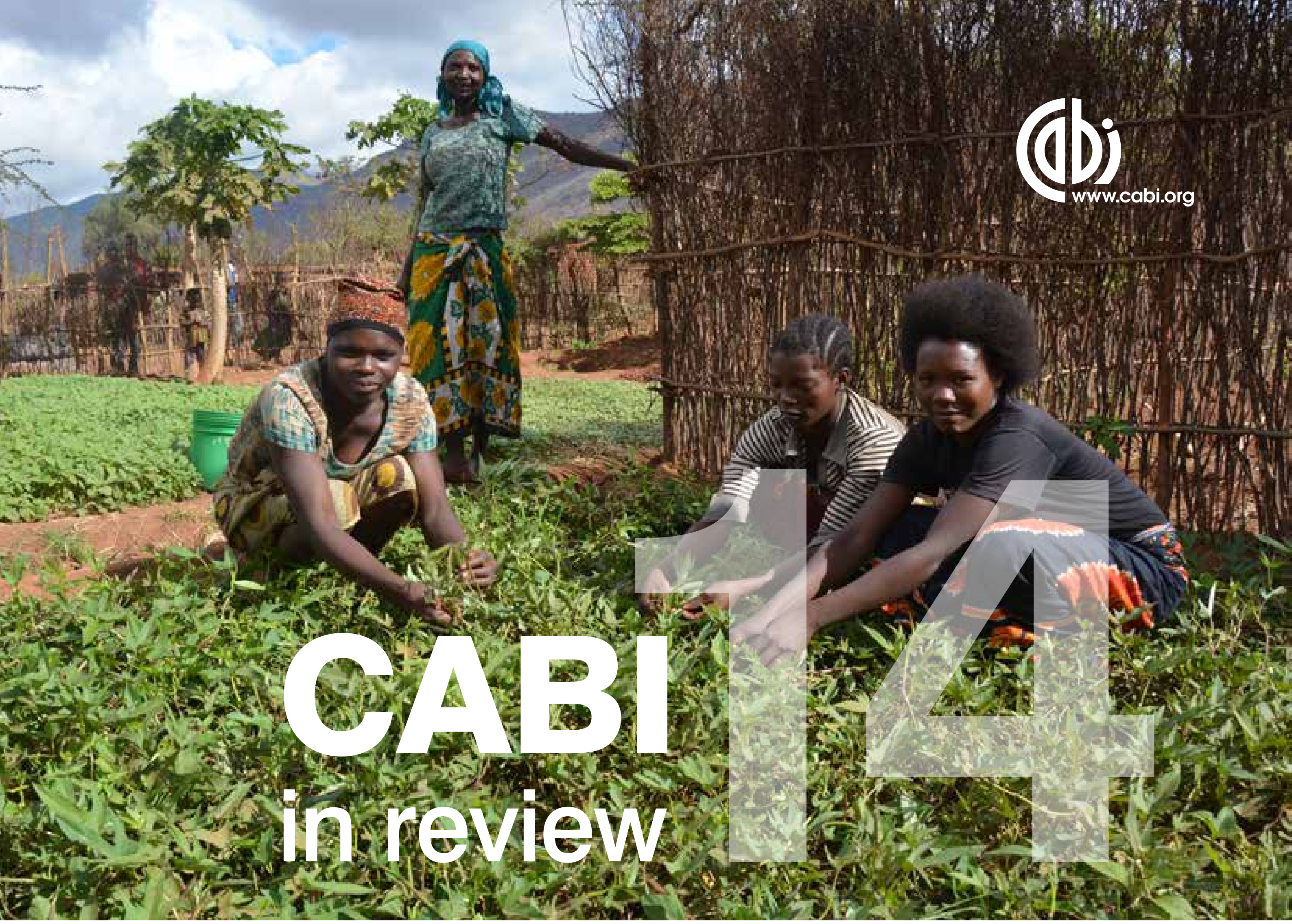
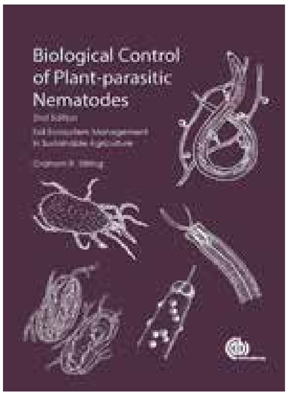


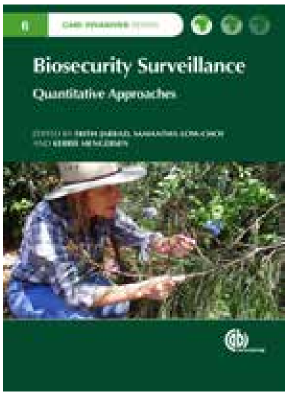
CABI in review 14

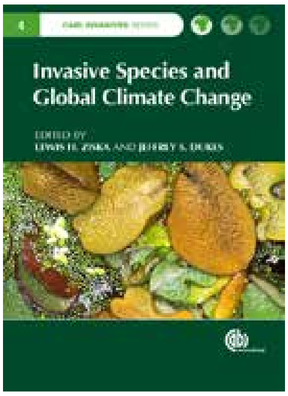
Selected book chapters

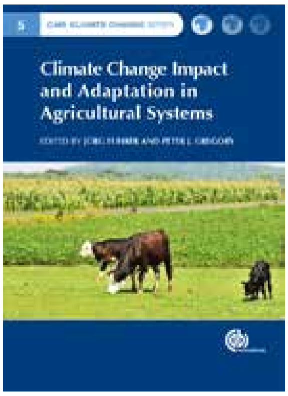
For our annual review this year, we have made available selected chapters from CABI books in a CABI in Review 2014 eBook.

The chapters have been taken from the following books (click on the book to take you directly to that chapter).









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Biological Control of Plant-parasitic Nematodes, 2nd Edition

Soil Ecosystem Management in Sustainable Agriculture

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Global Food Security, Soil Health and Sustainable Agriculture

The decision to commence this book with a broad overview of the many issues likely to affect the development of biological controls for plant-parasitic nematodes was deliberate. The complexity of the soil environment; the diversity of agricultural production systems; and the sheer number of economic and production-related issues that must be considered by today's food producers mean that numerous factors will impinge on any attempt to introduce alternative methods of managing nematodes. The soil environment; the soil biota; the role of organic matter; the biological interactions that occur at the root–soil interface; the soil food web; and the soil nematode community were discussed in Chapters 2 and 3. This chapter aims to cover some of the agricultural issues that affect our attempts to establish reliable systems of biological control. Land managers and farmers live in the real world, and so their management options are limited by climate, the inherent properties of the soil resource, economics, market requirements and many other factors. Alternative pest control strategies will only be adopted if they are feasible, cost-effective and consistently successful.

Global Food Security

Agriculture is a vibrant, innovative and successful industry. Despite a doubling of the global population in the last 50 years, food production has increased to an even greater extent, markedly decreasing the proportion of malnourished people in the world. New livestock and crop production technologies have enabled food to be produced in ways that would never have been contemplated by previous generations of farmers. However, world population is expected to reach 9 billion by 2050, and since steps are unlikely to be taken to regulate population growth, the level of innovation that characterized the latter part of the 20th century will have to continue unabated for many more years. Thus, the challenge facing agriculture is to meet the food requirements of a larger and more affluent population in an era when food producers are experiencing greater competition for land, water and energy (Godfray *et al.*, 2010; Gomiero *et al.*, 2011a).

Increases in crop production derive from three main sources: expansion of arable land; increases in cropping intensity (the frequency with which crops are harvested from a given area); and improvements in yield. Since the 1960s, the United Nations Food and Agriculture Organization (FAO) has shown that yield improvements made by far the greatest contribution to the increase in global food production, accounting for about 78% of the increase between 1961 and 1999. The remainder came from an expansion in the arable area (15%) and increased cropping intensity (7%) (Bruinsma, 2003). Future projections suggest that this situation is unlikely to change. There will be opportunities to expand the arable area in sub-Saharan Africa and Latin America, but in developing countries overall, 80% of increased crop production will have to come from intensification, higher yields, greater levels of multiple cropping and shorter fallow periods. In developed economies, where agricultural land is increasingly being planted to energy-producing biomass crops, virtually all the required increase in food production will come from yield improvements and intensification.

The need to produce more food on land that is already being used for food crops raises the question of whether land can be farmed more intensively without increasing the rate of soil degradation. Agricultural land is automatically degraded when nutrients are removed in harvested crops, but further degradation may occur through water and wind erosion, desertification, salinization and leaching of nutrients. Nevertheless, there are a number of reasons why agricultural intensification will not necessarily increase the rate of these processes: (i) evolving technologies in no-till/conservation agriculture can maintain year-round soil cover and increase soil organic matter, thereby reducing water and wind erosion while maintaining soil health; (ii) most irrigated agricultural land is relatively flat and is little affected by erosion, while abandonment of marginal land that is too steep for agriculture, together with practices such as contour banking, will reduce water erosion; (iii) agroforestry (the integration of cropping and or/livestock production with trees or shrubs) offers opportunities to reduce soil erosion, restore soil fertility and increase biodiversity; (iv) a shift towards raising livestock in more intensive systems will reduce grazing pressures on dryland pastures; (v) a range of intensification practices (increased fertilizer consumption, more efficient fertilizer use, the introduction of drought- and salt-tolerant crops, the use of grazing-tolerant pastures and the introduction of irrigation) will reduce erosion by increasing plant biomass, root growth and ground cover; and (vi) the cultivation of legumes in cropping and mixed crop–livestock farming systems will add nitrogen to soils and improve their stability and texture.

Attention to issues associated with soil degradation will always be an important priority for land managers, but the important message from the previous paragraph is that as food production becomes more intensive, many practices are available to minimize soil degradation, and they must be components of future soil management programmes. At the same time, future farming systems will have to address the environmental impact of agriculture. Agricultural activities, particularly those resulting in emissions to air and water, can have significant effects long distances from where those activities take place. Pesticides and nutrients can move into surface and ground water, while greenhouse gases can be emitted to the atmosphere, and so steps must be taken to minimize these negative impacts. Practices such as integrated pest management; optimization of water, nutrient and pesticide inputs through precision agriculture; and a whole range of practices to conserve soil and water (e.g. conservation tillage, cover cropping, controlled traffic, contour farming and mulching) will also have to be adopted more widely by farming communities. Food production must continue to increase in the 21st century, but it will have to be done in an environmentally sustainable manner, a process that has been termed ‘sustainable intensification’ (Royal Society, 2009).

