Echinochloa crusgalli*)), aquatic plants and by-products from the paddy fields as fish feed, while other plant-based feed included leaves from banana, cassava and maize, all of which are suitable for the grass carp. Animal-derived pond inputs include manure such as buffalo dung, although this tends to be a poor source of nitrogen, requiring significant quantities to be applied to reach the recommended rate of 4 kg N ha^{-1} day^{-1}. Appropriate developments in the husbandry included moving from grass carp to the common carp and using a culture system where natural food from the pond supplies sufficient protein and micro-nutrients; this requires careful control of water exchange so as to avoid washing out nutrients and thus requires a decoupling of the pond from the irrigation systems. Digging canals around the pond permits the capture of runoff water from the upland areas, while the application of lime and fertilisers are further improvements. Other developments include the complete draining of the pond between production cycles, the removal of sediment and indigestible feed (*e.g.* bark) so as to reduce oxygen consumption, and the regular use of pellet feeding. It is important to use feeds which help give the highest level of profit to the resource-poor farmers. In addition, lowering the turbidity of the water improves primary production. Finally, improving basic hygiene lowered the risk of mass mortalities from grass carp disease, while daily record-keeping enabled an economic analysis of the pond aquaculture process and an estimation of basic-feed conversions to be made.[90]

Stressed fish, poor husbandry and environmental conditions can all lead to, or exacerbate, a disease state. Being able to assess the various risk factors and using this assessment as part of the control procedure in respect of limiting a disease outbreak is being investigated. In Mexico, a semi-quantitative risk assessment model has been developed using risks known to be associated with an outbreak of white-spot disease in shrimps. The risk factors considered were the time of fallowing within a farm's region, health quality of the larvae, an estimate of the viral load and viral detection in wild hosts, pond water temperature, length of fallowing period, vector control at the water intake and stocking density. Twenty-one weighted factors were determined, which allowed the derivation of a low, medium or high risk categorisation.[91] The reliability of the data is of fundamental importance in such models, but this approach can aid in decision-making and ultimately contribute to a reduced need for the application of pesticides.

With the continuing issue of sea lice impacting on the Atlantic salmon aquaculture industry, considerations are being given to removing the host from the potential infective pressure. Sea lice are natural parasites which exist in the coastal waters that are used for rearing the Atlantic salmon.

Concepts being evaluated include land-based tank production and a form of tank production that remains in the sea to reduce the costs of pumping seawater.

Production could separate the host and parasite. In Scotland, onshore production is not new but it has never been a substantial aspect of salmon aquaculture and is currently focused on smolt production. It can be used for larger marine salmon, but such an approach is currently not economically viable. If made economically viable, this has the advantage of not limiting the farms to a specific geographical location; in the case of Scotland, salmon aquaculture does not take place on the east coast, but onshore facilities could extend the current west coast and Northern Isles focus to include all coastal areas.

5.3 *Minimising Infection Pressure by Cooperation Between Farms within a Geographically Connected Area*

Mariculture takes place in a mobile environment. Fish are moved between sites, both production fish and cleaner fish. Equipment, including wellboats, moves between sites. This can result in the movement of parasites, viruses and bacteria between farms and the associated spread of disease. For the sea louse (*L. salmonis*), interconnectivity between farms is now recognised as a source of infection.[92,93] The development of management areas can be used for the purpose of disease management, the control of sea lice, or indeed for other operational factors.[94] This reduces the use of chemicals because the farming cycle, including fallowing, can be coordinated within the area covered by the agreement, as can the time of treatment. Furthermore, coordination reduces the infection pressure from farms which are connected through the local hydrographic conditions, again limiting the requirement to administer medications. The optimal boundaries for management areas are not readily defined. Accordingly, biophysical sea lice dispersal models have been developed, including one for Loch Linnhe, one of the largest fjords in Scotland, with the objective of establishing more-effective management areas.[93,95] Modelling has shown that the median distance travelled by louse particles in the Loch Linnhe system is 6.1 km from the release site, with <2.5% transported beyond 15 km.[95] Consequently, infection levels are controlled by operating sites within distinct geographical areas where chemical treatment and fallowing of sites are coordinated.

Following an outbreak of infectious salmon anaemia (ISA; Table 4) in Scotland in 1998–99, greater consideration has been given to management of the Scottish industry at a scale larger than a single farm, since horizontal (site-to-site) transmission of the virus through the movement of fish and equipment poses the greatest risk of spreading the infection. A Code of Practice[96] was published outlining fish movements, disinfection stages, the reduction of risks from operational processes such as diving, the use of workboats or wellboats, harvesting and processing. It also outlines the principles of

Management Agreements, which are based on fundamental aspects of the oceanographic conditions found in Scottish waters. Management and operation of a fish farm in accordance with the agreement or (as the case may be) statement is now incorporated into Scottish Law through the Aquaculture and Fisheries (Scotland) Act 2013.[97] It has recently been shown[95] that the disease management areas created for infectious salmon anaemia may also have properties appropriate to salmon lice management in Scottish coastal waters.

5.4 Bioremediation

Although some pesticides degrade through exposure to sunlight, are lost as a result of volatilisation or can be physically removed by either dredging or dry excavation, there is the option of bioremediation, *i.e.* the use of living microorganisms to remove or detoxify pollutants.[64] Bacteria, fungi and yeasts can all be used to degrade pollutants and hazardous substances in soil and water, the products being non-toxic or less toxic than the initial substance. Plants and algae can also be used; in such cases, the process is termed phytoremediation. An example is the possible use of duckweed (*Lemna minor*) for the removal of flazasulfuron[98] ($C_{13}H_{12}F_3N_5O_5S$; a sulfonylurea herbicide that inhibits plant amino acid synthesis).

The use of bioremediation in wider aquaculture-waste management has the potential to limit disease as well as improve the aquaculture process.[99] However, as with the bioremediation of pesticides, there is a need for further research. This could lead to such techniques being a fundamental component of integrated aquaculture management.

5.5 Using Natural Compounds which are Environmentally Benign

As with any compound used as a biocide, there is a risk to non-target organisms, and antifoulants are no exception (see Section 4). However, more recently, natural antifoulants have been sought. These include the marine terpenoid elatol, originally isolated from the red algae *Laurencia elata* (Figure 9).[100] Although this was isolated in 1974, the total synthesis of this molecule was only achieved in 2008. Many marine natural products which may have antifouling activity have been discovered in the first decade of this century. However, such compounds have to be shown to be environmentally benign and be available in sufficient quantities to make a product viable. A challenge perhaps for the next two decades of this century.

5.6 Improving the Host's Resistance to Disease

The use of vaccines is being investigated with respect to providing protection to salmon, in intensive aquaculture, against sea lice.[53,101] In addition, immunostimulants are being given some attention as a method of disease

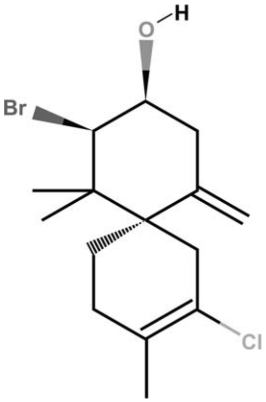

Figure 9 Elatol (4-bromo-10-chloro-5,5,9-trimethyl-1-methylidenespiro[5.5]undec-9-en-3-ol, $C_{15}H_{22}BrClO$), a possible natural marine antifoulant originally isolated from the red alga *Laurencia elata*.[100]

control in aquaculture.[102] Immunostimulants are a range of compounds, some natural and some synthetic, which enhance the non-specific cellular and humoral (or antibody) defence mechanisms in animals. Amongst them are levamisole (a synthetic phenylimidazolthiazole – a heterocyclic molecule containing sulfur and nitrogen; marketed as Ergamisol), *beta*-glucans (microbial derivatives) and chitosan (polysaccharide). Immunostimulants tend to operate by facilitating the functioning of phagocytic cells as well as stimulating the natural killer cells, complement system (part of the immune system), lysozyme activity and antibody response of the cultured species, leading to enhanced protection against infectious diseases.[103] Some immunostimulants have been found to elicit a degree of protection against *Aeromonas hydrophila* (which causes significant losses in farm-raised catfish), *Vibrio anguillarum* (causative agent of vibriosis) and *Aeromonas salmonicida* (causative organism in furunculosis; Table 4). Glucans are some of the most popular immunostimulants used in aquaculture[104] and have been shown to induce non-specific defence activity in Atlantic salmon, European sea bass (*Dicentrarchus labrax*), yellow croaker (*Pseudosciaena crocea*), common carp (*Cyprinus carpio*), and giant tiger shrimp (*Penaeus monodon*). *Beta*-Glucan has also stimulated non-specific immunity in artificially immunocompromised rohu (*Labeo rohita* Hamilton) and Asian catfish (*Clarias batrachus*). There is some way to go in terms of implementing the use of such compounds as a regular part of an integrated management programme. However, these compounds add to the range of options that should permit both mariculture and inland aquaculture to develop further.

5.7 Natural Predators

Given the ongoing substantial losses to the Atlantic salmon aquaculture industry due to sea lice, the use of ballan wrasse (*Labrus bergylta*) as a cleaner-fish is becoming part of the integrated management of the parasite. 'Cleaner-fish', where one fish removes dead skin and/or ectoparasites from another, exist in freshwater, brackish water and marine environments.[105] This symbiotic relationship is exemplified in nature by the bluestreak cleaner wrasse (*Labroides dimidiatus*) which removes dead skin and external parasites from the potato cod (*Epinephelus tukula*).

A number of wrasse are native to the waters around the UK, including the largest of the UK wrasse, the ballan wrasse, which can be found across the north-east Atlantic, from Norway to southern Europe. They can be found at depths from 1 to 50 m amongst rocks, seaweeds and reefs. They feed on a range of molluscs, including mussels, cockles, limpets and winkles, as well as crustaceans and small fish. Their more colourful relative, the cuckoo wrasse (*Labrus mixus*), can also be found around the UK but, as with the ballan wrasse, is more common in waters to the south and west of the UK.

The use of cleaner fish to control sea lice is not new; it was developed in the late 1980s.[47] Today, ballan wrasse, goldsinny wrasse (*Ctenolabrus rupestris*) and corkwing wrasse (*Symphodus melops* (L.)) are the species most frequently used in Norway. Currently, wild-caught local species predominate in wrasse use in aquaculture. This places a burden on the wild, un-assessed wrasse populations. Consequently, there is a need to actively pursue the cultivation of ballan wrasse since, at 3–5% of the salmon stocking level, Norway requires an estimated 15 million of the lice-eating wrasse to limit sea lice. Knowledge of the biology and life-cycle of wrasse is limited. Breeding wrasse is, however, being intensively studied. A recently initiated Scottish project, funded by the Scottish Aquaculture Innovation Centre (SAIC), is examining egg and larval productivity, larval juvenile nutritional requirements, health and management of the cleaner-fish and the optimisation of cleaner-fish welfare in commercial cages. A challenge is ensuring that the wrasse prey on the lice and not on any other food source. As such, keeping the nets and cages clear of molluscs and algal growth is essential. Labour-intensive hand-picking can be replaced with antifoulants, but this is itself not without risk (see Section 3.4). That said, it has become clear that supplementary feeding of the wrasse is required. The use of an appropriate food source does not appear to affect delousing efficiency.[106]

Managing the welfare, including any diseases in the cleaner-fish, is critical. Wrasse require in-cage shelter for protection when at rest and from the tides and currents. To this end, growth, stress and fin damage have been used to assess welfare of cleaner-fish.[107]

In Europe, the lumpfish (*Cyclopterus lumpus*) is being farmed to work as cleaner-fish, while in Canada the lumpfish and the cunner (*Tautogolabrus adspersus*), a member of the wrasse family, are being trialled as cleaner-fish. In Europe, the lumpfish are used at a density of 10%, which is higher than for wrasse, but this does provide a possible alternative to the wrasse. The use of cleaner-fish brings its own potential disease issues, since a parasite of the cunner, *Cryptocotyle linguai*, can cause untreatable black-spot disease in both the cunner and salmon. Furthermore, the high stocking density of the cleaner-fish may be problematic if there are escapes, since escapees may impact on local fish and crustacean populations through predation on their eggs and larvae.