Sustainable Farming Systems

Responsible and enduring stewardship of agricultural land is the essence of sustainable agriculture: land is managed in ways that maintain its long-term productivity, resilience and vitality while minimizing adverse environmental impacts. Although it has been variously defined (Hamblin, 1995; Lewandowski *et al.*, 1999; Gliessman, 2007; Gold, 2007;

Pretty, 2008), sustainable agriculture is generally considered to: (i) replenish the resource base that sustains agricultural production, and then maintain it in a condition that does not compromise its use by future generations; (ii) integrate biological and ecological processes such as nutrient cycling, nitrogen fixation, soil regeneration, allellopathy, competition and the regulatory effects of pests' natural enemies, into food production systems; (iii) utilize ecological knowledge, the basics of agricultural science and the management skills and ingenuity of farmers to develop farming systems appropriate for the soil, climate and production goals; (iv) optimize the use of resources and minimize the use of non-renewable inputs; and (v) minimize the impact of pest management, crop nutrition, irrigation and other production practices on human health and the environment.

Sustainable agriculture is not a prescribed set of practices. It challenges land managers to think about the long-term implications of the practices they use, and to understand the interactions that occur within and between the many components of agricultural systems. A key goal is to view agriculture from an ecological perspective and balance the requirements for productivity and profitability with an understanding of nutrient and energy dynamics and the biological interactions that occur in agroecosystems. Any new practice or technology that improves productivity for farmers but does not cause undue harm to the soil biological environment is likely to enhance sustainability.

Sustainable agricultural intensification

Sustainable agricultural intensification is essentially about increasing productivity in ways that make better use of existing resources while minimizing environmental harm. There are many pathways to agricultural sustainability, and no single configuration of technologies, inputs and management practices is likely to be applicable in all situations (Pretty, 2008). However, a number of key practices are consistently associated with sustainability (Goulding *et al*., 2008; Shennan, 2008; Wilkins, 2008; Kassam *et al*., 2009), and they are summarized next. Applied together, or in various combinations, these practices work synergistically to increase productivity and also to contribute important ecosystem services that enhance sustainability. However, it is important to recognize that there is no prescriptive list of sustainable practices: farmers have many options available to them, and their management practices must be chosen and adapted according to local production conditions and environmental constraints.

Reduced tillage

The negative impacts of mechanical tillage on soil carbon reserves and the increased susceptibility of cultivated soil to water and wind erosion have demonstrated that farming systems based on inversion tillage are not sustainable. Many options are available to reduce the depth, frequency and intensity of tillage operations, but no-till is associated with the least physical disturbance. It improves levels of soil organic matter, has profound direct and indirect effects on soil structure and aggregation, does not disrupt the soil biota, minimizes the consumption of fossil fuels and reduces labour requirements. Since a move to reduced tillage can increase compaction problems, particularly in farming systems with heavy equipment and random traffic, controlled traffic systems are usually an integral component of no-till agriculture.

Continual cropping and maintenance of a permanent cover of plant residues

This component of intensification minimizes the length of fallow periods and helps to ensure that the resources provided by roots and their exudates are continually available to the soil biological community. Continual cropping (within the limits imposed by the environment) and maintenance of a protective cover of organic matter on the soil surface mimics, to some extent, the way plants and soil interact in the natural environment.

Roots produced by previous crops are not disturbed, while the residues produced by the primary crops and any cover crops are left on the soil surface, where they moderate temperature fluctuations, conserve water and nutrients, protect the soil from erosion, minimize weeds and promote soil biological activity. Thus, crop residues are seen as a valuable resource in a sustainable farming system, rather than something that should be burnt or removed because it is a hindrance to future production. The extent of the benefits from residue retention will depend on the quantity and quality of the residues produced, and how they are manipulated.

Greater plant diversity

The practice of crop rotation plays a vital role in sustainable agriculture, as it is one of the simplest ways of minimizing losses from pests and pathogens that are often relatively crop-specific. However, there are many other options that can be used to increase biological diversity within agroecosystems, and enhance system resilience and sustainability. Examples include the maintenance of natural habitats in farming areas; integration of various forms of forestry with agriculture; the use of intercrop systems in which multiple crops are grown in mixed or structured arrangements; the planting of hedgerows and alley crops or the introduction of banker plants to encourage predators of pests; the retention or provision of windbreaks; and the introduction of legumes to fix nitrogen. In the long term, research aimed at replacing annual grain and oilseed crops with perennials (see Cox *et al*., 2006; Glover *et al*., 2007) will not only provide opportunities to increase crop diversity, but also help to make agriculture more sustainable.

Improved crop yield potential

The process of improving crops through plant breeding and genetic modification has played a major role in increasing world food production over the last 50 years. However, the effects on agricultural sustainability have been mixed. On the positive side, modern crop varieties with pest and disease resistance prevent the world's major food crops from being regularly decimated by rusts, mildews and a range of insect and nematode pests, and do so in such an effective manner that fungicides, insecticides and nematicides are not widely used on many crops. However, there are concerns that plant breeders working in high-input systems have inadvertently selected plants with poor root systems; that higher external inputs are often needed to obtain improved yields; and that genetic uniformity and a narrowing of the genetic base may lead to decreased resilience in the face of environmental stress. Future plant-breeding programmes must, therefore, concentrate on producing well-adapted varieties that not only resist or tolerate the effects of important pests and pathogens, but also have a root structure and biomass capable of retrieving nutrients effectively. The cultivars available in future must also have a greater capacity to cope with common abiotic stresses such as heat, drought and salinity.

Optimized crop nutrition

In many modern farming systems, fertilizers and manures are applied excessively because the economic response in crop yield far outweighs the cost of the fertilizer. Consequently, enormous quantities of fertilizer are being wasted. For example, about 50%, and sometimes even more, of the synthetic nitrogen applied to crops is usually lost to the environment as gaseous emissions to the atmosphere, leaching to groundwater, and runoff to surface waters (Tomich *et al*., 2011). Improved nutrient-use efficiency must, therefore, be one of the cornerstones of sustainable intensification. This is not an impossible task, as many relatively simple practices are available to optimize crop nutrition. Some of the options include the use of soil analyses to determine nutrient requirements; application of lime to maintain the appropriate pH for optimum nutrient supply; use of leaf and sap analysis to match nutrient applications to the crop's requirements; inclusion of organic soil amendments in the nutrition programme; use of controlled-release fertilizers or nitrogenous products containing nitrification inhibitors; and the introduction of legumes to provide biologically fixed nitrogen. Ultimately, however, sustainable nutrient management must also take into account the nutrients immobilized and mineralized by the soil biota. Interactions between soil organisms and organic matter govern nutrient availability to plants, and greater efforts must be made at a research level to reliably predict the outcome of these interactions, so that nutrient applications can be adjusted accordingly.

Efficient water management

Although only about 18% of the world's cropped land is irrigated, this land is vitally important, as it produces about 45% of the global food supply (Morison *et al.*, 2008). However, irrigation water will always be a scarce resource due to the competing demands of agriculture and industry, and the requirements for human consumption. From an agricultural perspective, misuse of irrigation water results in soil health and environmental problems, while current and future water supplies will be depleted if irrigation use outpaces recharge rates. Thus, efficient water management is the key to sustainable irrigated agriculture. It can be achieved by improving irrigation infrastructure; by reducing evaporative losses; and by matching water inputs to the crop's requirements through the use of technologies that monitor soil moisture, environmental conditions and plant growth.

Site-specific management

Precision farming or site-specific management involves observing, measuring and then responding to intra-field variability so that agronomic practices and resource allocation are matched to soil and crop requirements. Nutrients, pesticides and other inputs are applied differentially using predefined maps based on soil or crop condition, or with sensors that control application as machinery traverses the field (Srinivasan, 2006). The capacity of precision agriculture to vary inputs based on variability in soil properties (e.g. soil texture, water-holding capacity, organic matter status), or biological factors (e.g. weed populations, insect populations, disease occurrence, crop growth, harvestable yield) offers the potential to improve sustainability by maintaining or enhancing crop yields while reducing some of the environmental problems associated with nutrient and pest management.

Integrated pest management

Integrated pest management has been defined in various ways (Stirling, 1999), but is essentially about using our knowledge of pest and plant biology to prevent pests from causing economic damage. Pest populations are monitored; damage thresholds are determined; the impact of environmental factors on interactions between the pest and the plant are understood; a wide range of techniques (e.g. genetically resistant hosts, environmental modifications and biological control agents) are used to reduce pest populations to tolerable levels; and pesticides are only used as a last resort. IPM systems that reflect this philosophy will enhance sustainability because they are based on sound ecological principles.

Integrated crop and livestock production

One factor that impacts negatively on the sustainability of modern agriculture, particularly in developed countries, is the trend towards farm-level specialization. Crop production is becoming more specialized and crop and livestock enterprises are often separated, despite the clear soil health and environmental benefits associated with mixed crop–livestock systems. Farm livestock excrete some 50–95% of the nutrients they consume, and from an efficiency and sustainability perspective, there is a strong case for better integration of crop and livestock production, both at the individual farm and regional level (Wilkins, 2008; Kirkegaard *et al.*, 2010).

Soil Health

The quality or health of the soils used to produce crops and livestock is intimately linked to the issue of sustainable agriculture. Although some minor crops are grown hydroponically – and commercial facilities may be established to produce livestock, poultry and fish – food production is largely dependent on the thin layer of soil that covers the earth's surface. This non-renewable resource has a number of ecologically important functions: providing a suitable medium for plant growth; sustaining biological processes responsible for decomposing organic matter; cycling nutrients; maintaining soil structure; regulating pest populations; and detoxifying hazardous compounds (Powlson *et al*., 2011a). It is important from an agricultural production, environmental and sustainability perspective that those functions are maintained indefinitely.

Although it is widely recognized that maintaining healthy soil is a vital component of sustainable agriculture (Doran *et al*., 1994; 1996; Lal and Stewart, 1995; Doran and Safley, 1997; Rapport *et al*., 1997; Gregorich and Carter, 1997; Kibblewhite *et al*., 2008), the term 'soil health' has been the subject of fierce debate in the scientific literature (Sojka and Upchurch, 1999; Karlen *et al*., 2001; 2003a,b; Letey *et al*., 2003; Sojka *et al*., 2003). First, arguments abound as to how soil health should be defined and whether 'soil quality' is a more appropriate term. Second, it has been particularly difficult to find a definition of soil quality/soil health that satisfies everyone, because soil performs multiple functions simultaneously. Thus, high soil quality for one function (e.g. crop production) does not guarantee high quality for another function (e.g. environmental protection), and vice versa. Third, attempts to develop soil-quality indices have been criticized on the basis that the process does nothing more than provide a highly generalized and non-specific assessment of the overall worth, value or condition of a soil. One of the major concerns is that assessment tools do not objectively and simultaneously consider both the potential positive and negative impacts of all indicators on production, sustainability and the environment. Thus, some highly valued parameters such as levels of soil organic matter and numbers of earthworms are almost always viewed positively, even though an increase in these parameters may sometimes result in negative outcomes. Finally, there are differences between those who evaluate soil health or quality on the basis of biodiversity, bioactivity or some other attribute believed to be reflective of 'natural' benchmark conditions, and those who argue that production agriculture is not a natural system, and that the debate should be about how soils are managed to achieve the required production and environmental outcomes.

The terms 'soil health' and 'soil quality' are often used synonymously, but the former term is used here because most farmers have at least some understanding of the concept. Soil is healthy if it is fit for a purpose, which in the case of agriculture is the production of a particular crop. However, agricultural land is a component of a larger ecosystem, so it must also provide functions that prevent degradation of neighbouring environments. The definition used by Kibblewhite *et al*. (2008) encompasses both of these important functions:

> a healthy agricultural soil is one that is capable of supporting the production of food and fibre, to a level and with a quality that is sufficient to meet human requirements, together with continued delivery of other ecosystem services that are essential for maintenance of the quality of life for humans and the conservation of biodiversity.

Management impacts on soil health and the role of conservation agriculture

Farmers and land managers are well aware of the many constraints that affect the productivity of the soils used for agriculture. Those constraints are too numerous to discuss here, but include soil compaction; poor structure; surface crusting; limited water infiltration; excessive leaching of nutrients; susceptibility to erosion; high weed pressure; poor nutrient retention; low water-holding capacity; nutrient deficiencies; sub-optimal pH; excessive salinity; low biological activity; limited biological diversity; and high levels of soilborne pathogens. Although most soils have only some of these problems, no soil could ever be considered completely healthy from a production perspective, while environmental issues such as off-site movement of nutrients and pesticides, and greenhouse gas emissions, are universal problems. Thus, one of the most important roles of a farm manager is to identify and prioritize the main factors causing soil-related problems, and then attempt to improve the health of the soil through management.

In a complex system such as soil where many factors interact, the most robust approach to soil health problems is to consider how a farming system could be modified to rectify existing problems and prevent them from recurring. For example, poor soil health is often associated with low levels of soil organic matter, and so tackling that issue in particular can lead to improvements in a whole range of soil physical, chemical and biological properties. Thus, the practices previously identified as the keys to sustainable agriculture are also the keys to improving soil health.

The three most important soil improvement practices (minimal soil disturbance, permanent plant residue cover and crop rotation) form the basis of conservation agriculture (Baker *et al*., 2006; Hobbs *et al*., 2008; Kassam *et al*., 2009), a relatively recent agricultural management system that has been adopted widely in some parts of the world, particularly North America, Latin America and Australia. Conservation tillage (variously described as minimum tillage, reduced tillage, no-till or direct drill) and retention of crop residues are the primary components of conservation agriculture, and when used together, these practices reduce soil erosion and slow or reverse the precipitous decline in soil organic matter that has occurred in conventionally tilled agricultural soils over the last 100 years (Reeves, 1997; Uri, 1999; Paustian *et al*., 2000; Franzluebbers, 2004). When combined with diversified crop rotations that include cover crops, mulch-producing crops and nitrogen-fixing legumes, many soil properties are affected (Table 4.1), soil health generally improves, and suppressiveness to root pathogens is often enhanced (Sturz *et al*., 1997). However, as pointed out by many authors, including Blevins and Frye (1993) and Sojka *et al*. (2003), there are situations where the effects of conservation agriculture and increased levels of soil organic matter are not always positive. Examples include the impact of mulch cover on soil temperature, which can improve crop growth in a hot climate but slow early emergence and growth in temperate regions; decreased availability of plant-available nitrogen due to immobilization; exacerbation of diseases caused by pathogens that survive on crop residues; difficulties associated with managing some weeds in the absence of tillage; herbicide carryover and runoff; the potential for weed populations to become resistant to herbicides; and the impact of soil organic matter and earthworm burrowing on porosity and macropore formation, which can increase the risk of nutrients and pesticides becoming groundwater contaminants.

The individual economic, soil health and other benefits listed in Table 4.1 will not be obtained in every situation, but collectively these benefits provide compelling reasons for farmers to minimize tillage and incorporate residue retention and crop rotation into their farming systems. However, perhaps the most persuasive reason for adopting the soil and crop management practices associated with conservation agriculture is that they enhance soil organic carbon pools, thereby reducing atmospheric CO_2 emissions associated with climate change (Powlson *et al*., 2011b). Continuous surface cover and the increase in water-holding capacity associated with higher levels of soil organic matter also help mitigate the effects of any change in climate by increasing the tolerance of crops to higher temperatures and drought conditions (Lal, 2009: Lal *et al*., 2011).

Other management practices to improve soil health

Although integrating conservation tillage, residue retention and crop rotation is the first step towards greater sustainability and improved soil health, further incremental improvements can be obtained by adopting a range of other practices.

Well-adapted, high-yielding varieties

Genome sequencing, DNA marker technologies, and phenotype analysis are just some of the many tools currently being used by plant breeders to improve the resistance of crops to pests and diseases, and to increase their tolerance to abiotic stresses. The additional biomass produced by higher-yielding

Table 4.1. The effects of the principal components of conservation agriculture on soil health and sustainability.

	Component		
Effect	Mulch cover (crop residues, cover crops, green manures)	No tillage (minimal or no soil disturbance)	Crop rotation (includes legumes for nitrogen fixation)
Maintains a permanent residue cover on the soil surface	+	+	+
Reduces evaporative loss from upper soil layers	+	+	
Maintains the natural stratification of the soil profile	+	+	
Minimizes oxidation of soil organic matter		+	
Sequesters carbon and minimizes CO_2 loss	+	+	+
Minimizes compaction by intense rainfall	+		
Minimizes temperature fluctuations at the soil surface	+		
Maintains a supply of organic matter for the soil biota	+	+	+
Increases and maintains nitrogen levels in the root zone	+	+	+
Increases cation exchange capacity	+	+	+
Maximizes rainfall infiltration and minimizes runoff	+	+	
Minimizes erosion losses from water and wind	+	+	
Increases water-holding capacity	+	+	
Minimizes weeds	+	+	
Increases the rate of biomass production	+	+	+
Speeds the recuperation in soil porosity by the soil biota	+	+	+
Rebuilds damaged soil conditions and dynamics	+	+	+
Recycles nutrients	+	+	+
Reduces pests and diseases			+
Reduces labour input		+	
Reduces fuel-energy input		+	

Modified from Kassam *et al.* (2009).

crops should result in soil organic matter gains that will improve the health of agricultural soils. Well-adapted, disease-resistant varieties could also help to reduce the off-site impacts of agriculture, provided they have root systems that utilize applied nutrients more effectively than their susceptible counterparts.

Optimal nutrient management

In soils used for agriculture, nutrient levels must be maintained by replacing the nutrients removed in the harvested product. However, whenever industrially produced fertilizers and their organic alternatives are applied excessively, the nutrients they contain will either become environmental pollutants or be detrimental to some components of the soil biota. Thus, high nutrient-use efficiency is an important component of maintaining soil fertility, but is also essential for minimizing off-site impacts.

Efficient water management

The soil health and environmental problems associated with irrigation are widely recognized. Water tables rise when irrigation water is applied; salinity is a constant threat to irrigated agriculture; excessive inputs of water cause waterlogging and drainage problems; and salts, nutrients, herbicides and pesticides that are leached through the soil profile or transported by overland water flow will reduce the quality of downstream water. However, it is possible to avoid these negative impacts. Trickle irrigation; precision land levelling to improve surface irrigation; and monitoring soil water at multiple depths in the profile and then using the data to match irrigation inputs to plant uptake are just some of the practices that will markedly reduce deep percolation losses to groundwater. Deficit irrigation and partial root-zone drying are other management techniques that can be used to improve water use efficiency and minimize the off-site impacts of irrigation (Loveys *et al.*, 2004; Morison *et al.*, 2008).

Integrated pest management

Although IPM is widely promoted as a pest and disease-control strategy, the rates of adoption and the tactics employed vary considerably from industry to industry and from one pest to another. In some crops, pest populations are monitored and crop losses are minimized by integrating various cultural and biological controls, while in others, IPM involves little more than pesticide management. In situations where insecticides and fungicides are included in IPM programmes for above-ground pests, the possibility that residues could impact negatively on the soil biological community is rarely considered. Thus, the ultimate land management objective should be to develop a fully integrated system of managing the soil, the crops, and all pests and diseases. The IPM component would ideally be effective enough to control the key pests with minimal need for pesticides, while the crop and soil management component would aim to generate a healthy, biologically active soil capable of degrading any pesticide that might be required, thereby preventing it from becoming an environmental contaminant.

Variable-rate application and site-specific management

Intra- and inter-field variability in soil properties such as texture, depth, nutrient content and disease levels are the norm in an agricultural landscape. Variable-rate application techniques associated with precision agriculture provide the tools to optimize management in such situations. Soil variability across a field is mapped, a satellite positioning system (e.g. GPS) determines the location of farm equipment within the field, and variable-rate applicators can then apply fertilizers, pesticides and biological products in amounts that are appropriate for the crop's needs in a given location. In the same way, optical sensors are used to detect weeds and ensure that chemical or non-chemical weed controls are applied only where they are needed. Thus, variable-rate application minimizes the environmental footprint of farming, reduces costs and ensures that soil is not degraded by excessive external inputs.

A range of soil sensors is available in precision agriculture to measure various soil physical and chemical properties (Adamchuck *et al.*, 2004), while geo-referenced soil samples are widely used to determine nutrient requirements in fields that may vary in soil type, topography, cropping history or previous fertilizer inputs. Such samples can also be used to obtain an accurate base map of organic matter status. Although such information is a useful starting point for managing the soil biological community in a site-specific manner, the ultimate research objective should be to provide growers with data on the spatial and temporal variability of key soilborne pests and their natural enemies. High-throughput molecular methods of enumerating soil organisms are currently too expensive to be used in diagnostic services, but since this will change with improvements in sequencing methods and advances in bioinformatics, it will eventually be possible to integrate molecular diagnostics with the technologies available in precision agriculture.