The use of cleaner-shrimp (*Lysmata amboinensis*) in aquaculture is being investigated. An advantage of using a crustacean rather than a fish is that there is a natural, evolutionary distance between the crustacean and fish. This means that the chance of disease transferring from the cleaner-shrimp to the fish being cultured is reduced. Furthermore, this particular cleaner-shrimp also consumes off-host life-stages of parasites that are of concern to aquaculture.[108]

Clearly there is some way to go in terms of optimising the use of cleaner-fish. However, as part of an integrated pest-management strategy, the use of cleaner-fish is likely to be a key component in the Atlantic salmon aquaculture industry.

6 Conclusions

The production of high quality protein through both mariculture and inland aquaculture continues to increase in importance. The application of intensive aquaculture has exacerbated some of the issues associated with both mariculture and inland aquaculture. Ultimately, disease problems are best overcome through effective management practices, including management of stock, soil, water, nutrition and environment. However, there is no single solution to limiting disease and thus the requirement for chemicals is likely to continue. That said, an increasing number of alternative processes and methodologies are becoming available such that there can be considerable optimism in respect of the long-term future of global aquaculture.

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Horticulture

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ABSTRACT

Horticultural crops are extremely diverse and from a wide range of plant families. They may be grown as annuals, biennials or perennials, either outdoors or under protection in glasshouses or polytunnels. Altogether horticultural crops are likely to be restricted to a relatively small footprint in comparison with arable crops and with grassland supporting livestock. However, per area of crop grown, the use of fertilisers and pesticides may be relatively high in some cases. Most horticultural crops are grown to be consumed or used fresh, rather than as processed products, and the appearance and quality of the produce is a key determinant of marketable yield. The requirement for produce that is completely free from blemishes may disproportionately affect the amounts of pesticide applied. This chapter summarises approaches used in the production of horticultural crops, focusing on the use of agricultural chemicals and potential approaches to reducing their environmental impact. The chapter includes two case studies which consider carrot production in the UK and Integrated Pest and Disease Management in apple orchards, respectively.

1 Introduction

Globally, horticultural crops are extremely diverse and from a wide range of plant families. They include fruit, vegetables and ornamentals grown to

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provide cut flowers, pot, garden or landscaping plants. These crops may be grown as annuals, biennials or perennials. Perennial crops include tree fruit, bush fruit, asparagus, ornamental trees and shrubs and bulbs. Annual crops include vegetables and salads grown outdoors, outdoor flowers, and edible and ornamental plants grown under protection, in glasshouses and polytunnels.

Altogether horticultural crops are likely to be restricted to a relatively small footprint in comparison with arable crops and with grassland supporting livestock. For example, in the UK, 174 000 ha are devoted to horticulture compared with 4 522 000 ha for arable crops and 9 719 000 ha permanent grassland.[1] Potato is usually considered to be an arable crop in the UK. For protected crops grown in glasshouses, the footprint in most countries is very small (2516 ha in the UK).[1] The use of less permanent structures, such as polythene tunnels, is widespread and increasing and is often termed 'semi-protection'. For example, polythene tunnels are used intensively in certain Mediterranean countries such as Spain[2] and are being used increasingly in northern Europe for the production of vegetables, fruit and ornamental plants, *e.g.* for the production of raspberry crops (Figure 1).[3] According to a study in 2011, within Europe, Spain has the largest area of greenhouses at over 50 000 ha, whereas globally China has the largest area by far, at over 2 500 000 ha.[4]

Most horticultural crops are grown to be consumed or used fresh, rather than as processed products and the appearance and quality of the produce is a key determinant of marketable yield. Aspects of quality include uniformity in size and shape, freedom from blemishes and contaminants, together with extended shelf life and other characteristics such as colour and taste.

Figure 1 Production of raspberry in polythene tunnels (polytunnels).

2 Overview

2.1 Fertilisers

Fertilisers are used in the production of most horticultural crops. In most cases these will be applied directly to the growing medium, which is usually soil, or compost in the case of crops such as ornamentals grown in containers. Although the situation may have changed since then, according to data summarised in 1997, banana, citrus, vegetables and potato were in the top five 'crops' globally in terms of fertiliser application rates.[5] This has led to some significant disadvantages in many cases. For example, leaching of nutrients from fertilisers and contamination of drinking water with nitrates close to citrus production areas in Florida has been a serious concern.[6]

Recovery of fertilisers by plants is generally poor and probably 50% or more of applied nutrients are leached out of the soil profile or beyond rooting depth.[7] The biggest environmental concern is the loss of nitrates and phosphates since they contribute to eutrophication of surface and ground waters. The evidence that nitrates and phosphates resulting from intensive agriculture (including horticulture) can cause environmental pollution is overwhelming.[8] Also important is the concentration of nitrates in drinking water, which is regulated in some countries to protect human health. Nitrites and nitrates are considered harmful to humans and a considerable proportion of the daily intake of nitrates in foodstuffs is related to consumption of vegetables and salads such as spinach and lettuce.[9] Although arable crops contribute considerably to nitrate leaching as a result of the large area occupied, horticultural crops, which sometimes grow only in a small area, can leave considerable residues, which are at risk of leaching large amounts of nitrogen.[10,11] Soil type influences the amount of leaching and sandy soils are of greater concern since they have a very low capacity to retain nutrients.[12]

In terms of glasshouse production, the small footprint means that the release of chemicals to the environment may be limited, depending on how plant material and growing media are disposed of. However, in China the land area used for greenhouse vegetable production has increased rapidly and the amount of nitrogen fertiliser used is typically much higher than that used for cereal crops, leading to eutrophication of surface water and loss to ground and surface water by leaching and runoff.[13] Nutrient losses from greenhouse production of tomato in Poland have also been considered to be high.[14] Some glasshouse crops such as tomato are grown using systems where the plants are grown in a 'soil-free' medium and plants are fed on a solution which contains mineral nutrients. Where possible, nutrient solutions are re-circulated and re-used to avoid nutrient losses and to protect the environment. However, there need to be methods for maintaining the concentration of all elements within narrow limits and for preventing the spread of disease. In some countries there are restrictions on the discharge of waste water due to the risk of pollution by nutrients and also by pesticides.[15]

Synthetic fertilisers are used in the production of most field vegetable crops with the exception of crops grown organically. Growers may apply large amounts of nitrogen fertiliser (>200 kg N ha^{-1}) to maximise crop yield, but such large amounts can lead to nitrate loss through denitrification, volatilisation, leaching, runoff and erosion.[16] In terms of reducing environmental impact, the focus has often been on minimising nitrogen loss during the growing season, but nitrogen loss may also be very high once the crop is harvested, particularly in crops such as brassicas which have low nitrogen harvest indices, low C : N ratios, and where there are considerable amounts of nitrogen in crop residues.[16] Management approaches include improving the nitrogen use efficiency of the crop and reducing leaching during the winter. These will be influenced by crop variety and cultural practices, including calculation of fertiliser rates using an approved recommendation system, and allowing for soil mineral nitrogen and any manures applied.[10] One approach may be to amend the soil with various organic carbon materials to reduce nitrogen loss.[16]

Alternatives to the use of synthetic fertilisers include the application of animal manures, composted plant material, or the use of fertility-building crops, often legumes such as clover. In organic production systems all of these approaches are used.[17] However, their use does not obviate the need for careful management of nitrate levels. In the case of the application of organic manures there may be potential issues with them being a source of human pathogens such as *Escherichia coli.*[18]

2.2 Soil Health

Many vegetable producers are specialists and may produce crops from one plant family only, *e.g.* brassicas. Crop rotation can be critical for the avoidance of certain pests and pathogens; for example, carrot fly (*Psila rosae*) on carrot or clubroot (*Plasmodiophora brassicae*) in brassicaceous crops. As a consequence, many field vegetable crops are grown as part of an arable rotation and may be grown on land rented from arable farmers. This enables vegetable growers to achieve a rotation without the need to grow alternative crops themselves. However, it does reduce the incentive to invest in soil management practices that will benefit the field over the longer term. There are certain situations where conventional rotations are not employed and this applies to the production of certain brassica crops. This may, for example, be practised where the soil pH is high, which reduces the risk of clubroot infection. Crop rotation is a fundamental principle that growers practising organic production or Integrated Pest, Disease and Weed Management must adhere to (*e.g.* Integrated Production Guidelines issued by the International Organisation for Biological Control, West Palaearctic Regional Section).

Many of the pathogens and pests of crops found in soil can be controlled with pesticides. However, approaches to controlling them, including the application of chemicals, are likely to affect the entire soil biota and may have adverse impacts on soil health.[19] Organic producers in particular have access to a very small number of products with efficacy against soil pests and pathogens. Research is being undertaken to seek non-pesticidal approaches to pest and disease control,[20] including the use of biofumigants.[21] These approaches may, of course, also affect the wider soil biota adversely.

Minimal tillage is often promoted as an approach to maintaining soil structure and reducing the risk of erosion and leaching. Whilst this approach can be used successfully on some arable crops it is less easy to use in horticultural production systems where a well-prepared seed bed can be key to uniform and rapid crop establishment. Crop uniformity is in most instances a very desirable attribute for annual horticultural crops, ensuring that all plants within a field are ready to harvest at approximately the same time, minimising the number of passes that have to be made. With perennial crops such as asparagus and fruit, soil cultivation is likely to be more restricted.

The harvesting of many horticultural crops requires the use of specialised equipment drawn by tractors. The harvest date of most crops is time-critical and so it is impossible to delay harvest until conditions are dry. Thus harvesting can lead to significant amounts of damage to soil structure through compaction and to soil erosion, with consequent impacts on runoff if conditions are wet, and this can apply particularly to crops harvested in the autumn and winter, such as brassicas and carrot.

2.3 Pests, Diseases and Weeds

2.3.1 The Problem. Levels of pest and disease control generally need to be very high and synthetic chemical pesticide treatments are likely to be applied; exceptions are crops grown organically, which usually make up a relatively small proportion of the market, and some protected crops, particularly tomato, where biological control is used extensively,[22] either in response to pesticide resistance or because the crop is pollinated by introduced bumblebees,[23] and pesticide usage needs to be kept to a minimum.