Integrated crop and livestock production

The permanent nature of pastures and the continual presence of perennial plant species mean that soils under pasture are generally healthier than cropped soils. Pasture-based crop and livestock production systems (e.g. mixed farming systems and zero-grazing cut-and-carry systems) also require fewer external nutrient inputs than systems dominated by cropping, and so they tend to be more sustainable (Wilkins, 2008). Also, in landscapes that are subject to dryland salinity, the inclusion of deep-rooted perennials such as lucerne in a cropping rotation reduces deep drainage and prevents salinization (Bellotti, 2001). Thus, from soil health and sustainability perspectives, it makes sense to integrate livestock production and cropping.

Ecologically sound management systems: the pathway to healthy soils

The ultimate challenge of agricultural land management is to integrate the best available practices into a farming system that is not only productive and profitable, but also sustains the soil's productive capacity. The actual farming system that is chosen will depend on climatic factors, the basic properties of the soil being farmed, the resources available to implement change, and the commodity being produced. However, there is little doubt that major improvements are possible in all the world's current farming systems. The fact that the principles of conservation agriculture are being incorporated into a diverse range of farming systems in developed and developing countries around the world (Hobbs *et al*., 2008; Kassam *et al*., 2009) is testimony to the fact that progress is being made.

Soil-health benefits from conservation agriculture and precision farming: Australian examples

Conservation agriculture is widely practised in five countries: the United States, Brazil, Argentina, Canada and Australia, but the Australian situation is of particular interest. Australia has the poorest soils and one of the most variable climates in the world, and its successes with conservation agriculture suggest that the principles involved could be adopted by farmers producing almost any crop, in most regions of the world. Australia's major crops are grains (wheat and other cereals, pulses and oilseeds) and sugarcane, and the practices now used to produce those crops, and their impact on productivity and soil health, are summarized next. Further detail on grain-cropping systems can be obtained from various chapters in Tow *et al*. (2011); the sugarcane farming system is discussed by Garside *et al*. (2005); while issues associated with soil health and the soil biota are reviewed by Bell *et al*. (2007), Stirling (2008), Gupta and Knox (2010) and Gupta *et al*. (2011).

In Australia, grain is grown in a wide variety of climatic zones (dry subtropics to cool temperate and Mediterranean climates) and on vastly differing soil types (from heavy clays to coarse sands), and crops are almost always produced under rainfed conditions. Rainfall is generally low and highly variable, with most cropping regions receiving between 250 and 600 mm of rain per year. However, despite the limitations of soil and climate and the absence of government subsidies, Australian agriculture has achieved greater productivity growth than most other agricultural economies over the last 30 years (Mullen, 2007). This success has largely been achieved through the widespread adoption of conservation agriculture. Although management practices vary at a regional and local level, most leading farmers have made the change to no-till agriculture; crops are sown using equipment that incorporates improved disc-seeding technologies; in-field traffic is controlled using GPS guidance; rotational cropping or pasture leys are included in the farming system; legume crops provide nitrogen inputs; crop residues are retained on the soil surface; scanning technologies and variable-rate injection systems are used to optimize chemical application; optical-sensing devices ensure that herbicides are applied on weeds rather than on bare soil; while in-vehicle, aerial or remote sensing systems are available to provide information on environmental factors such as temperature and humidity, and the health status of the crop.

From the perspective of soil health, the introduction of these practices has generally had a positive effect. The move towards reduced-till and direct-drill systems, with associated stubble retention and traffic control, has improved most measures of physical structure (e.g. aggregate stability, the presence of stable macropores and shear strength) and also reduced compaction, thereby reversing the negative effects of conventional tillage on soil physical properties. Soil organic carbon levels have generally improved, particularly in the upper 10 cm of the profile, although studies in some environments have shown no significant change. The development of biologically mediated suppression of two of the most important soilborne diseases of wheat (Rhizoctonia bare patch and take-all) has also been observed in long-term experiments and some commercial fields (Roget, 1995; Roget *et al*., 1999; Pankhurst *et al*., 2002; Gupta *et al*., 2011) and is associated with a build-up of organic carbon and microbial biomass under direct-drilling with stubble retention (Pankhurst *et al*., 2002). There is also evidence that soil in the upper 25 cm of the soil profile is suppressive to root lesion nematode, *Pratylenchus thornei*, a major constraint to production in subtropical grain-growing areas (Stirling, 2011b). Another important soil-health benefit has been an increase in the capacity of soils to infiltrate and store water, and an improvement in the ability of roots to extract water from the soil (Turner, 2004). Therefore, crops are much more likely to reach their water-limited yield potential, with concomitant effects on productivity and the amount of organic matter returned to soil. Because there have also been negative effects in some situations (e.g. slower early-season growth under direct drill, nutrient stratification in surface soils and increases in diseases such as crown rot where pathogen inoculum survives on stubble), ongoing research and constant fine-tuning by farmers is required to continually improve and fully optimize the new system.

The Australian sugar industry is vastly different from the grains industry. Farms are much smaller (commonly 40–200 ha), the crop is grown largely as a monoculture, and inputs of fertilizer and pesticides are much higher. Also, the industry's location in the tropics and subtropics means that water is not a limitation: between 1200 and 4200 mm of rain is received each year, and in the drier areas, rainfall is supplemented by irrigation.

In the early 1990s, the Australian sugar industry was facing an uncertain future because productivity was declining due to a problem known as yield decline. At that time, sugarcane was grown on beds 1.5 m apart, machinery wheel spacing did not match crop row spacing, and the crop residues remaining after harvest were often burnt. After a plant and 3–4 ratoon crops, an expensive programme of ripping and cultivation was required to remove the old crop, alleviate compaction caused by farm machinery and then replant the field to sugarcane. A multidisciplinary research team was established to develop solutions to the problem, and its initial studies showed that soils under long-term sugarcane monoculture were physically and chemically degraded. Results of later experiments indicated that biological constraints were also limiting productivity, as large yield responses were obtained when soil fumigants, fungicides and nematicides were applied; or pasture, another crop species, or bare fallow were included in the rotation (Garside and Bell, 2011a, b). Ultimately, the 12-year research programme (summarized by Garside *et al*., 2005; Stirling, 2008) resulted in the development of a new farming system based on permanent raised beds, residue retention, minimum tillage, a leguminous rotation crop and controlled traffic using GPS guidance. This system is now being adopted by growers because it increases sugar yields, reduces costs and provides additional income from rotation crops such as soybean and peanut.

Although economic considerations (lower fuel and labour costs, and the replacement of fertilizer nitrogen with biologically fixed nitrogen from legumes) motivated growers to adopt the new sugarcane farming system, improvements in soil health were the main reason that yield increases of 20–30% were consistently obtained. Random trafficking of fields, often in wet conditions, by the heavy machinery used to plant, harvest and transport the crop meant that soil compaction was a major problem in the previous farming system. Soil physical properties improved markedly when beds were widened to accommodate controlled traffic. The introduction of a rotation crop reduced populations of fungal and nematode pathogens that were constraining crop production. A reduction in tillage increased earthworm populations, with consequential effects on macroporosity and water infiltration rates. In rainfed situations, improved water capture in periods of low rainfall contributed to yield increases, while improved percolation through macropores and retention of surface cover protected soils from erosion during intense tropical storms. There have also been signs of improvement in some chemical, biochemical and biological properties associated with soil health (Stirling *et al.*, 2010), and surface soils are now suppressive to *Pratylenchus zeae*, the main nematode pest of sugarcane (see Chapter 11 for details). Further improvements are expected to occur over time, but it is likely to take at least 15 years to fully realize the benefits from the new farming system (Stirling *et al.*, 2010, 2011b).

In summary, these Australian examples show that: (i) the principles of conservation agriculture are applicable in diverse environments and quite different farming systems; (ii) major changes in farming systems can be made relatively quickly in an environment where there is a strong level of agronomic research and good communication between scientists, extension personnel and farmers; and (iii) the economic and other benefits of conservation agriculture (e.g. reduced labour costs, much lower energy inputs, improved timeliness of operations and greater profitability) are so compelling that growers are generally willing to consider making changes to their farming system.

Although minimum tillage, residue retention and crop rotation interact together to improve a whole range of physical, chemical and biological properties associated with soil health, this does not mean that farming systems based on these practices are problem-free. Numerous issues are the subject of continuing research (e.g. nutrient stratification; management of herbicide-resistant weeds; overcoming soil structural problems during the transition to minimum till; alternative crops for inclusion in rotations), while growers may need to modify some management practices to fit the soil and climatic conditions on their farms. It is also recognized that soil organisms are a major determinant of a soil's productive capacity, and that further research is needed to fully harness the biological potential of soil.

Indicators of soil health

Soil health cannot be measured directly, because a soil's capacity to produce crops and also safeguard the environment is determined by numerous physical, chemical and biological properties, and the way they interact. However, the literature is replete with lists of measurable properties that collectively provide a broad indication of the health of a soil, and can be used to assess the impact of soil management practices on soil health (e.g. Doran and Parkin, 1994; Pankhurst *et al.*, 1997). A variety of physical, chemical and biological parameters are usually measured during the soil-health assessment process (e.g. Idowu *et al.*, 2009) and a subset of these indicators is then used to compile a relatively simple report that is designed to help growers make management decisions (e.g. Gugino *et al.*, 2009). Although such reports are useful, the practicality of measuring numerous parameters is often questioned, as certain parameters (e.g. total carbon and labile carbon) are often closely correlated with the physical and chemical properties assessed in soil-health tests.

Although it is recognized that most soil properties are ultimately determined by interactions between soil organic matter and the soil biota, biological measurements are rarely included in soil-health tests, as levels of organic matter and active carbon are often used as surrogates for biological activity and diversity. Hundreds of 'potentially useful' biological indicators have been proposed, but in many cases they simply reflect the discipline bias of the proponent. Also, most do not meet the criteria proposed by Doran and Zeiss (2000) as being required for any biological parameter that is to be used as an indicator of soil health: (i) sensitivity to variations in management; (ii) well-correlated with beneficial soil functions; (iii) useful for elucidating ecosystem processes; (iv) comprehensible and useful to land managers; and (v) easy and inexpensive to measure. This prompted Ritz *et al.* (2009) to look for biological indicators that not only provided information on important soil functions, but were also suitable for use in national-scale soil-monitoring programmes. A list of top-ranked indicators was developed (Box 4.1), but at the end of the process, the authors recognized that many of the selected indicators did not

Box 4.1. Biological indicators for use in monitoring soil health or quality

Ritz *et al*. (2009) ranked the plethora of biological methods that have been suggested for monitoring soil quality and produced a list of 21 biological indicators that were considered ecologically relevant. However, four of these could not be deployed in national-scale monitoring schemes, as further methodological development was required. The remaining indicators have been consolidated into eight groups, and the authors' comments on each of these groups are outlined as follows.

Soil microbial taxa and community structure using molecular techniques

Recent advances in molecular technologies have provided a range of methods that can be used to monitor various components of the soil biological community. Although terminal restriction length polymorphism (TRFLP) analysis has been used widely, the advent of faster, cheaper and higher-resolution sequencing technologies is providing many other options. Molecular methods are useful because high throughput is possible; information on biodiversity is obtained; results can be related to function; and DNA can be archived. However, further work is required to identify the most suitable primers, and to optimize the polymerase chain reaction (PCR), restriction and fingerprinting steps for particular groups of organisms. Also, these methods are extremely sensitive and discriminatory, and so it is not yet known how they are best applied in field situations, where spatial and temporal variability is the norm.

Soil microbial community structure and biomass from phospholipid fatty acids

Extracted lipids, in particular phospholipid fatty acids (PLFA), can be used as signature lipid biomarkers in studies of soil microbial communities. The total PLFA content is indicative of total viable biomass. Individual PLFAs (or suites thereof) can be related to community structure, as they are found predominantly, but not exclusively, in distinct microbial groups (e.g. fungi, bacteria, Gram-negative bacteria and actinobacteria). The main advantage of PLFA profiling is that it is semi-quantitative, does not rely on cultivability and provides wide coverage of the soil microbial community.

Soil respiration and carbon cycling from multiple substrate-induced respiration

Carbon cycling is fundamental to soil function, and the respiration of CO_2 from soils, arising from community-level biotic activity, is an intrinsic indicator of carbon cycling. Since measurement of this property in isolation does not provide discrimination, a multiple substrate-induced respiration (MSIR) approach is more useful, as it characterizes how a soil community responds when exposed to a range of carbon substrates of differing chemical status. As it is a laborious process to generate MSIR profiles, this method is constrained by difficulties involved in achieving high-throughput systems.

Biochemical processes from multi-enzyme profiling

Biochemical reactions in soils are mediated by enzymes produced by the soil biota. A plethora of individual enzymes can be profiled, relating to virtually any defined biochemical transformation. However, a multiple enzyme fluorometric approach is particularly useful, as sensitive measurements can be made on small samples; high-throughput assay systems are possible; and several ecological processes can be assessed in a single assay. Another advantage of this approach is that many different fluorescently labelled substrates are available to target carbon-transforming enzymes, and phosphatase and sulfatase activity.

Nematodes

The potential of nematodes as biological indicators has long been recognized, as they are abundant in soil and have a wide range of feeding habits. The total number of nematode taxa, the abundance of individual functional groups and a wide range of indices that reflect the composition of the nematode community are widely used as indicators. Since nematode extraction methods are laborious, and highly trained experts are required to identify nematodes (even to functional group level), ultimately nematode community analysis will be carried out using molecular techniques.

Continued

Box 4.1. Continued.

Microarthropods

Acari (mites) and Collembola (springtails) have been proposed as potential biological indicators because they are the dominant arthropods in many soils. Extraction methods are fairly straightforward, but the use of arthropods as indicators has been limited by the need for expert skills in identification, and by concerns about which metrics are most useful in ecological studies.

On-site visual recording of soil fauna and flora

Organisms that are readily visible (ants, earthworms and fungal fruiting bodies) are considered useful biological indicators because data can be collected relatively easily. However, consistent methodologies are required before such parameters can be used in on-site recording.

Pitfall traps for ground-dwelling and soil invertebrates

Pitfall traps are a well-established technique for assessing ground-dwelling and soil invertebrates, and are used widely in environmental surveillance. However, one disadvantage is that return visits are required to collect data.

satisfy all of the criteria considered essential by Doran and Zeiss (2000). Also, they did not know whether the indicators would prove to be reliable when used across diverse landscapes, and under environmental conditions that vary from season to season.

Soil microbial biomass is one of the simplest and most widely used means of estimating a soil's biological status, but it did not appear in the suite of top-ranked indicators identified by Ritz *et al*. (2009), largely because it was seen as a relatively gross measure that did not discriminate between various components of the soil biological community. Gonzales-Quiñones *et al*. (2011) generally agreed with that assessment, and argued that soil biomass data would be more useful if critical values were established at a regional level for specific soil type × land use combinations. They also indicated that the relationship between soil microbial biomass measurements and management practice would have to be better understood before farmers could use this parameter as a reliable indicator of soil health.

Although a paucity of reliable biological indicators limits the value of most soil-health assessments, an even greater problem is that soilborne pests and pathogens are usually ignored. A soil cannot be considered healthy if the crops that are grown in it suffer losses from soilborne diseases, and yet few of the data sets used to evaluate soil health attempt to quantify populations of nematode or insect pests; measure the inoculum density of particular pathogens; or assess the suppressiveness of the soil to key pests or pathogens. The latter characteristic is a particularly useful indicator of soil health, because a capacity to prevent soilborne pests from multiplying to destructive levels demonstrates that an active and diverse biological community is present, and that the regulatory functions within the soil food web are operating effectively. Unfortunately, however, there is not yet any simple way to assess suppressiveness to root diseases. Pathogen-specific bioassays are time-consuming and labour-intensive; multiple measurements are required to monitor characteristics that are related to suppressiveness (e.g. resilience in the face of a disturbance or stress event); and the various microbial parameters that have been assessed do not show consistent relationships to suppressiveness (van Bruggen and Semenov, 2000; Janvier *et al*., 2007).

Ecological Knowledge, Biotic Interactions and Agricultural Management

Modern agriculture faces the twin challenges of being both highly productive and sustainable, and as Gliessman (2007) pointed out, this can only be achieved by applying ecological concepts and principles to the design and management of agroecosystems. Although there is general agreement on the need for an ecological approach to farming, discussion on what constitutes ecologically sound agriculture is often polarized by arguments about what type of farming system (e.g. traditional, organic, biodynamic, conventional, integrated, community-based, free-range, low input, etc.) is best able to provide the world's food needs with the least environmental impact (Trewavas, 2001, 2004; Badgley *et al*., 2007; Badgley and Perfecto, 2007; Cassman, 2007). However, when farming systems are viewed from an ecological perspective, they all contain both positive and negative elements. Thus, it is more enlightening to focus on the impact of management on the ecosystem services provided by the soil biota: production of food and fibre; maintenance of soil structure; storage and supply of nutrients; retention and release of water; and regulation of populations of soil organisms.

Management effects on the soil biota and the limiting role of the environment

It should be clear from this and preceding chapters that the provision of ecosystem services by the soil biota is intimately linked to the quantity and quality of soil organic matter. Management practices determine carbon inputs and losses, with flow-on effects to the soil biota, but levels of soil organic matter will also be influenced by climatic factors (particularly temperature and precipitation) and numerous soil properties (e.g. texture, depth and mineral composition). Thus, management plays an important role in determining the biological status of a soil, but the environment limits what is achievable.

The role of environmental factors in limiting carbon sequestration in soils was recognized by Ingram and Fernandes (2001), who used the term 'attainable' to describe the amount of carbon that could be sequestered in a particular situation, given the limitations of soil and climate. Since there is a close association between soil organic matter and the soil biota, this conceptual framework was extended by Gonzales-Quiñones *et al*. (2011) and used to explain the size of the soil microbial biomass pool. *Potential* soil microbial biomass was considered to be the maximum microbial population that could be sustained given otherwise non-limiting conditions, and was constrained by inherent site and soil characteristics (Fig. 4.1). For any particular land-use system, the *attainable* target value for soil microbial biomass was defined by factors controlling inputs of organic carbon to soil. Any management practice that increased carbon inputs (e.g. greater net primary production due to fertilization or irrigation) would tend to increase *attainable* soil microbial biomass towards the *potential*. For soil-monitoring purposes, two lower limits were added. *Critical* was the soil microbial biomass value below which biological soil function was lost irreversibly, while *constraining* described the situation where soil biological function still occurred but was at the lower limit of the desirable range of values (Fig. 4.1). Once appropriate *attainable* values were determined, management action could be initiated to move the *actual* value towards the desired target.

Although these concepts are relevant to soil carbon and microbial biomass, there is no reason why they could not be applied to other soil biological characteristics of interest (e.g. the level of nutrient cycling; the extent of biodiversity; the rate of a particular biochemical transformation; or the level of suppressiveness to a particular pest or pathogen). The advantage of visualizing soil biological attributes in this way is that it encourages scientists and land managers to consider the edaphic and climatic constraints that limit what is possible in a specific situation, and then think about how management might move levels of a particular attribute from current or *actual* levels towards an *attainable* target. The challenge for biological scientists is to provide farmers with some indication of what targets are achievable in a given soil type, land use and environment.

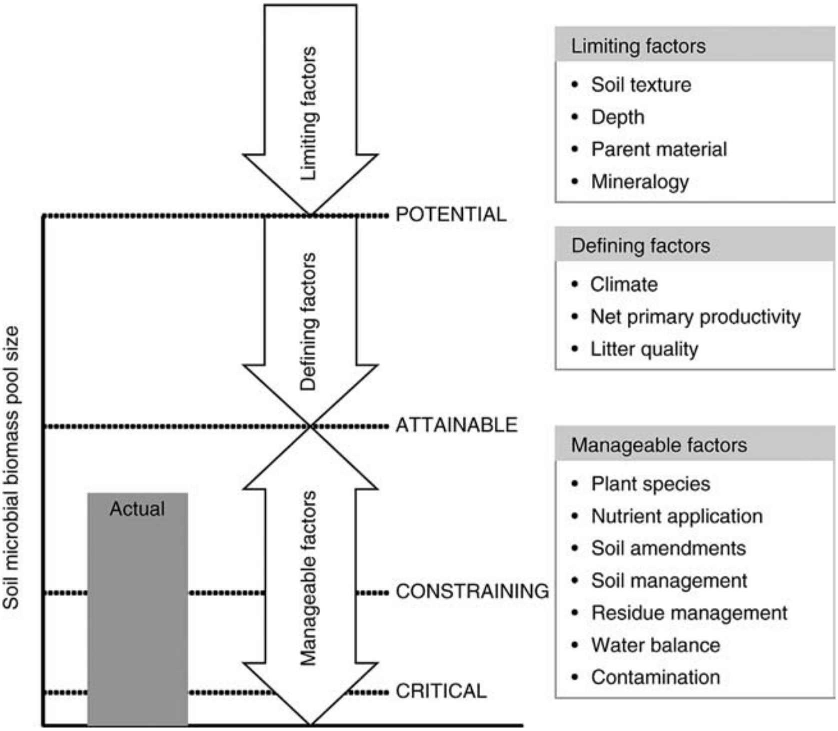

Fig. 4.1. Conceptual diagram showing the size of the soil microbial biomass pool in relation to target values and their defining factors. (From Gonzales-Quiñones *et al*., 2011, with permission.)