The requirement for produce that is completely free from blemishes may disproportionately affect the amounts of pesticide applied. For example, Pimentel *et al.*[24] estimated that 10 to 20% of additional insecticide is used on fruits and vegetables overall to reduce the incidence of insects in foods and/or to meet the required “cosmetic appearance” standards. In addition to legal requirements, there can be additional retailer requirements with regard to pesticide residues in marketed produce[25] and some retailers have a longer-term ambition for there to be no detectable residues in produce. This may be achievable for some crops through a change in management practices rather than a complete cessation in pesticide use.[3]

The majority of pests of horticultural crops are invertebrates, particularly insects but also mites. In the main, infestations by invertebrates are managed with pesticides. However, for certain species there are alternative approaches, including host plant resistance, cultural control (including rotation, intercropping and companion planting), physical barriers, use of synthetic pheromones to disrupt the mating behaviour of pest insects, and biological control, all of which, together with careful use of pesticides, contribute to Integrated Pest Management[26] strategies. Molluscs (slugs and snails) are worthy of mention since their control relies on pesticides in the main and at least one of the pesticides used currently, metaldehyde, can be a major contaminant of water.[27] Slugs and snails are pests of certain field vegetable and fruit crops and they also infest a range of arable crops, which may cover a significantly larger area.

Horticultural crops may be infected by a range of pathogens including fungi and viruses. Management of pathogens relies mainly on pesticides to control either the pathogens or their vectors, which for viruses may be aphids or other invertebrate species. However, as with invertebrate pests, some alternative approaches are available to control certain pathogens, including host plant resistance and biological control, which can contribute to Integrated Disease Management strategies.

It is probably true that, in general, biological control of pests and pathogens is 'easier' to implement in protected cropping systems than outdoors. This is likely to be for several reasons. For example, there is a degree of environmental control in protected cropping systems; once 'released', mobile biological control agents are confined and are unable to disperse, and protected crops are usually a relatively simple system with few other prey species available, so hungry predators are more likely to feed on the target pest.

Many horticultural crops are sensitive to competition from weed species and, where they are available, herbicides are used for weed control. In the absence of an effective herbicide, and in organic production systems, growers may use cultural or physical methods of weed control.[28] Again there are opportunities for the development of Integrated Weed Management strategies.

2.3.2 Pesticides. In 1995 Pimentel[29] concluded that less than 0.1% of the pesticides applied may reach their target pests. This was partly due to 'poor' application methods and partly because of the tiny amount of pesticide consumed or acquired by the pest. Both pesticide chemistry and application technology have improved since 1995 but a considerable proportion of pesticides are still applied to crop foliage or to the soil as sprays, and in many cases this continues to be a relatively untargeted method of application, with consequences for effective pest control and survival of non-target species. However, new approaches are being developed all the time and, for example, equipment is now available to apply herbicides to specific locations within a field. One such system developed in the UK uses video cameras and image analysis software to locate crop rows and/or individual plants. This technology enables the application of non-selective herbicides such as glyphosate between crop rows or 'spot' sprays of herbicide to clumps of weeds.

Over the years there has been much emphasis on the development and use of pesticides that are selective for certain pest species. This is a result of the chemical structure and mode of action of the pesticide and the physiological and biochemical attributes of organisms;[30] for example, the carbamate pirimicarb is a relatively selective compound, being effective against sucking pests such as aphids, but having considerably less impact on insects from other taxa.

There has also been consideration of ‘ecological selectivity’, which is the careful use of pesticides (which are often broad spectrum), based on timing of applications, dose, formulation and placement. For example, there has been considerable emphasis over the years on accurate timing of pesticide applications, evidenced by the considerable amounts of research on monitoring and forecasting systems for pests and pathogens, and their subsequent uptake by farmers and growers (see the case studies at the end of this chapter).

There are a number of approaches that can be used to minimise and localise the dose of pesticide applied, which reduce the total amount applied per unit area and its consequent impact on the environment. One such example is the use of the organophosphorus insecticide chlorpyrifos in the UK to control the cabbage root fly (*Delia radicum*), which is a pest of brassicaceous crops such as cabbage and cauliflower. Table 1 gives examples of the different amounts of chlorpyrifos applied to vegetable brassicas per hectare using four methods of application (most of which are no longer available in the UK). These application methods have been ranked in terms of their efficacy for cabbage root fly control based on data from a range of insecticide trials undertaken at the University of Warwick over the last 20 years. The module drench applied immediately before the crop is transplanted is the most effective treatment and uses an application rate per hectare that

Table 1 Amounts of chlorpyrifos typically applied per hectare using a seed treatment, a pre-planting module drench, a field spray and a field drench (*e.g.* for 30 000 plants ha^{-1}). The ranking of efficacy (Rank 1 is most efficacious) for control of cabbage root fly is based on experience from experimental work undertaken at the University of Warwick. *N.b.* a.i. stands for ‘active ingredient’.

Treatment	Rate applied	Amount of chlorpyrifos applied per hectare (g)	Ratio compared to seed treatment	Ranking of efficacy for control of cabbage root fly
Seed	9.6 g a.i. per 100 000 seeds	2.9	1	2
Module drench	4.5 g a.i. per 1000 plants	135	47	1
Spray	0.9 kg a.i. ha^{-1} (2 applications allowed per crop)	900	310	4
Field drench	31.5 g a.i./1000 plants (based on per plant application)	945	325	3

is <15% of the rate used for a field drench, which is often a less effective treatment. The seed treatment uses approximately 2% of the active ingredient applied with the module drench treatment and in most cases provides an adequate level of control.

The range of pesticides available to commercial growers changes over time. The discovery and registration of new pesticides requires a considerable amount of investment by agrochemical companies. Whilst a number of new modes of action for control of insects have been discovered in recent times and there are also some new modes of action for plant pathogens, no new mode of action for weed control has come to the market for some time.[31] Within Europe, European Union policy is directed towards significant reductions in pesticide use over time and current European Commission Directives have led to the loss of a number of crop protection products. The continuing review process could result in de-registration of many more pesticides and, for example, weed control in carrots, onions and other vegetable crops is becoming difficult.[32]

2.3.3 Pesticide Resistance. There are well-documented examples of development of pesticide resistance in the pests and pathogens of horticultural crops as a result of the selection pressure applied by repeated use of pesticides containing active ingredients with a single mode of action (*e.g.* pyrethroids). This includes the peach-potato aphid (*Myzus persicae*), which is a generalist species and is a pest of a wide range of horticultural and arable crops including brassicas, lettuce, potato, oil seed rape, sugar beet and pepper throughout the world. Over time this species has become resistant to organophosphorus, carbamate and pyrethroid insecticides and resistance to neonicotinoid insecticides has now occurred, though only in a small number of locations to date.[33] The diamond-back moth (*Plutella xylostella*), which is a globally-important pest of brassica crops, has also shown resistance to a range of insecticide groups around the world.[34] Over the last decade or so, incidences of pest insect resistance to pyrethroid insecticides in the UK have increased to include pests of horticultural (and arable) crops such as *Thrips tabaci*, *Meligethes aeneus* and *Aleyrodes proletella*, undoubtedly reflecting the widespread use of pyrethroid insecticides on both horticultural and, possibly more importantly, arable crops.[35,36] Resistance to fungicides is also significant; for example, to *Botrytis cinerea*, which is a pathogen of several fruit, vegetable and ornamental crops.[37] Weed species resistant to herbicides are prevalent globally, with 372 unique herbicide-resistant biotypes being confirmed in 2012.[38] Approaches to resistance management include alternation of modes of action and the use of other methods of control as part of an Integrated Weed Management strategy.

2.3.4 Non-target Species. Pollination by bees and other insects is very important for maximising the yield and quality of a range of horticultural crops.[39] There is evidence that many species of pollinators are in decline in certain parts of the world, both in their abundance and their distribution.[40] There are many potential causes of the decline in beneficial arthropods, including pollinators, and the use of agricultural chemicals, particularly insecticides, is certainly implicated as these may have both lethal and sub-lethal effects.[41] In recent years there has been concern that neonicotinoid insecticides, in particular through their use in seed treatments, are at least partially responsible for the decline in the abundance of bees.[40] This relates particularly to flowering crops such as oil seed rape. Whilst the detail of this debate is beyond the scope of this chapter, it is worth noting that seed treatments with neonicotinoid insecticides are also used in the production of field vegetable and salad crops in certain parts of the world and are especially effective for the control of sucking pests such as aphids. They present a method of applying small amounts of insecticide in a targeted way, reducing environmental contamination that might arise from foliar sprays. As these crops (*e.g.* carrot, brassicas, lettuce) do not flower, they present no risk to pollinating insects through uptake of pesticide through feeding.

The pests, pathogens and weeds that colonise horticultural crops are subject to natural control by animals and microorganisms, including predatory insects, parasitoids, viruses, bacteria and fungal pathogens. Since in outdoor crops the levels of control achieved by these natural control agents are rarely sufficient to reach the quality standards demanded by the multiple retailers, with the exception of organic production, synthetic chemical pesticide treatments are likely to be applied. Some of these treatments have direct effects on the beneficial organisms whilst with others there will be no, or only indirect, effects.[41–43] Broad-spectrum insecticides such as pyrethroids can be especially detrimental to invertebrate natural enemies and can lead to resurgence of pest infestations.[44] In instances where biocontrol agents are used to control pest insects in horticultural crops it is important to ensure that any pesticide applications are compatible.[45]

A proportion of the natural enemies of insects are fungi and in some instances they can provide high levels of pest insect control; for example, through natural epizootics.[46] It is likely that some of the pesticides applied to control the fungal pathogens of crops affect these beneficial pathogens adversely.[47]

Effective management of weeds is critical for the production of all horticultural crops and some, particularly those with slow germination such as onion and carrot, are particularly sensitive to weed competition. The overall effect of herbicides is to reduce plant density and diversity within the cropped area and this has consequences in terms of loss of habitat and food resources for a number of beneficial species.[48] However, mechanical weeding of the area or another physical method of weed control such as flaming would have a similar effect, although would obviously not involve the use of chemical pesticides.

A considerable number of studies have been undertaken to determine the impact of pesticides on natural control agents and, whilst the data can be found in individual publications, they have also been summarised in databases; for example, in the database created and managed by the International Organisation for Biological Control, West Palaearctic Regional Section.

There are various approaches to reducing the impact of pesticides on non-target species that involve the use of selective pesticides and reducing the coincidence of non-target species with pesticide residues both temporally and spatially, in addition to seeking alternatives to the use of pesticides for crop protection. The carbamate insecticide pirimicarb has been used widely on horticultural crops because it is relatively selective for aphids in particular. However, most uses of this insecticide have now been withdrawn in the UK, following a European Food Safety Authority (EFSA) review of maximum residue levels (MRLs) during re-registration, and the permitted MRL for pirimicarb has been reduced on several crops, leading to its withdrawal.

2.4 Water Use and Water Quality

A study in the UK showed that most horticultural businesses have a high demand for water, either for irrigation, spraying or for washing and processing produce.[49] This study showed that the largest use of water was for irrigation of field crops, including field vegetables and potatoes. The protected and nursery crops sector also used a relatively large amount of water, despite its relatively small footprint. Obviously water use for irrigation in particular will be very dependent on climate and is likely to be substantially greater in warmer parts of the world.

Water use has implications for chemicals in the environment, mainly through the environmental impact of contaminated water released through runoff, leaching and the disposal of waste liquids (also see Chapter 2 in this book). There is a need to improve knowledge of the impacts of irrigation on diffuse pollution, including leaching of nitrate and phosphate.[50] Because nitrogen is highly mobile, good management practices for nitrogen fertiliser application can be linked to efficient use of water. For example, efficient water management in irrigated orchards results from the use of conservative micro-irrigation systems, from scheduling water applications to meet estimated crop demand and from reduction in evaporative loss from the soil through the use of mulches or sub-surface drip irrigation.[51] Application of nitrogen through irrigation systems (fertigation) can be used to improve management, by targeting the root zone with nitrogen at the time of nutrient demand.[51]

It is very difficult to remove the molluscicide metaldehyde from water and in the last 10 years or so high levels of metaldehyde have been detected in surface water in a number of catchments in the UK, which means that water companies are in danger of failing to comply with drinking water standards.[27] Whilst horticulture has a relatively small footprint in terms of land area, slugs are a major problem in some outdoor vegetable and salad crops. Water companies are developing a range of initiatives in collaboration with farmers and farming organisations that centre around finding alternative methods of slug control and using existing control methods in ways that reduce the risk of contamination. A major constraint is that slugs are most active in wet conditions, which are also likely to be the conditions that lead to increased leaching and runoff from crops.

3 Case Studies

Two case studies have been chosen to indicate some of the issues and potential solutions associated with the use of chemicals in horticulture. There is obviously an enormous range of potential examples from different crops and climates; these case studies focus on a vegetable crop and a fruit crop which are within the authors' areas of expertise.

3.1 Case Study 1: Carrot Production in the UK

3.1.1 Introduction. The UK produces over 700 000 tonnes of carrots each year from about 11 000 ha and the sales value of British carrots in 2016 is around £290 million.[52,53] Carrot crops are harvested almost all year round using land in different parts of the country and different techniques. Early season carrots are sown in the winter and very early spring and are protected from the cold with plastic or fleece covers (Figure 2). They are harvested from June until August. Carrots grown for bunching are sown in the open ground in spring and are harvested from August until the first frosts start to appear. Carrots that are overwintered under straw are sown in April until early June, and harvested from December to late May. Straw is applied in October–December to protect the carrots from the winter weather and keep them dark as they attempt to grow in the spring.[52]

Figure 2 Early season carrots protected from the cold with fleece covers.

Other apiaceous crops include parsnip and celery, which are grown on a smaller area (about 4000 ha).[53] The UK statistics for crop production often consider these three crops together.

3.1.2 Fertilisers. Almost all carrot production areas in the UK are within recognised Nitrate Vulnerable Zones. As a result, growers are advised that nitrogen should be applied in accordance with crop requirements and large single or excess applications are to be avoided. Carrot crops are particularly effective at taking up residual soil nitrogen and can play a valuable part in the reduction of nitrate losses from the soil. High-yielding root crops can take up large amounts of phosphate and potash. Carrot is also a root crop with low residual nitrogen, where the amount of crop residue is relatively small. Where straw is used to protect carrots and is subsequently incorporated into the soil, it contributes approximately 1 and 8 kg phosphate and potash, respectively, per tonne of straw, which growers should consider when calculating the phosphate and potash requirements of following crops.[54]

3.1.3 Weed Control. Carrot is a crop which grows slowly and can suffer considerable loss in yield from weed competition.[55] The 'best' land in the UK is used for a range of high-value crops such as carrot and potato and so carrot growers may also be required to control volunteer potatoes (potatoes left in the ground following harvest of a potato crop, which grow as a weed in subsequent years), as these are often grown in the same rotation. In the UK in 2013, herbicides were applied to 99 000 ha of the carrot, parsnip and celery crops grown in the UK, of which the most commonly used was Linuron (approximately one third of the treated area).[35] Crops received an average of 6 herbicide treatments. Peak times of herbicide application were May–July. Carrots are generally grown on soils prone to leaching; therefore, care must be taken that no herbicides appear as major pollutants of ground water.

There are concerns that Linuron may be withdrawn in the future, which may also be the case for Pendimethalin,[56] which was the second most-widely used herbicide in 2013. This is as a result of EU legislation, which means that active substances will not be approved or re-approved if they are classified as having certain properties, including being Endocrine Disruptors or Persistent Bio-Accumulative and Toxic.[56] A study undertaken to determine the impact of pesticide withdrawals in the UK[56] suggested that this would lead to a potential loss in yield from the carrot crop of 17% due to broad-leaved weeds, 10% due to grass weeds and 10% due to volunteer potatoes. However, it is always possible that a new herbicide will become available, although the rate of herbicide discovery is slow.[31] In addition, crop sprayers which use novel technologies to identify the position of crop rows can be used to apply non-selective herbicides such as glyphosate to the inter-row spaces.

Alternative approaches to the application of synthetic herbicides include mechanical weed control for removal of weeds from between rows. It would be virtually impossible to remove weeds within rows as the interplant spaces are small and uneven. Hand weeding is very expensive.

3.1.4 Pests. About 100 000 ha of carrot, parsnip and celery crops were treated with insecticides and nematicides in 2013.[35] Crops received 7 insecticide treatments on average. Carrot fly was the main reason for insecticide use (on 48% of occasions), followed by aphids (23%) and other pests (22%). Caterpillars accounted for 5% and nematodes for 2% of pesticide use. Pesticide use was dominated by pyrethroid insecticides, mainly for carrot fly control, followed by pirimicarb for aphid control. Use of pirimicarb on this crop has now been withdrawn following a European Food Safety Authority (EFSA) review of maximum residue levels (MRLs) during re-registration. The permitted MRL for pirimicarb has been reduced on several crops, including carrot, leading to its withdrawal.

The carrot fly (*Psila rosae*) is an important pest insect colonising carrot crops in temperate climates (northern Europe, North America). The larvae feed on the roots, often killing young plants. Damage to older plants consists of tunnelling in the roots, which severely affects quality and thereby marketability. The rate at which the carrot fly develops and completes a generation is dependent on temperature; in the UK, carrot flies complete two or three generations per year, depending on average temperatures.[57] At the moment it can be necessary to control the larvae resulting from the first two generations. The numbers of adult carrot flies in a crop can be monitored using orange-coloured sticky traps (Figure 3).

Figure 3 The numbers of adult carrot flies in a crop can be monitored using orange-coloured sticky traps.

During the latter part of the 20th century carrot fly was controlled with organophosphorus and carbamate insecticides in the UK. However, in 1995, as a result of research on residue levels in individual carrot roots, a limit of three organophosphorus treatments per crop was imposed by regulators for soils with up to 10% organic matter and four treatments for soils with higher organic matter content.[58] At about the same time, off-label approvals were granted for a seed treatment and foliar sprays using pyrethroid insecticides[58] and the foliar sprays, in particular, proved to be very effective. The industry moved away quite rapidly from using organophosphorus insecticides and has relied solely on pyrethroid insecticides for at least 15 years. This reliance on one group of insecticides could be potentially risky in terms of selection pressure for insecticide resistance but there is no evidence that this has occurred, at least in the UK. Newer modes of action, particularly those of the diamides, are now offering opportunities to expand the range of modes of action used. Pyrethroid insecticides are very likely to have an adverse effect on non-target invertebrate species within the crop. Their application close to watercourses is restricted by regulators because of their adverse impact on fish. About a third of the crop is grown from seed treated with insecticide to control carrot fly.

Carrot fly has been a major pest for many years and research on this pest has spanned several decades. This has led to an understanding of its biology and life-cycle and has indicated ways in which it might be managed to reduce the need for insecticide use. The basis of an effective management strategy is crop rotation but also isolation of new crops from established or recently harvested crops infested with carrot fly. Adult carrot flies are unable to fly great distances and so separation of new crops from 'old' crops by as little as 1 km can reduce the risk of colonisation considerably.[59] In addition, it is known that adult carrot flies are more abundant in sheltered locations and so growing crops in exposed locations may also reduce the risk. It is also possible to 'break' the life-cycle of carrot fly by sowing the first crop of carrots towards the end of the period when first generation flies are laying eggs.[57]

Commercial varieties of carrot show a range of susceptibilities to carrot fly damage, although none are completely resistant.[57] Research was undertaken in the UK in the last few decades to search for sources of resistance in cultivated carrot and wild relatives.[60] Breeding lines with increased levels of resistance were released subsequently to seed companies and in recent years interest in developing varieties with higher levels of resistance to carrot fly has taken advantage of new molecular breeding techniques. Studies have shown that partial resistance to carrot fly in carrot can reduce the effective dose of insecticide required to control this pest.[61]

When control of carrot fly became dependent mainly on foliar sprays of pyrethroids, research showed that these were effective only against the adult fly and therefore to be effective they had to be applied before the female flies laid eggs.[57] Thus a forecasting system to predict emergence and egg laying[62] became very useful to growers and is used currently in the UK. The majority of growers access pest forecast outputs, which use weather data generated by a small network of weather stations, from a website hosted by Syngenta. This enables growers to target insecticide applications and might in some cases give them the confidence to avoid insecticide applications in the periods when carrot fly is not about to lay eggs. A similar forecasting system has been developed in Germany.[63]

The other most-promising methods of control are to use physical barriers to exclude carrot fly from vulnerable crops.[57] This can be through the use of fine mesh netting, used widely on swede crops in the UK in the absence of an effective approved insecticide to control cabbage root fly. This method can be effective provided the covers are applied before the flies enter the crop, the edges of the covers sealed well and there are no tears in the covers. There are associated difficulties in terms of several other aspects of crop management since the covers reduce light levels, increase humidity/temperature and impede weed control. The carrot fly forecast[62] might be used to determine when it is safe to remove the covers to weed the crop. Use of covers also has implications for the environment as they impede the movement of other invertebrate species into the crop and, although they have a reasonably long life of several years, they must eventually be disposed of. More recently a number of research groups have investigated the possibility of erecting physical barriers (fences) around fields of carrot. The fences have usually been 1–2 m high with an outward facing overhang angled at 45° to 'trap' any insects attempting to move up and over the fence. Levels of control were not always good, but in one instance the fences appeared to exclude about 85% of the flies.[57] The fences have not been used successfully yet for control of carrot fly in commercial crops.

Aphids are contaminants, affecting plant growth, crop quality and yield if abundant. They may also transmit plant viruses. The main pest aphid of carrot in the UK is the willow-carrot aphid (*Cavariella aegopodii*) and large infestations may sometimes develop, distorting the foliage. Several viruses are known to affect commercial carrot crops in the UK and there is a strong link between the presence of virus, crop quality, and an overall reduction in crop yield.[64,65]

At present growers can manage aphid infestations and attempt to manage associated virus transmission through use of insecticide treatments. There is currently one neonicotinoid seed treatment (thiamethoxam) and this systemic insecticide provides very effective aphid control and has some effect on virus transmission for an, as yet, undefined period. This insecticide is implicated in concerns about the effect of neonicotinoid insecticides on bees and other pollinators, but in the case of carrot there is no route through which the bees can access this insecticide, as the crops do not flower prior to harvest. In many years this treatment may be sufficient for crops that are infested soon after sowing. At present the foliar sprays available are relatively ineffective and the pyrethroids in particular may be having adverse effects on naturally occurring parasitoids, which often move into the crop quite rapidly and suppress the aphid infestation. Other more-effective insecticides are approved on other crops and hopefully will become available to carrot growers quite soon. As yet there are no effective methods of biological control and varieties with resistance to aphids and/or viruses are not available.

In the UK the only other important pest insect is the larva of the noctuid moth *Agrotis segetum*. The female moths lay eggs in May–June and, whilst the young larvae feed on crop foliage and any weeds that are present, the larger larvae move down into the soil and feed on the carrot roots, causing large cavities. This pest is sporadic in abundance and this is related mainly to the impact of rainfall/moisture on the young larvae.[66] If conditions are wet then survival of young larvae is poor. The occurrence of adults can be monitored with commercially available pheromone traps that capture male moths, the assumption being that female moths are also present. For many years, the need to apply treatments to control this pest has been based on a forecasting system[67] which uses temperature and rainfall data to predict the survival of daily cohorts of larvae. Although insecticides are used to control this pest when necessary, the application of irrigation is an equally effective method of control.