Provision of ecosystem services by the soil biota and the role of management

The soil biological community is responsible for providing a range of ecosystem services, and when these natural services are lost due to biological simplification, they must be replaced by external inputs (Altieri, 1999; Shennan, 2008). Thus, insecticides, nematicides and fungicides are required when regulatory processes are no longer effective enough to suppress pests and pathogens. The essence of ecologically sound agriculture is to understand the biological interactions involved in the provision of a desired service and then use that knowledge to manipulate the biota through management, thereby minimizing or eliminating the need for external inputs. In the case of crop nutrition, this process might involve: (i) knowing the level of nutrients required to replace the nutrients removed in the harvested product; (ii) reducing leaching losses by increasing the soil's cation exchange capacity; (iii) minimizing denitrification losses through better drainage; (iv) including legumes in the rotation to supply biologically fixed nitrogen; (v) optimizing mycorrhizal symbioses with plant roots to enhance phosphorus and micronutrient uptake; (vi) understanding the mineralization and immobilization processes associated with soil organic matter, and then adjusting residue management practices so that naturally cycled nutrients are available when they are required by the crop; (vii) ensuring that nutrients are not applied in excess of crop requirements; and (viii) applying nutrients in forms that do not impact negatively on key components of the soil biota.

Given the number of issues listed above, it should be apparent that taking an ecological approach to nutrient management is a huge challenge. Biotic interactions are important mediators of nutrient availability, but we are not yet able to connect population and community ecology with fluxes of nutrients. Also, the interactions involved in biological nutrient cycling are complex and often multitrophic, and our understanding of the processes involved is too rudimentary to be used successfully in crop management (Plenchette *et al*., 2005; Goulding *et al*., 2008). Results from organic farming systems, where nutrient-cycling processes form the basis of crop nutrition, are testimony to the difficulties involved in taking such an approach to maintaining soil fertility: yields are generally lower than in conventional farming systems (Posner *et al*., 2008); the biological community is not always enhanced by organic inputs (Shannon *et al*., 2002); and high levels of mycorrhizal colonization do not necessarily overcome phosphorus deficiency (Kirchmann and Ryan, 2004). Thus, there is a need for research to better understand and manage the microbially mediated processes that impact on soil nutrient dynamics. A return to more diverse crop rotations and increased use of cover or catch crops, for example, is likely to improve soil health and provide some pest and disease control, but may have both positive and negative effects from a nutritional perspective. Fertilizer nitrogen requirements may be reduced and nutrient-use efficiency may improve, but more nitrates may be leached from the profile, an outcome which indicates that changes in practice do not always produce positive results (Goulding *et al*., 2008).

A similar situation applies to another important service provided by the soil biota: regulation of soilborne pests and diseases. There is plenty of evidence to demonstrate that biological mechanisms of suppression operate in agricultural soils; that they act against a wide range of pests and pathogens; and that they are influenced by management (Baker and Cook, 1974; Stirling, 1991; Hoitink and Boehm, 1999; Kerry, 2000; Weller *et al*., 2002; Stone *et al*., 2004). Sometimes the suppressive agents are highly specialized antagonists, while in other cases suppression is associated with the wider biological community. However, we are not yet able to define the type of biological community and the level of biological activity required to maintain populations of specific pests and pathogens at levels that do not cause economic damage.

Integrated Soil Biology Management

The material presented in this chapter outlines the many issues that must be considered by anyone wishing to manage soil biotic interactions in such a way that crop productivity is maintained or improved; soil health is enhanced; off-site environmental impacts are minimized; natural processes are contributing to crop nutrition; and regulatory mechanisms are providing some pest and disease control. Clearly, this is an overwhelming task that involves what was referred to in Chapter 1 as ‘integrated soil biology management’: a management approach that not only requires crop-specific and site-specific knowledge, but a capacity to integrate various practices into a productive and sustainable farming system that provides a full range of ecosystem services. Although the complexities associated with this approach are obvious, it is only by considering the full gamut of issues that affect crop production (crops, soils, climate, water, organic matter, crop rotations, tillage practice, nutrients, weeds, pests, diseases and beneficial organisms) that farming systems can be improved. Improvements will always be incremental, but that is to be expected, given the inherent complexity of all farming systems.

The essence of integrated soil biology management is to manage agroecosystems at a farm and landscape level so that services such as soil formation, carbon sequestration, nutrient cycling, water regulation and pest and disease suppression are maximized and disservices such as nutrient runoff, sedimentation of waterways and greenhouse gas emissions are minimized. The issues involved were depicted previously in Fig. 1.1 and discussed by Power (2010) and Powlson *et al*. (2011a). Although the approach involves manipulating soil, crops and farm animals to achieve the desired effects, the term 'integrated soil biology management' is used because the outcomes are manifested through the soil biota.

Managing soil organic carbon is central to integrated soil biology management because the quantity and quality of soil organic inputs affect the activity and diversity of organisms within the soil food web, and they, in turn, influence numerous soil properties relevant to ecosystem function and crop growth. Since organic carbon levels in many cropped soils have declined to the point where agricultural productivity is being compromised, practices that promote carbon sequestration are actively promoted in the literature on sustainable farming systems, and soil organic carbon is always seen as a keystone indicator of soil health. There is no particular critical threshold for organic carbon that is applicable across different soils and environments (see review by Loveland and Webb, 2003), but it is clear that carbon levels in most agricultural soils are well below the maximum level attainable in a given soil type and location. Raising total carbon levels normally provides benefits, but as the above review indicated, the 'active' or 'fresh' fraction seems to be more important in determining services associated with soil structure and aggregation. Since these fractions support the soil biota, they are also the key to maintaining functions such as nutrient cycling and biological suppressiveness.

The organic carbon content of a soil is the result of a balance between inputs (plant roots, root exudates, plant residues and manures) and outputs (evolution of CO_2 due to respiration by the soil food web, leaching of soluble organic carbon compounds down the soil profile, and particulate losses from erosion). However, in the absence of substantial inputs of manure or other organic materials, it is difficult to influence these processes and increase the total organic carbon content of arable soils. Nevertheless, this is a worthwhile objective, as small changes in total carbon content can have disproportionally large effects on a range of soil properties (Powlson *et al.*, 2011a). Thus, from the perspective of enhancing the activity and diversity of the soil biological community, farmers must focus on adopting practices that increase total carbon inputs, maintain labile carbon fractions in the rooting zone and reduce the rate of decomposition of organic matter. Such practices include rotational cropping, intercropping with perennials, green manuring, residue retention, mulching and minimum tillage.

Since nutrient cycling/recycling is one of the ecosystem services provided by soil organisms, plant nutrition is one of the key elements to be considered when attempts are made to manipulate the soil biological community. Crop residues and organic amendments are the only source of nitrogen and other plant nutrients in low input and organic farming systems, and their availability to the crop is mediated by the soil biota. However, in conventional farming systems, these natural decomposition and mineralization processes are largely overridden, with crop nutrient requirements being supplied as mineral fertilizers. The challenge of integrated soil biology management is to manage carbon inputs so that biological processes provide a greater proportion of the nutrients required by the crop. Instead of applying a single pulse of fertilizer at excessive rates (because leaching or other losses are expected later in the growing season), the aim would be to develop better ways of utilizing the nutrients gradually made available from soil reserves, crop residues and biological nitrogen fixation. The plants' additional growth requirements would be satisfied with judiciously placed and appropriately timed inputs of organic or synthetic fertilizers at critical periods.

As we learn more about the organisms that provide these nutrient-cycling services, and are more easily able to enumerate them using molecular methods, this type of management will become increasingly feasible. For example, in a series of studies cited by Ferris (2010), bacterial-feeding nematodes mineralized nitrogen throughout the growing season, but due to the different temperature adaptations of the nematodes involved, the nutritional service was mainly provided by rhabditids in spring and cephalobids in summer (Fig. 4.2). In another example, concentrations of mineral

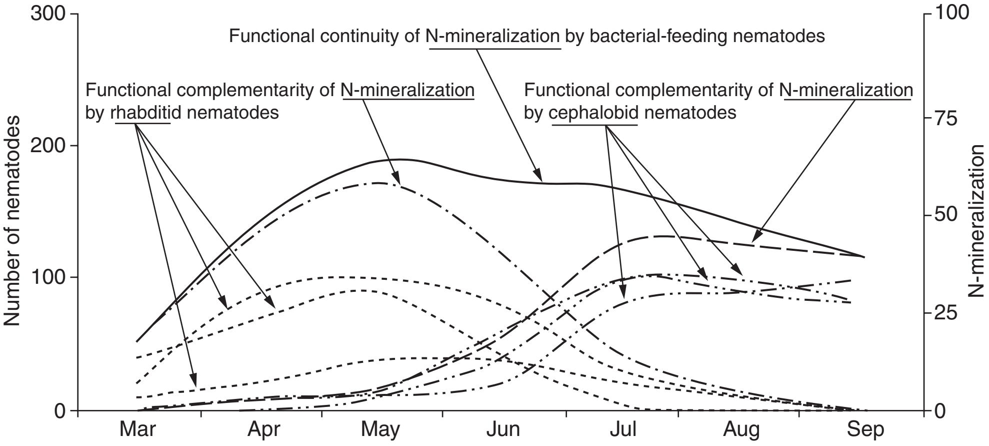

Fig. 4.2. Functional continuity of nitrogen mineralization (based on lifetime μg N per individual) for diverse assemblages of rhabditid and cephalobid nematodes adapted to temperature conditions in California during spring (March–May) and summer (June–September), respectively. (From Ferris, 2010, with permission.)

nitrogen available to a tomato crop were enhanced by manipulating cover cropping and irrigation practices to create conditions suitable for biological activity, particularly bacterivore nematodes (Ferris *et al.*, 2004). Since environmental conditions that favoured bacterivore nematodes probably also favoured other microbial grazers, including protozoa, the abundance of these nematodes was considered a useful indicator of overall grazing activity and nitrogen mineralization rates from soil fauna. Therefore, both these examples suggest that identifying the key organisms responsible for nutrient-cycling services and then manipulating their populations through management is a pathway to more sustainable nutrient usage.