3.1.5 Pathogens. In 2013, 72 000 ha of carrot, parsnip and celery crops were treated with fungicides.[35] The main reason for application of fungicides was general disease control (71%) followed by cavity spot (10%) and then a range of pathogens, including sclerotinia and alternaria. Each crop received an average of 4 fungicide applications. Much of the crop was grown from seed treated with fungicide.

Cavity spot is the major disease of carrot in the UK and is caused mainly by the soil-borne oomycete *Pythium violae* but also occasionally by other species such as *P. sulcatum* and *P. intermedium*. Management of the disease relies on the fungicide metalaxyl-M, although its efficacy can be variable. The reliance on this single fungicide is of major concern.

Although *P. violae* has been studied extensively in the past, progress has been hampered by the lack of effective procedures for detection and quantification of the pathogen in soil. Molecular tools, including specific DNA-based tests for *P. violae*, have enabled a preliminary understanding of pathogen dynamics in soil and the effects of some abiotic and biotic factors. However, there are still fundamental gaps in knowledge concerning the epidemiology of *P. violae* and how it interacts with its environment and its hosts. Effective tools and methodologies for *P. violae* research are also lacking, including a reliable, realistic and reproducible artificial inoculation system that would allow the infection strategy of the pathogen to be further investigated, as well as different control methods. In terms of alternative methods of control, long rotations between carrot crops are recommended but not always possible. Research has indicated that levels of cavity spot may be affected by the crops grown previously in the rotation and by growing the crop with certain companion species.[68] These findings require further research.

Sclerotinia disease caused by *Sclerotinia sclerotiorum* is a widespread and increasingly serious problem in carrot, affecting both yield and quality.

Sclerotia (resting bodies) of the fungus survive in soil for at least five years and germinate to produce apothecia, which release airborne ascospores. Control currently relies predominantly on the use of fungicides to kill this airborne inoculum. Although disease levels can be reduced with fungicides, the potential level of crop loss, and the fact that even a low incidence can result in production of large numbers of sclerotia, means that growers must minimise disease pressure as much as possible.

Approaches to integrated management of Sclerotinia include a monitoring programme for sclerotial germination run by BASF and ADAS and a new canopy-clipping technique that involves trimming the foliage between the rows when the carrot foliage starts to fall over, which limits spread of the disease. Recent research[21] has identified biofumigation treatments which suppress sclerotial germination, providing a potential alternative and long-term approach to disease management. It was clear from this study that biofumigant crop plants could be used as part of an integrated disease management system for control of *S. sclerotiorum*.

Alternaria dauci causes leaf blight in carrots, resulting in reduced plant populations and damaged foliage. Furthermore, foliage that is weakened by blight is likely to break when gripped by a mechanical harvester. Seed treatments can control the seed-borne phase of the disease whilst good field hygiene and crop separation limits the spread of *Alternaria* between crops. A number of fungicides are also available that have good protectant activity against *Alternaria*. Many carrot varieties now exhibit improved tolerance to *Alternaria* and should therefore be used in high-risk situations. At least one decision-support system is available to UK growers to help with the timing of treatments. It uses weather data to predict when there will be a high risk of infection and when fungicide treatments should be applied.

3.1.6 Summary. Carrot is one of the vegetable crops for which the UK is almost self-sufficient and it is harvested virtually year-round. With the exception of crops grown organically, all other crops receive applications of synthetic fertilisers and pesticides. Some of the pesticides such as pyrethroids are broad spectrum and may affect non-target species adversely. There are a number of non-chemical approaches to controlling some pests and pathogens, but more effective alternative control methods are required to develop truly integrated management strategies. This is particularly the case with regard to weed control, where a lack of effective herbicides in the future may impact on crop yield and the financial viability of the crop.

3.2 Case Study 2: Integrated Pest and Disease Management (IPDM) in Apple Orchards

3.2.1 Introduction. Apple is highly susceptible to numerous damaging pests and diseases, most commercial apple varieties having little or no resistance. Apple is grown as a long-term perennial crop and pests and diseases can build up from year to year and reach catastrophic levels if uncontrolled. The range of pests and diseases in different production regions of the world varies considerably with climate and location, but adequate yields of fruit of the very high standard of quality demanded by markets cannot be produced everywhere and the crops cannot be grown profitably unless pests and diseases are controlled efficiently. If uncontrolled, pests and diseases cause substantial losses in yield and quality; average losses exceeding 50% have occurred when no effort is made at control.[69] Efficient weed control is also important. Apple trees in modern orchards are grown on dwarfing rootstocks for productivity and ease of management and harvesting. They are very sensitive to competition from weeds for soil moisture and nutrients, so in conventional orchards a weed-free strip with no or sparse herbage is maintained under the trees, by use of herbicides, to minimise weed competition.

The life of commercial apple orchards is generally in the range of 15–30 years. The tree canopy is semi-permanent and the soil is normally undisturbed by cultivation. Ground herbage (predominantly grass) is usually maintained in the inter-row alleys and kept short by mowing. Thus, apple orchards provide relatively stable ecological habitats. Unsprayed apple trees can support a large fauna of arthropods (>2000 species recorded, roughly a quarter are pests, a quarter natural enemies of pests). However, even a small number of insecticide sprays can greatly reduce this fauna. Many apple pests also occur on wild Rosaceae, including hawthorn, rose and rowan, which provide a source of infestation for apple orchards. Apple leaf and fruit surfaces are colonised by a range of microorganisms which may influence apple diseases. Use of broad-spectrum fungicides can greatly reduce the microflora, but the effects of this have not been sufficiently studied. Weeds and hedgerow species can be a source of inoculum for apple diseases. A small proportion of the arthropods that feed on apple are important (key) pests, especially those that damage the fruit and cause damage at low population densities. They are usually not regulated effectively by natural enemies and tend to reoccur after control with insecticides (*e.g.* codling moth, *Cydia pomonella*). There are several important secondary pests, outbreaks of which are caused by natural enemy disturbance. They have a tendency to develop resistance to insecticides and are difficult to control (*e.g.* the European red mite, *Panonychus ulmi*). The preservation of natural enemies of secondary pests is a crucial part of successful integrated pest management (IPM). Most other apple pests are minor because they do not cause a reduction in fruit yield or quality, are very localised or sporadic in their occurrence, or are easily controlled with insecticides and do not resurge frequently. Apples are attacked by a complex of diseases, including storage rots. Most sprays are directed at control of scab (*Venturia inaequalis*) and powdery mildew (*Podosphaera leucotricha*), both of which are serious diseases in unsprayed apple orchards. Recently, European canker (caused by *Neonectria ditissima*) has become a serious problem in many apple production regions, including the Netherlands, UK, New Zealand and Brazil, particularly in newly planted intensive orchards of several new cultivars. Unlike with pests, although fungal parasites or antagonists may be present, their ability to regulate disease incidence has not been studied sufficiently. Disease incidence is more dependent on seasonal weather conditions and host or varietal susceptibility. In favourable seasons on susceptible apple trees, both scab and mildew seriously reduce yield and fruit quality and weaken the tree. Disease control therefore very much depends on using fungicides.

Pesticides are relied upon in most commercial apple orchards to control the pests and diseases, for growth control and to maintain a weed-free strip. Foliar sprays of insecticides, fungicides and plant-growth regulators are applied with airblast sprayers. The axial fan design, which generates a large radial spray plume prone to high losses to the soil and as drift, predominates (Figure 4). Practically every commercially grown apple variety worldwide is highly susceptible to apple scab and many are highly susceptible to powdery mildew. For this reason, most commercial apple orchards receive an intensive programme of sprays of fungicides to control these diseases. The number of applications depends on the growing region: in wetter apple-producing regions, 15–20 fungicide spray rounds are required per season, many with more than one fungicide; in drier regions (*e.g.* in the major USA apple production region in Washington State) fungicide applications are rarely required for scab control. Further, routine fungicide applications are

Figure 4 Axial-fan airblast sprayers are the most commonly used for foliar spray applications in apple orchards worldwide. This design is comparatively simple, low cost and flexible for use in a wide range of orchard structures but a large radial spray plume is generated which is prone to drift and losses to the soil.

often made before harvest to prevent rotting in store. The average number of insecticide applications per season varies greatly between apple-producing regions of the world (range <5–15). Most orchards receive sprays of insecticides before blossom to control early-season pests including aphids and caterpillars, a spray at petal fall for these and other pests such as capsids or apple sawfly and a programme of insecticides in summer to control codling and tortrix moths. The number of generations of codling moth, the most important pest of apples, varies greatly with climate, one generation occurring in the coolest production regions, four or more generations occurring in the warmest regions. Where insecticides are used for its control, 1–2 insecticide applications may be needed for each generation, resulting in heavy insecticide use. However, in warmer production regions in response to intensive insecticide use, codling moth has developed resistance to a wider range of insecticides. As a result alternative, more costly control measures, especially sex-pheromone mating disruption are used, reducing the reliance on insecticides. Insecticide use has also increased markedly in response to the arrival of the brown marmorated stink bug, *Halyomorpha halys*, a highly damaging alien invasive pest in some production regions in the USA and southern Europe, for which few alternative control measures are available and which can only be controlled currently by programmes of sprays of broad-spectrum insecticides. Routine use of pesticides in orchards greatly reduces losses due to pests and diseases, but does not eliminate them, control rarely being perfect.

Thus pesticides are heavily relied on for pest and disease management worldwide. However, there has been significant progress along with some great success in the development of Integrated Pest and Disease Management (IPDM) systems for apple, some of which are widely implanted in commercial practice, and which have resulted in reduced, more rational use of pesticides, which otherwise would have been even more intensive and less sustainable. Successful Integrated Pest and Disease Management in apple orchards is complex and challenging, needing a range of effective methods to control the important pests and diseases without harming important natural enemies and antagonists, and having effective and non-disruptive management methods for the myriad of minor pests and diseases that can become troublesome from time to time. For diseases, to overcome total dependence on fungicides, resistant varieties have to be used and the resistance protected by small numbers of sprays of fungicides at key times. Integrated Pest Management (IPM) is a decision-based process involving coordinated use of multiple tactics for optimising control of all classes of pests (insects, mites, diseases, weeds, *etc.*) in an ecologically and economically sound manner. Key aspects are: (1) monitoring of pest, disease and natural antagonist populations and risks and the use of economic treatment or risk thresholds; (2) priority given to non-pesticidal control methods, including natural, genetic, cultural, biological and biotechnological methods; (3) multiple, compatible suppressive tactics; (4) minimal use of the safest pesticides.

Here we overview the progress made in developing the individual components of IPDM and in IPDM systems and consider special issues, including pollination, pesticide application and residues. The topic has been reviewed recently.[69,70]

3.2.2 Apple IPDM Components

3.2.2.1 Monitoring and Risk Forecasting

Sampling and economic thresholds: Deciding if and when to treat, *e.g.* with pesticide sprays, is vital to rational and effective pest management. Predictions of pest outbreaks or damage provide a warning of the timing and extent of pest attack and are essential to deciding if and when to treat with pesticides or other control measures. Central to any insect pest-monitoring programme are the sampling techniques used to measure changes in insect abundance and the damage or action thresholds used to interpret them, which together provide the essential measures by which control decisions should be made. Intensive research in the 1960s–1970s determined comprehensive sampling methods and economic thresholds for most of the common pests of apple in Europe. Sampling and assessment was done using the beating method and visual inspection of different parts of the tree (whole tree, blossoms, fruitlet clusters, leaves, shoots) with the aid of a hand lens at key growth stages during the season (pre-blossom, post blossom, June, July, August).[71] Thresholds were applied to schedule whether insecticide applications were needed, which led to a substantial reduction in insecticide use compared to routine spraying, according to growth stage and calendar date.[72] Unfortunately, the scientifically determined sampling methods proved too exacting and time-consuming for commercial practice. Simpler, rapid-assessment systems have been developed, *e.g.* the UK agronomists scoring system (0: pest absent or not found; 1: pest present at trace level; 2: pest present at significant level but not sufficient to cause immediate damage; 3: pest present at damaging levels justifying treatment; 4: pest at high levels causing very significant economic damage; 5: serious highly damaging infestation). Most commercial orchards are inspected fortnightly by an agronomist. Whilst pests can be monitored and treatment applied according to threshold in this way, the use of treatment thresholds for diseases, particularly scab, is not possible because considerably higher levels of disease may be present than are visible, such that damage has already occurred before treatment is applied. Most growers therefore rely on routine fungicide spray programmes. Disease monitoring, however, still plays an important part in integrated disease control. It provides a means of checking the success of fungicide treatments and allows modifications to be made where necessary.[73]

For fungal diseases, frequent monitoring is essential in determining the level of current disease, which can be used as an estimate of inoculum level (key determinant of disease risks), particularly for powdery mildew. Incidence of powdery mildew may be assessed on individual leaves and extension shoots;[74] more accurate information on lesion densities on individual leaves may be estimated from the incidence data.[75] For apple scab, in addition to in-season monitoring of disease development, disease severities in late autumn can also be used to estimate potential levels of overwintered inoculum in the form of ascospores,[76] which is particularly important for regions where there is snow cover during winter. For European canker, monitoring inoculum does not offer as much practical benefit as for powdery mildew and scab.

Monitoring traps for pests: Semiochemical attractants (mainly female sex pheromones) of many apple pests have now been identified, not only for moth species, for which almost all have been determined, but now for a wide range of non-lepidopteran species, including apple-leaf midge (*Dasineura mali*), common green capsid (*Lygocoris pabulinus*) and brown marmorated stink bug (*Halyomorpha halys*). Sex pheromone traps are widely used and relied on for timing insecticide sprays for codling and various tortrix moths. The strategy and density of deployment of traps varies very widely, as do the catch thresholds used for scheduling sprays. Sticky traps are used effectively for some other apple pests, *e.g.* non-UV reflective white sticky traps are used to monitor populations of apple sawfly (*Hoplocampa testudinea*) during blossom of apple and to determine whether treatment with an insecticide (*e.g.* thiacloprid) at petal fall is needed. Sticky bands made of double-sided sellotape wrapped round branches can be used to monitor mussel scale (*Lepidosaphes ulmi*) crawlers as they emerge in spring. Counts of trapped crawlers give data on the progress of the mass spring migration, one or more sprays (*e.g.* of a neonicotinoid) being applied when the migration reaches a peak.

Predictive models for apple pests and diseases: Development data are available for phenological forecasting models for many apple pests and, consequently, many such phenology models have been developed. However, only very few models are made available or used by growers in commercial practice. Unlike disease-prediction models, the primary purpose of pest phenology-based models is to assist users in interpreting trap-catch data, namely whether the pest population is likely to go up or down in relation to pest life-cycles. These data can then be used to inform growers for decision-making in relation to the pest-damaging threshold and crop-development stage. In contrast, the primary purpose of predictive models for diseases is to help growers in timing fungicide applications. Many models have been developed to predict scab primary inoculum in spring (maturation and discharge of ascospores),[77,78] and subsequent infection by ascospores and conidia.[79,80] In contrast, only one model has been developed to predict apple powdery mildew.[81] Use of disease-forecasting models together with other farming management can lead to significant savings (up to 45%) in fungicide input, depending on weather conditions.[82] Nevertheless, use of these forecasting models in commercial apple production is limited due to additional input needed to operate the models. Recent advances in cloud computing and reduced cost of weather data-logging instruments has increased the use of these models in commerce where forecasts generated by a central server using data from a network of weather stations are automatically disseminated to subscribed users.

3.2.2.2 Resistant Varieties

There are very few examples of successful deliberate use of pest- or disease-resistant apple varieties to combat important pests or diseases in commercial apple production to date. The reason for this is that varieties are chosen for market acceptability, productivity and ease of storage and handling and the resistant varieties have not met these requirements. For example, many scab-resistant apple varieties with the Vf resistance gene from *Malus floribunda* have been bred, but to date none has found large-scale market acceptance. Furthermore, the Vf gene has already been overcome in several regions.[83,84] Current efforts in breeding cultivar resistances focus on pyramiding resistance genes to minimise the risks of resistance breakdown. Varieties vary in their susceptibility to other pests and diseases and in some cases varieties have been avoided because of high susceptibility to a particular pest or disease (*e.g.* Spartan to canker, *N. ditissima*). Examples of true resistance include the use of the MM.106 rootstock with good resistance to woolly aphid (*Eriosoma lanigerum*) and varieties bred with resistance to the rosy leaf-curling aphid (*Dysaphis devecta*). The failure to exploit varietal resistance for scab and mildew control is clearly a very significant failure of apple IPM. A way to manage diseases using (partially) resistant/susceptible cultivars is the use of mixed orchards with cultivars that have differential resistance to diseases, which is shown to be effective against apple scab.[85] Research also suggests that the risk of the emergence of a fungal 'super race' to overcome multiple resistance factors in mixtures is minimal.[86] Use of mixed orchards has great potential in cider- and juicing-apple productions where disease control is not as stringent as in dessert apple.

3.2.2.3 Cultural Control Measures

Cultural measures are an essential component of any integrated pest management programme for plant diseases and can be used to reduce the level of inoculum, to manipulate microclimatic conditions, and to reduce the area of susceptible tissues. A very widely used cultural measure in apple is the application of urea spray in autumn to inhibit the sexual reproduction of *V. inaequalis* on leaf litter, hence reducing the level of ascospores for the next season[87,88] and leading to the reduction of primary infections next spring.[89] Removal of heavily infected shoots with scab, mildew and canker *via* careful pruning can lead to an appreciable reduction of inoculums, hence reducing disease pressure. Burning or removing pruned shoots with canker or scab is essential for reducing inoculum level since inoculum production in dead wood is possible for these two pathogens (unlike powdery mildew). Timing pruning is also critical since the canker pathogen (*N. ditissima*) can easily infect fresh pruning wounds and the risk of canker infection decreases with increasing wound age[90] with the rate of wound healing depending primarily on temperature and host metabolic activities.

3.2.2.4 Biological Control

Conserving existing natural enemies: Predatory mites (Phytoseiidae) are very important predators of phytophagous mite pests in apple orchards and their role has been reviewed.[69,70] The development of insecticide-resistant strains of predatory mites and the realisation of their crucial importance in the natural regulation of pest mites, especially spider mites and rust mites, is one of the main success stories of apple IPM worldwide. The species of predatory mite that has developed resistance and become the key natural enemy varies in different regions of the world, but in commercial orchards in temperate northern and central Europe *Typhlodromus pyri* predominates, though recently *Amblyseius andersoni* has become dominant in many regions, *e.g.* in France[91] and Hungary.[92] Up to the 1980s, insecticides and fungicides harmful to predatory mites were extensively used in orchards and phytophagous mites, which rapidly developed resistance to new acaricides, were the most troublesome orchard pests. In the UK for instance, for many years it was almost routine practice to spray pirimiphos-methyl after bud burst for apple rust mite (*Aculus schlechtendali*) and cyhexatin after flowering for European red mite. In the 1980s, once the importance of orchard predatory mites had been realised, most growers stopped using pesticides harmful to them (*e.g.* synthetic pyrethroids, pirimiphos-methyl, dinocap, *etc.*). The predatory mite re-colonised and the phytophagous mites ceased to be a problem. There are many pome fruit farms where acaricide treatment has not been necessary for more than 30 years.

Another natural enemy increasingly recognised as being very important in conservation biocontrol in apple orchards is the common European earwig (*Forficula auricularia*). *Forficula auricularia* is an important predator of many orchard pests, including codling moth (*Cydia pomonella*), aphids, psyllids, scale insects and midges. Excluding *F. auricularia* from *E. lanigerum*- or psyllid-infested trees has been shown experimentally to lead to a proliferation of the pests. The benefits of *F. auricularia* as voracious predators of apple pests with high prey-consumption rates and relatively stable populations, and the vital part they play in naturally regulating populations of several key pests, is now widely recognised. The connection between outbreaks of *E. lanigerum* in plots repeatedly treated with diflubenzuron with the low numbers of earwigs in these plots was first recognised by Ravensberg.[93] The relationship between the earwig density and the extermination of woolly apple aphid colonies was demonstrated by Mueller *et al.*[94] and by Mols.[95] Assessments of the abundance of *F. auricularia* and pests in 40 apple and pear orchards in SE England in 2013–2014 showed that the orchards that had the highest numbers of codling moth, woolly aphid or pear psylla all had zero or near-zero *F. Auricularia.*[69] Although other orchards that had zero or near-zero *F. auricularia* did not necessarily have high pest levels, none of the orchards with high *F. auricularia* numbers had high pest levels. Note that *F. auricularia* is omnivorous and can cause economic damage to some crops with a thin or soft skin (*e.g.* peaches and strawberries).[96] *F. auricularia* used to be considered to be an important pest of apple which growers controlled with sprays of insecticides (*e.g.* carbaryl, diflubenzuron, often applied at night to maximise direct interception with sprays), but damage to fruits is now generally considered to be only secondary, at points where the skin has already been damaged. Feeding on blossoms and leaves is common but of little importance.

It is important to minimise, preferably to avoid the use of insecticides harmful to *F. auricularia* in order to increase its abundance. Several broad-spectrum insecticides (*e.g.* carbaryl, chlorpyrifos, most selective products) are known to have direct toxic effects but other insecticides are now known to be harmful in more subtle ways, affecting young stages, reducing feeding, or having long-term effects on reproduction or survival (*e.g.* indoxacarb, methoxyfenozide, spinetoram, thiacloprid).[97,98] Fortunately, some insecticides and bioinsecticides appear to be safe to earwigs (*e.g. Bacillus thuringiensis*, chlorantraniliprole, codling moth granulovirus, flonicamid). Given that *F. auricularia* is an important natural enemy of apple pests, enhancing numbers by use of additional artificial shelters or refuges has been assessed in apple and other crops. However, it is yet to be demonstrated that provision of shelters leads to long-term increases in *F. auricularia* populations or increases in pest predation. Potentially it should be possible to transfer *F. auricularia* from orchards or other crops where they are abundant to apple orchards where populations are low, which might be particularly beneficial in newly planted orchards where *F. auricularia* populations take the time to establish and where the trees have smooth bark, providing few natural shelters.

Many other apple pests are naturally regulated by natural enemies, notably the guilds of parasitoids that regulate a complex of leaf-mining moth pests. For reviews of predators and parasitoids in orchards see Cross *et al.*[99] and Solomon *et al.*[100]

Introduced natural enemies: There have been a small number of instances where natural enemies have been introduced to regulate an invasive pest. On apple, the best known is the introduction in the 1920s of the parasitoid *Aphelinus mali* to control woolly aphid, an invasive pest from America. *Aphelinus mali* is now an important natural enemy of woolly aphid present in most places where the pest occurs. It certainly greatly helps to regulate woolly aphid outbreaks, but is often not quite good enough on its own, requiring the assistance of earwigs. Inundative releases of arthropod predators or parasites as biocontrol agents to orchards are generally too costly and are often not successful because of climatic instability.