One ecosystem service that has been lost in modern agriculture is the capacity of the system to suppress soilborne pests and diseases. Plant-parasitic nematodes and other soilborne pathogens normally do not cause problems in natural systems because they are kept under control by organisms that compete with them for the same food resource, and by parasites and predators at higher trophic levels in the soil food web. This interacting biological community remains active and diverse because it is continually maintained by carbon inputs from plants. The suppressive services provided by this community have largely disappeared from agricultural soils because the soil food web is repeatedly disrupted by cultivation; beneficial organisms are disturbed or killed by pesticide and nutrient inputs; vital food reserves are depleted because carbon is exported as harvested product and not replaced; and decomposition processes that convert organic matter to CO_2 are accelerated by tillage. Integrated soil biology management means thinking holistically about all the practices used to produce crops; recognizing that the suppressive services provided by the soil food web are affected by management; and then redesigning the farming system so that those services begin to operate effectively. This issue is explored in more detail in Chapter 11.

Ecologically Based Management Systems and the Role of Farmers

It is easy to idealize that ecologically based decision making should play a greater role in agriculture. However, achieving this in practice will require mechanisms for dealing with the complexity that is inevitably associated with production systems that rely heavily on ecological processes. Shennan (2008) encapsulated the issues in this way: (i) in real farming systems, multiple variables interact in site-specific and farmer-specific ways; (ii) the outcomes of complex biotic interactions can be unpredictable and idiosyncratic; (iii) crop-specific and site-specific knowledge, together with an understanding of general system behaviour, is required to manage the whole system; and (iv) management complexity and perceived higher risks (relative to the continued use of chemical inputs) are a significant barrier to the wider adoption of ecological agriculture. It was also noted that discipline-based researchers are not well equipped to cope with this complexity, as they study only a few variables and try to control others in their attempts to understand the mechanisms driving ecological interactions.

Given the difficulties involved in managing ecologically based systems of agriculture, there is a need to consider how growers can assimilate the knowledge that is generated by research and use it to improve their farming systems. The traditional approach to agricultural extension has been to develop management recommendations based on mechanistic research and then extend them to farmers in different growing regions. Shennan (2008) argued that this research/extension model was no longer applicable and should be replaced by an interactive learning model involving farmers and researchers. This process would accommodate knowledge held by both parties and should, therefore, result in two outcomes: farmers would increase their understanding of ecological processes so they could better adapt management approaches to suit their own situation, while researchers would become more aware of the multiple variables that were interacting within a real farming system and could begin to consider how they might be responding to management. The new model would be accompanied by an increase in field-based adaptive research, with an emphasis on monitoring performance as adaptations were made.

Implications for Biological Control

The first section of this chapter highlights the fact that food security will be one of this century's key global challenges. More food must be produced from existing resources without damaging the environment, and this will largely be achieved through a process of sustainable intensification. Those involved in agriculture will continue to innovate, but proven technologies associated with conservation agriculture and site-specific crop management will form the basis of future farming systems. Thus, in the foreseeable future, farmers in many countries face the challenge of introducing practices such as reduced or zero tillage, cover cropping, residue retention, crop rotation and site-specific management into crop production systems where such practices are not yet used widely. Given the complexity of farming systems, together with the natural predisposition of farmers to resist change, and the fact that many governments stifle innovation by subsidizing agriculture, this will not be an easy task. Nevertheless, on-farm research sites must be established to demonstrate that farming systems can be modified, and agronomists and extension personnel will need to work with farmers to develop and then fine-tune the new systems. Nematologists must be involved in this process, because the task of reducing losses from nematode pests, and the problems involved in manipulating the free-living nematode community to improve nutrient cycling and regulatory processes, are inextricably linked to the development of crop and soil management systems that improve soil health, increase productivity and enhance sustainability.

Once farmers begin to use variable-rate-application equipment and other methods to optimize nutrient inputs, and crop moisture stress is reduced by minimizing evaporative losses, increasing the soil's water-holding capacity and improving irrigation management, nematologists will have to address the issue of whether plant-parasitic nematodes are still causing economic losses. Stress associated with inadequate water or nutrient uptake exacerbates damage caused by nematodes (Barker and Olthof, 1976; McSorley and Phillips, 1993), and so it is likely that problems caused by nematodes will become less severe when these stress factors are ameliorated or removed. Thus, estimates of the severity of losses caused by nematodes (see Box 3.4) may no longer be relevant, as they were obtained in farming systems that in many cases are markedly different to those operating today. Crop loss estimates must, therefore, be redetermined under conditions where crops are grown in a more sustainable manner, and water and nutrients are managed using the best available technologies. The critical question to be answered is whether the optimization of crop management results in situations where damage thresholds increase to a point where plant-parasitic nematodes become a relatively minor constraint to crop production. All available evidence suggests that nematodes will cause fewer problems when environmental stresses are minimized, opening up opportunities to manage them using strategies that focus on improving soil and plant health rather than eliminating the pest.

From an ecological perspective, the main benefit from introducing some or all of the practices associated with conservation agriculture will be to enhance levels of soil organic matter, particularly in surface layers. Given the role of soil organic matter and its associated biota in improving soil moisture relations and in storing and cycling nutrients, this improvement will have major flow-on effects to the crop loss/damage threshold issue discussed in the previous paragraph. However, it will also affect the natural processes that regulate populations of nematodes and other soilborne pathogens. Organic matter-mediated disease suppression is a widely recognized phenomenon (Stone *et al*., 2004), and so levels of suppressiveness should increase when soil is no longer tilled and growers begin to see organic matter as a valuable resource rather than something that interferes with farm operations. The challenge facing nematologists is to understand how the quantity, quality and timing of organic inputs, and how they are managed, influence the regulatory processes that stabilize populations of plant-parasitic nematodes. There are many questions to be answered:

- What level of soil organic carbon is required to achieve useful levels of suppressiveness?
- How does this vary with soil type and climate?
- Are particular forms or fractions of soil organic matter associated with suppressiveness?
- What practices must be implemented to maintain the continuity of regulatory services?
- What suppressive agents are involved and does their relative importance vary with crop, soil type and environment?
- What easily measured parameters can be used as indicators of suppressiveness?
- What is the impact of potentially disruptive treatments (e.g. tillage, nutrient inputs, pesticides) on suppressiveness?
- Are particular soil properties (e.g. clay content) associated with suppressiveness?
- What is the role of environmental factors such as moisture and temperature?
- Can organic inputs be manipulated to achieve higher or more constant levels of suppression?

These issues are discussed later in this book, but it will be apparent from the discussion in Chapter 9 that we have taken no more than a few small steps towards understanding how organic inputs influence natural regulatory processes in managed ecosystems. Organic amendments, for example, are often used as a nematode management tool, but outcomes are essentially unpredictable due to our lack of knowledge of the chemical and biological processes associated with the decomposition of organic matter.

Complexity is a theme that runs throughout this book. Biological complexity is inevitable when dealing with terrestrial ecosystems, as all six kingdoms of life (Bacteria, Archaea, Protista, Plantae, Fungi and Animalia) occur in soil and there is incredible diversity within each kingdom. Since it is simply impossible for one person to be familiar with the taxonomic and ecological attributes of all these organisms, soil biologists tend to specialize. Thus, if science is to ever come to grips with the complexity of the soil biota, interdisciplinary cooperation must occur, and biologists working with soil must have a broad understanding of soil ecology.

When the complexity associated with modern farming systems is added, it should be apparent that biological control of nematodes cannot be considered in isolation from the many other economic, environmental, productivity and sustainability issues that affect the way crops are grown. It is for this reason that integrated soil biology management, rather than biological control, is emphasized throughout this book. Biological control will only become a component of nematode management programmes if the interactions required to achieve it operate within farming systems that are both profitable and sustainable. Thus, the first step in establishing effective methods of biological control is to work towards developing farming systems that provide a better biotic and abiotic environment for growing plants. Once those systems are in place, the stresses associated with poor soil health should be minimized, while the mechanisms regulating nematode populations should start to function as a result of interactions between plants, crop residues, the nematode community and the environment. In many situations, no further steps will be necessary, other than the ongoing process of stewardship, as nematodes will no longer be pests of major economic concern. However, there will also be situations where a particularly virulent nematode pest is attacking a crop, and in those cases, the level of nematode control may have to be increased by fine-tuning the new farming system or introducing other management tactics.

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Biosecurity Surveillance in Agriculture and Environment: a Review

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2.1 Introduction: the Concept of Biosecurity

The term **biosecurity** has many definitions. It is frequently perceived as a new, more coordinated approach, generally led by a particular governmental authority or network of authorities, to understand and manage natural and human-caused threats to a range of biological resources. The approach includes an 'increasing reliance on systematic risk analysis' (FAO, 2007) and integration of existing sectoral capacities, which consequentially highlights any gaps in authority or coverage of risk management measures. The holistic, almost organic nature of the concept (for which the specific objective or desired outcome may not always be clear) is balanced against a pragmatic insistence on cost-effective, efficient steps towards protection of valued resources.

In keeping with the theme of this book, the focus of this chapter will be on biosecurity and biosecurity surveillance among plants, animals and ecosystems. In this sense, the term biosecurity includes: (i) the protection of countries against alien (non-endemic or non-native) plant, animal or marine pests (Waage and Mumford, 2008); (ii) measures to contain or reduce existing disease (Defra, 2005); and (iii) food safety, sometimes known as food defence (Zmorzynska and Hunger, 2008). In this context of agricultural and environmental biosecurity, definitions vary in detail but are similar in intent at international, regional, national and local scales. Definitions and commentaries from various sources are shown in Table 2.1.

However, we commence the chapter with a broader review of the definition of biosecurity and biosecurity surveillance to clarify the usage of the term. The term has also been employed to mean a framework for evaluation of introductions of living organisms, including defence against biological weapons and bioterrorism (O'Toole and Inglesby, 2003; Normann, 2010). The term appeared in publications about the growing bioterrorist threat around 1995 (Zmorzynska and Hunger, 2008). Its use in that context then expanded rapidly after the 2001 incident of bioterrorism of anthrax in postal letters. A 2006 report, 'Globalization, Biosecurity, and the Future of the Life Sciences' (National Research Council, 2006), defines biosecurity as 'security against the inadvertent, inappropriate, or intentional malicious or malevolent use of potentially dangerous biological agents or biotechnology, including the development, production, stockpiling, or use of biological weapons, as well as natural outbreaks of newly emergent and epidemic diseases'.