Microbial agents and nematodes: There are a small number of significant success stories in the use of microbial biopesticides and nematodes in apple growing.[101,102] The widespread use of codling moth granulovirus is the most important.[103] Formulations of the virus are approved in most countries and are applied to the foliage as sprays. The virus is highly selective and virulent. In orchards, only codling moth can be infected. A single virus particle is sufficient to kill a first instar codling moth larva. The virus is safe to humans, plants and the environment. It has to be ingested by the newly hatched larva when feeding on the skin of the apple before it penetrates the flesh. The larva continues feeding for a few days before the virus acts. This results in small, shallow, larval feeding holes in the surface of the fruit. Although this injury is superficial, it can result in downgrading of fruit to a lower quality class. The virus is sensitive to UV light and high temperatures, which limit its persistence. A programme of sprays of the virus through the egg-hatch period is required. No 'pesticide residues' occur on fruits at harvest. Strains of the codling moth resistant to the virus have developed in some regions in continental Europe where the virus has been relied upon for control for many years. The problem has been overcome by using a different strain of the virus. However, this development highlights the need to use multiple suppressive tactics to minimise the risk of resistance. Other uses of microbial agents for pest control include the use of sprays of *Bacillus thuringiensis* to control caterpillars and sprays of entomopathogenic nematodes (*e.g. Steinernema carpocapse*) applied in autumn to control overwintering codling moth. However, the extent of use of these is very limited currently. The recent approval of *Bacillus subtilis*, active against a range of apple diseases, provides a future opportunity for biological control of diseases in orchards.

Biological control of diseases has proved to be more challenging in general. Relatively few commercial biocontrol products based on microorganisms have been commercialised to control pathogens. Even for these products, the efficacy achieved is usually less than fungicides and, most importantly, is inconsistent. Most success in biocontrol of pathogens is achieved under protected conditions. Much research has been conducted to find effective biocontrol agents for apple scab. Although several candidate organisms (*e.g. Cladosporium*) have shown promising results, none of these organisms has yet been further developed into a commercialised product. For powdery mildew, a commercial product (AQ10) based on a single strain of *Ampelomyce quisqualis* is commercially available; *A. quisqualis* is a hyperparasite of powdery mildew in general.[104] However, the efficacy of AQ10 on its own against apple mildew is insufficient for commercial apple production. Recent research has been focusing on whether mildew can be effectively managed by integrating AQ10 with plant defence elicitors and reduced fungicide inputs.

3.2.2.5 Sex Pheromone Mating Disruption and Biotechnological Control Methods

In areas where the codling moth has developed resistance to insecticides, sex-pheromone Mating Disruption (MD) is used for controlling codling moth, often on an area-wide scale. Mating disruption occurs by a number of different mechanisms: (1) sensory fatigue; (2) false-trail following;

(3) masking of natural sources; and (4) imbalance of pheromone components.[105,106] Different commercial MD treatments attempt to exploit one or more of these mechanisms. The most common MD treatments deploy a high rate of pheromone (up to 150 g active ingredient (a.i.) ha^{-1} each season) emitted from 300–1000 dispensers per ha. They cause sensory fatigue. Other MD systems, which operate by false trail following, release a small amount of a precise attractive blend of pheromone from 2000–3000 points ha^{-1}. They are effective for up to 60 days. Sprayable MD formulations deposit a very high number of microcapsules on the foliage and fruits and result in a "fog" of pheromone which is considered to act principally by masking the natural pheromone sources. Sprays containing 25 g pheromone per ha are applied monthly. MD treatments are most effective against low to medium insect populations, but are valuable at higher pest densities because they significantly reduce the requirement for insecticide applications. A major weakness of sex-pheromone-based control approaches is that only males are attracted by the sex pheromone and females are unaffected. The use of sex pheromones to control codling moth has been reviewed.[70,107]

3.2.2.6 Minimal Use of Safest Pesticides

Pesticides remain the only effective control method for a large number of apple pests and diseases. Where there is a choice of control options, they are often inexpensive compared to other control approaches. Growers only use more-costly non-pesticidal methods where they are forced to by circumstances such as the market and consumers. For example, sex-pheromone-based control of codling moth has been widely implemented in southern Europe because codling moth has developed resistance to many pesticides. Selectivity also presents the grower with a dilemma: is it better to use a single spray of an inexpensive broad-spectrum insecticide which poses a greater risk to the environment or human health (*e.g.* chlorpyrifos), which will control several target pests, or to use several (more expensive) safer, more selective ones? Growers often choose the cheaper option.

3.2.2.7 Pollination and Avoiding Adverse Effects of Pesticides on Bees and Pollinating Insects

Adequate pollination is essential for profitable apple production. Most apple varieties are not self-compatible. Furthermore, different varieties often do not bloom in unison. Therefore, two or more varieties that can pollinate each other, as well as insect pollinators to move pollen from variety to variety, are needed for adequate pollination. Managed honeybees and bumblebees, and native wild bees, play key parts in pollination in apple orchards. It should be noted that many modern apple varieties produce an excessive quantity of blossom and if a high degree of pollination occurs, fruit set can be excessive, resulting in the need to reduce the numbers of fruitlets by thinning. In some countries, where chemical thinning agents are not available, thinning has to be done by hand, which can be costly. For this reason, some apple growers do not provision orchards with honeybees and in some orchards no pollinating varieties are provided.[69]

Many, though by no means all, apple growers provide honeybee hives in their orchards for pollination. The hives may be present permanently but often are introduced for the blossom period only. Wild bees, predominantly solitary bees from the family Andrenidae, make up to two-thirds of apple-blossom visitors and probably play a significant part in apple pollination.[108] Solitary bees can exhibit higher activity in adverse weather conditions compared to honey bees,[109] different foraging behaviour and different anatomy for pollen collection being important factors. Increasing the numbers of managed and wild bees in apple orchards improves pollination, which results in improved seed-set, reducing misshapen fruits and improving fruit quality.

Susceptibility to insecticides. Managed and wild bees can become contaminated with harmful pesticides by many routes, including direct interception by sprays, by contact with deposits on plant surfaces (on the cropping trees or on ground herbage), or by feeding on pollen or nectar (which may be contaminated by surface deposit or uptake through the plant) or honeydew from insects. Contamination may occur in the orchard itself or in surrounding habitats contaminated by spray drift. Pesticide registration processes include an assessment of risks to bees (largely based on honeybee studies), which aims to ensure that pesticides with unacceptably high risks to bees are not registered and that pesticides with risks that are registered are used in ways to ensure that the risk is acceptably small. The risk assessment process is a tiered approach where data are collected on individual bees that are representative of different life stages (larval/pupal *versus* adults) and castes. While additional data may be available on other bee species, and these data can be included in the tiered risk-assessment process as an additional line of evidence, the primary process relies on honeybee data as a surrogate for both honeybee and wild bees. In this process, laboratory-based studies of larval/pupal and adult honeybees provide data on individual bees that can be used as a surrogate for other species of bees, including solitary species. At the semi-field and full-field levels, studies of the colony can be used to represent effects to honeybees themselves and as a surrogate for other social bees. An advantage of using honeybees is that the husbandry and life-cycle of the species and its significance in pollination services is well known and test protocols are available. As the science evolves, methods and studies using wild bees may be considered and incorporated into the risk assessment.

In general, in apple crops, pesticides with risks to bees cannot be used during blossom. Many insecticides used in apple orchards pose a high or significant risk to bees and cannot be used during flowering, including most organophosphates (OPs) (chlorpyrifos, diazinon, methidathion, phosmet), some carbamates (carbaryl, methomyl), avermectins (abamectin), many synthetic pyrethroids (SPs) (bifenthrin, cyfluthrin, cypermethrin, deltamethrin, fenpropathrin, λ-cyhalothrin, *etc.*), some neonicotinoids (imidacloprid, thiamethoxam), spinosysns (spinosad, spinetoram) and some juvenile hormone analogues (fenoxycarb). Fortunately, many insecticides pose low or negligible risk to bees, including the chitin synthesis inhibitors buprofezin and diflubenzuron, the diamides chlorantraniliprole and flubendiamide, the tetronic acid derivatives spirodiclofen and spiromesofen, the juvenile hormone analogue pyriproxyfen, and Insect Growth Regulator (IGR) methoxyfenozide. It is important to note that insecticides in the same chemical class pose very different risks to bees, *e.g.* the neonicotinoids acetamiprid and thiacloprid are comparatively bee-safe but imidacloprid and thiamethoxam are very harmful, with persistent effects; the carbamate pirimicarb is safe to bees whereas carbaryl is very harmful; the diamide chlorantraniliprole is safe to bees whereas its sister compound cyantraniliprole is harmful. Most fungicides do not pose risks to bees but some widely used fungicides are known to have harmful effects, *e.g.* fenariomol, captan.

Best practices for minimising pesticide risk to bees include:

- choosing less-toxic pesticides with lower risk to bees (including pesticides with short residual action that dissipate quickly)
- choosing a less-toxic formulation (avoid dusts and wettable powders which can adhere to the hairs on bees' bodies and be accidentally transported back to the hive or nest, where the residues may end up in the bees' food resources)
- spraying late in the day when bee activity is low
- placement of honeybee hives in a protected location
- locating pollinator foraging and nesting habitat away from apple orchards
- providing undisturbed areas for soil-nesting bees, and flowering plants to provide forage when the crop is not in bloom
- providing a clean water source within the flight range of bees on the farm
- reducing drift onto areas where bees are living or foraging
- removing flowering plants in crop fields before spraying

3.2.2.8 Pesticide Application

Prior to the advent of spray machines, orchards were sprayed with hand lances, a practice known as 'washing'. Very large volumes of water were used (>5000 L ha^{-1}), the aim being to saturate the tree to form a continuous deposit over the plant's surface. This practice was laborious and wasteful, but it had the advantage of producing the most uniform, reproducible deposit which was independent of tree size and structure. Air assistance was recognised as being vital to the efficient transport and distribution of sprays to orchard trees and spray applications to orchards in the early to mid-20th century. Axial fan airblast sprayers were the first air-assisted spray machines and are still the most popular for orchard spray applications worldwide today. They are comparatively inexpensive, robust, durable, and can be used in a wide range of types of orchard. Unfortunately, they produce a large radial spray plume that is often poorly targeted, resulting in high spray losses to the ground and as spray drift. Growers rarely make adequate adjustments to optimise sprayer performance in particular orchards. In parallel to the development of dwarf tree training, simple axial fan airblast sprayers are gradually being replaced by more-efficient and better-targeted designs with better matching of the spray plume to the target, including cross-flow machines and those that use air ducting. Several designs of tunnel sprayer, which partially enclose the spray plume in a canopy to reduce spray losses, are available including those that recycle captured spray, but tunnel sprayers are only used by a few growers because of their high cost and technical disadvantages. Multi-row sprayers are being increasingly adopted to increase work rates. Sprayers with canopy sensors that adjust sprayer output (spray liquid and/or air-flow rate) in real time in response to the physical characteristics of the target and/or environmental conditions are currently at the cutting edge of orchard spray machinery development. There has been a gradual evolution from simple machines where nozzles are switched off in response to gaps in the canopy to those that make adjustments in real time in response to target canopy size and density. Such sprayers have been shown to be considerably more efficient and there is a key need to foster their adoption into practice.

Spray volumes used in modern orchard spraying vary widely between farms and production regions but are typically in the range 200–1000 L ha^{-1}. Very fine and fine spray qualities are typically used, but increasingly much coarser spray qualities produced by air-induction nozzles are used to mitigate drift. Spray drift and losses to the soil from orchard spraying are large compared with arable crop spraying and a range of methods of drift mitigation of varying degrees of effectiveness and practicality have been developed, some of which are now legally required, notably mandatory buffer zones on pesticide labels and the use of low-drift air-induction nozzles which produce very coarse spray qualities. There is considerable variation in mandatory schemes in different countries. There are important changes in the way dose rates are being expressed on pesticide labels and efforts are underway to develop methods of adjusting dose rates according to the size and density of orchard canopies to achieve deposits that do not vary between orchards with different canopy sizes and at different growth stages. Regular sprayer testing is now mandatory in many countries, to ensure that sprayers are adequately maintained and calibrated. The state of the art of orchard spray application in Europe has recently been overviewed by Cross *et al.*[110]

3.2.2.9 Pesticide Residues and Minimising Their Occurrence

As described above, apples are often treated intensively with pesticides, many applications being made in summer during fruit development, with some close to harvest. Until recently, apple fruit was drenched in fungicides and/or an antioxidant after harvest to control post-harvest rots and the physiological disorder superficial scald. Such pesticides use inevitably results in pesticide residues in a high proportion of fruit and many samples contain multiple residues. Despite the intensive use of pesticides, residue levels in apples do not exceed Maximum Residue Levels (MRLs), providing Good Agricultural Practice (GAP) is adhered to. Amounts below the reporting limit are regarded as zero, even though trace amounts might be present.

Government agencies and food producers and retailers round the world conduct regular retail surveillance of pesticide residues in fresh produce, including apples. For example, the European Food Safety Authority (EFSA) publishes an analysis of the results of the surveillance and controls on pesticide residues provided by EU Member States annually. In 2013, 1610 samples of apples were analysed; 1077 (67%) samples contained one or several pesticides in measurable concentrations, multiple residues being reported in 739 samples (46%); up to 17 different pesticides were detected in an individual apple sample. In 1% of the samples the residue concentrations exceeded MRLs. In total, 55 different pesticides were detected. The most frequently found pesticides were captan/folpet (detected in 27.9% of the tested samples), dithianon (23%) and dithiocarbamates (17.7%).[111]

An important development, which first came to prominence in the UK, is the desire by multiple retailers, sometimes passed on as a requirement to their suppliers, to minimise, ideally to eliminate, pesticide residues from fresh produce. In the UK, government residues-surveillance reporting policy changed in 2001, after which the location from where the samples were taken was included. In response, several major retailers, who did do not wish to be 'named and shamed' began asking their suppliers to work towards elimination of pesticide residues from fresh produce, including apples, to maintain and improve consumer trust. Similar developments followed in several other EU countries, different retailers adopting different requirements such as a maximum number of reported residues and/or a requirement for residues not to exceed a maximum percentage (*e.g.* 30%) of the MRL. The diversity of the requirements by different retailers presented difficult challenges for many producers.

A further, very challenging, subsequent development in the 2000s was the lowering of reporting limits for pesticides in the EU and internationally, which accompanied the use of much more sensitive LC MS/MS analytical methods for measuring residues. The lowering of reporting limits by 10–20 fold (typically from 0.1 to 0.01 mg kg^{-1}) and the use of the more-sensitive analytical methods resulted in a sharp rise in the incidence of reportable residues in some produce, including apples, even where average levels had actually been reduced. This unfortunate development was demotivating for producers striving to reduce residues.

Minimum Pesticide Residues IPDM imposes important additional requirements on IPDM, but is also a powerful driving force in the development and implementation of IPDM practices. NIAB East Malling Research (EMR) work to develop Minimum Residues IPDM for apples[112–114] started in the late 1990s before the market requirement came to the fore, EMR being the first in the world to work seriously on this topic.

The generic approaches to reducing pesticide residues are well known. The most important are: (1) grow resistant varieties; (2) use non-chemical control methods, especially cultural, biological and biotechnological methods wherever possible (more attention needs to be devoted to developing and using new biopesticide products which do not leave pesticide residues); (3) avoid use of pesticides except where absolutely necessary (this is done by frequent crop monitoring and risk forecasting); (4) use products more intensively earlier or later in the season (*e.g.* pre-flowering or post-fruiting to minimise problems during fruit development and fruiting); (5) use shorter-persistence products; (6) use products that have a high reporting limit relative to their dose (reduce the dose of applications closer to harvest); (7) increase the harvest interval; (8) by training, improving knowledge and expertise of all those involved in decision making.

The EMR minimum residues Integrated Pest and Disease Management (IPDM) programme for apples: There had been no concerted research efforts focused primarily on the development of pest and disease management programmes to eliminate reportable residues from conventionally produced (non-organic) apple, or from other fresh produce for that matter, prior to the work at East Malling Research (EMR) in the 1990s and early 2000s. Investigations by Jones *et al.*[115] reduced but did not eliminate residues. The EMR minimum residues IPDM programme for apples is based on the use of conventional pesticides (excluding organophosphorus (OP) insecticides) up to petal fall and after harvest, but during fruit development it relies on biocontrol and sulfur sprays (residues of which above the reporting limit are not detected) for dealing with pests and diseases. To avoid the use of fungicides for post-harvest (which are applied shortly before harvest, always resulting in residues), rot risk assessment is used to determine likely rot problems in the orchard, together with cultural controls and selective picking to reduce/control rot problems in store. Only sound fruit (to avoid brown rot) and fruit above knee height (to avoid Phytophthora rot) are picked for storage. An insecticide and a fungicide treatment are also made in the orchard post harvest, to reduce problems with overwintering inoculum. A 6-year large-scale replicated orchard experiment was done at EMR from 2001 to 2007 to investigate the above minimum-residue IPDM programme. Good results were obtained with this IPDM programme. Scab control was as good as, and often better than, in the conventionally treated plots, even on susceptible varieties in challenging weather conditions. Acceptable levels of pest and disease control were achieved and residues were eliminated. Large-scale grower trials were less successful as the growers were unwilling to completely stop using fungicides after blossom.

The ‘Apple Futures’ minimal residues programme in New Zealand was highly successful, developed at a time when many competing apple-producing countries were rejecting the supermarkets’ call for ‘residue-free’ fruit. It succeeded in eliminating the use of pesticide ingredients classified as Extremely and Highly Hazardous to human health. Pre-harvest intervals were increased, often substantially, for many pesticide products prone to leaving residues. IPDM components included computer modelling to optimise disease prediction, monitoring of insect pests and beneficial organisms, pheromone-based mating-disruption technologies, and targeted spraying of selective pesticides when justified. Subsequently, pesticide residues on fruit at harvest were reduced to significantly below regulatory requirements and below even the most stringent levels required by leading European supermarkets.

3.2.3 Integrated Fruit Production. Integrated Fruit Production (IFP) is defined as the economical production of high-quality fruits, giving priority to ecologically safer methods, minimising the undesirable side-effects and use of agrochemicals, to enhance safeguards to the environment and human health. The aim of IFP is to ensure that production methods are sustainable and as safe as possible for the environment and human health, with a minimum of pesticide use. Emphasis is placed on a holistic systems approach involving the entire farm as the basic unit, on the central role of agro-ecosystems and on balanced nutrient cycles. The preservation and improvement of soil fertility and of a diversified environment are essential components. Biological, technical and chemical methods are balanced carefully, taking into account the protection of the environment, profitability and social requirements. The IFP concept was first developed in apple as an extension of IPM and can be traced back to the early 1950s, but the breakthrough first came in 1988 when some European apple-producing regions started producing IP-labelled fruit. The International Organisation of Biological Control of Noxious Animals and Plants (IOBC) played a central role in the development of IFP and first published guidelines and standards in 1991,[116] which have been continuously updated ever since. The IOBC IFP guidelines contain the following sections: definitions; professionally trained and environmentally and safety-conscious growers; conserving the orchard environment; site, rootstocks, cultivar and planting system for new orchards; soil management and tree nutrition; alleyways and weed-free strip; irrigation; tree training and management; fruit management; integrated plant protection; efficient and safe spray-application methods; harvesting, storage and fruit quality; post-harvest chemical treatments; mode of application, controls, certification and labelling. The IOBC guidelines are used as a basis for national, regional and local guidelines in IFP applied in many apple-growing regions. IFP schemes foster the implementation of IPM and impact agrochemical use directly by specifying red, amber and green lists of pesticides which are forbidden, allowed in exceptional circumstances, or preferred chemical-control options, respectively. Apple IFP has recently been reviewed.[70] The regulations used by different production regions or organisations vary considerably and they are not always consistent with the IOBC Guidelines. Being ‘Guidelines’ they are not precisely defined or legally specified in an EU or international agreement and the level of implementation varies considerably; there are no common requirements which are imposed on growers. Instead there are many certification and market authorities which set up specific standards, creating IPM labels that offer economic advantages to marketing and producer organisations and to individual growers.

4 Future Perspectives

All horticultural crops, be they edible or ornamental, are considered to be important to human well-being. Whilst they do not provide a large amount of calorific value, fruits and vegetables do provide vitamins, anti-oxidants and fibre, as well as protein in some cases, and the impact of ornamental horticulture on human health is now also well-documented.[117,118] Thus, unlike the concerns about the increased production of animal-based products, there is a global consensus that an increase in horticultural production is beneficial and indeed essential.

Horticulture is one of the more innovative crop sectors and new methods of production are being developed all the time. This has included the increasing use of semi-protection in certain parts of the world, improved approaches to irrigation, and the more recent discussions about urban farming, including vertical farming. The use of hydroponic systems is also developing. The cost of energy has been, and will continue to be, a constraint in some horticultural systems. However, research into alternative sources of energy will help with this. Water is also a constraint, to be addressed by novel approaches to water application and use. For the foreseeable future a good proportion of horticultural crops will require the application of fertilisers and pesticides, with their consequent impacts on the environment.

Going forward, there are considerable legislative, environmental and financial incentives to reduce chemical use in horticulture and this will be addressed in a number of ways. The first will be through crop improvement to produce crop varieties that are less susceptible to pests and diseases, more competitive with weeds, and which make better use of nutrients and water. This may be through conventional breeding or a range of techniques broadly described as ‘genetic modification’ (see Chapter 5 for further detail on GM crops). In addition, since many horticultural crops are relatively ‘high-value’ compared with arable crops, there is a better economic argument for developing alternatives to pesticides, such as biological control. In contrast, virtually all horticultural crops are considered by the support industries (agrochemicals, biological control, seed companies) to be ‘minor’ crops compared with broad-acre crops such as maize, wheat and soya and, as such, companies are often less willing to invest in these niche markets, as the return will not be as great. There are a number of examples of this with regard to conventional pesticides and biological control with arthropods or microorganisms. Finally, it is likely that more crops will be grown using some form of protection, to improve yield and quality as a result of protection from adverse weather conditions or to reduce the impact of pests, diseases and weeds.

5 Conclusion

Bearing in mind the relatively small cropped area devoted to horticulture in many countries, the production of these crops is likely to have less impact on the environment overall than arable production. However, on a unit area basis some horticultural production systems do have a considerable impact on the environment, and potentially on human well-being, through the chemicals applied. The sector is very diverse and highly innovative, so it is likely that, over time, more and more solutions will be found to address the problems which occur as a result of the use of chemicals.

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