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Biosecurity Surveillance: Quantitative Approaches (eds F. Jarrad *et al.*)

Table 2.1. Biosecurity definitions and commentaries relevant to agriculture and environment.

Organization or country	Definition/commentary	Reference
Food and Agriculture Organization of the United Nations (FAO)	Biosecurity is a strategic and integrated approach that encompasses the policy and regulatory frameworks (including instruments and activities) that analyse and manage risks in the sectors of food safety, animal life and health, and plant life and health, including associated environmental risk. Biosecurity covers the introduction of plant pests, animal pests and diseases, and zoonoses, the introduction and release of genetically modified organisms (GMOs) and their products, and the introduction and management of invasive alien species and genotypes. Biosecurity is defined as a holistic concept of direct relevance to the sustainability of agriculture, food safety, and the protection of the environment, including biodiversity.	FAO (2005)
FAO paper on biosecurity and forests	…'harm' is the damage done by something that might have been prevented through biosecurity, whereas 'risk' is the chance of that harm occurring.	Cock (2003)
FAO paper on farm biosecurity	Biosecurity plans require the adoption of a set of attitudes and behaviours that reduce risk in activities involving … production and marketing. A comprehensive, detailed, practical and easily understood plan is most effective.	FAO (2011) (on poultry)
Windhoek Declaration on an aquatic biosecurity framework for southern Africa	… biosecurity … safeguards animal health, protects biodiversity, promotes environmental sustainability and enhances food safety. The livelihoods of many people depend on fisheries and aquaculture, including some of the most vulnerable in the region.	Windhoek Declaration (2009)
Australia	Environmental biosecurity is the protection of the environment and social amenity from the negative effects associated with invasive species: including weeds, pests and diseases. It occurs across the entire biosecurity continuum: pre-border preparedness, border protection and post-border management and control.	Australian Government, Department of Sustainability, Environment, Water, Population and Communities (2013)
New Zealand	… the exclusion, eradication or effect management of risks posed by pests and diseases to the economy, environment and human health.	New Zealand Government, Ministry for Primary Industries (undated)
Canada (dairy cattle)	Farm-level biosecurity is a series of management practices designed to minimize or prevent and control: (i) the introduction of infectious disease agents onto a farm; (ii) spread within a farm production operation; and (iii) export of these disease agents beyond the farm that may have an adverse effect on the economy, environment and human health.	CFIA (2013)
Canada (beef cattle)	Those practices that prevent or mitigate disease from entering, spreading within or being released from operations that may contain livestock.	CFIA (2012)

Organization or country	Definition/commentary	Reference
Bhutan	Biosecurity shall contribute to achieving Gross National Happiness by ensuring Bhutanese people, the biological resources, plants and animals are protected from the harmful effects of pests and diseases, invasive alien species, genetically modified organisms, toxic chemicals and food additives.	Frampton (2010)
Tasmania Australia	… the protection of industries, the environment and public well-being, health, amenity and safety from the negative impacts of pests, diseases and weeds.	Government of Tasmania (2007)
Victoria Australia	… the protection of the economy, the environment, social amenity or human health from negative impacts associated with the entry, establishment or spread of animal or plant pests and disease, or invasive plant and animal species.	State Government of Victoria, Department of Primary Industries (2010)
Great Britain Non-native Species Secretariat (GB NNSS)	Biosecurity means taking steps to make sure that good hygiene practices are in place to reduce and minimize the risk of spreading invasive non-native species.	GB NNSS (2011)

The term is further convoluted through translation: for example, in Chinese, French, German and Russian, the terms biosecurity and biosafety translate into the same word. This is despite the fact that, in English, 'biosafety' is frequently linked with laboratory safety and biocontainment when research involves hazardous materials (e.g. pathogens), or to frameworks for evaluation of genetically modified organisms (GMO). Either as biosafety or biosecurity, this usage aligns with the World Health Organization (WHO) definition as the 'protection, control and accountability for valuable biological materials within laboratories in order to prevent their unauthorized access, loss, theft, misuse, diversion or intentional release' (Secretariat of the Biological Weapons Convention, 2011). One commentary suggests that including the plant and animal health issues under the rubric of biosecurity would link these too closely to the mentality of national security measures and make activities less transparent (Zmorzynska and Hunger, 2008). These definitions focusing on threats to security through biological means are not explored in depth in this chapter.

Even when narrowed down to the agricultural and environmental usage of biosecurity, major differences in understanding of the term do arise. As a result of the broad and changing usage of this term, there is controversy over what is 'in' and 'out' of the definition of biosecurity. Arguments exist about whether the concept is 'animal and plant biosecurity' or simply 'biosecurity' (see Box 2.1). Of course, the nature of, and positions on, this question, typically depend on the discipline base of the proponents, as discussed throughout this chapter.

Moreover, the intent of biosecurity seems always to be interdisciplinary or intersectoral, aimed at balancing multiple objectives and based on a more holistic approach to protecting and using the biological resources of the place under consideration. Some definitions consider biological resources in terms of entire ecosystems, populations of one species, individual organisms and down to the genetic level. Many of the definitions of biosecurity instead implicitly refer to actions or practices of monitoring or surveillance or control measures, or on the risk and risk management or mitigation of the threats. In this instance, sometimes the pathway or mechanism for the threat to biosecurity is highlighted.

Frequently, factors that are not strictly biological are covered by the definitions,

Box 2.1. Is biosecurity about plant and animal health?

Arguments exist about whether the concept is 'animal and plant biosecurity' or simply 'biosecurity'. In most cases when a biosecurity approach is adopted, plant and animal health will persist as distinct sectors, at both legislative and operational levels (FAO, 2007). Economically, animals are comparatively higher value investments per head but plants can impact equally on food security. Biological differences include the comparatively larger number of plant pests, the modes and states of transport or pathways for entry of the pests, the biosecurity treatments and the timeframe required for response to an outbreak. Historically, animal biosecurity is more established and more cohesive. Furthermore, under the existing system for animal health, for the large part, surveillance is aimed at detection of 'notifiable diseases' of animals, which is a predetermined list of fewer than 50 well-defined diseases or syndromes that may occur in livestock or poultry (OIE, 2013). This leaves the health of many animals (essentially all non-domesticated ones) outside the vision of surveillance (Convention on Biological Diversity (CBD) Secretariat, 2001a).

In further recognition of the importance of the historic sectors for animal and plant health, the FAO Biosecurity Toolkit (FAO, 2007) emphasizes the concept of biosecurity as one of integration rather than harmonization of sectors. This means that biosecurity surveillance encompasses the existing approaches to surveillance, plus a more coordinated and comprehensive monitoring of organisms, which might not traditionally be covered by the national authorities for plant or animal health. The new approach, which addresses gaps in these historic sectors but also emphasizes a more coordinated strategic approach, has suggested to many that a new term and, in some cases, a new governmental entity with new authorities, is required to face today's threats to biological resources. This now clearly includes genetic resources, resources of individual organisms and populations, as well as ecological systems.

such as economic and social issues. This approach was taken up by smaller nations, in particular, where limits in resources demand an efficient and coordinated public sector. Early examples of biosecurity initiatives from the 1990s include Norway (see Sandlund *et al.*, 1996; Håstein *et al.*, 2008), New Zealand (Froud *et al.*, 2008; MAF Biosecurity New Zealand, 2009) and Belize (Government of Belize, 2000; FAO, 2008; Outhwaite, 2010), all relatively small nations.

Spatial aspects of the definitions vary (e.g. farm level, country level, etc.) or are not defined. Few pin down a time scale for the concept. The emphasis seems to be on an 'approach', 'strategy' and 'attitude' as much as on the actions to be taken, as laid out in Table 2.1. Given the multisectoral nature of the concept, biosecurity cannot be defined in specific terms as a state of health and well-being, as one might define clean air or potable water. Therefore, many of the definitions of biosecurity instead implicitly refer to actions or practices of monitoring or surveillance or control measures, themselves.

Certainly, a common understanding of surveillance of biosecurity is hampered by the broad uses and wide variation of meanings for biosecurity. We consider, then, the concept of surveillance in the traditional sectors for animal and plant health.

2.2 Plant and Animal Health Surveillance

2.2.1 Historic authorities and approaches for plant and animal health surveillance

In the context of animal biosecurity, the major source of guidance is the World Organisation for Animal Health or OIE (formerly the Organization International des Epizooties). The OIE is the inter-governmental organization for improving animal health worldwide (OIE, 2013). Created in 1924, the OIE remains the primary body for global coordination, with a total of 178 member countries in 2013. It was also subsequently recognized as a reference organization, with all of its standards being recognized by the World Trade Organization (WTO) through the Agreement on the Application of Sanitary and Phytosanitary Measures (SPS). In the context of plant biosecurity, guidance, primarily in the form of standards, is developed through the International Plant Protection Convention (IPPC) and its 179 contracting parties. The IPPC is an international agreement on plant health, deposited with the Food and Agriculture Organization of the United Nations (FAO) and operating under its administrative structure, now over 60 years old. The aim of the treaty is to prevent the transboundary spread of exotic pests of plants and plant products, in order to preserve plant resources and facilitate safe trade (IPPC, 2012a).

As with animal health (OIE, 2013), plant health guidance is implemented on the national level by the appropriate authority in the national governments (i.e. the National Plant Protection Organizations), although surveillance programmes may also be regional or subregional, or (less frequently) global (IPPC, 2012b).

In plant health, surveillance is further clarified in the definitions in Table 2.2, which, taken as a whole, identify who does the surveillance, what is being monitored, the time period and how data will be recorded. In plant health, as in animal health, surveillance is a critical component of determination of the health status of the country (i.e. pest status – present or absent). Official programmes are linked to international recognition of the health status (e.g. for animal diseases), which directly affects the opportunities for trade. Surveillance can also be used to orient and inform control programmes or ensure the

Table 2.2. Definitions from the International Plant Protection Convention (IPPC) relating to surveillance. (From International Standards for Phytosanitary Measures (ISPM) 5; FAO, 2012.)

Term	Definition	References
Surveillance	An official process which collects and records data on pest occurrence or absence by survey, monitoring or other procedures	CEPM (1996)
Monitoring	An official ongoing process to verify phytosanitary situations	CEPM (1996)
Monitoring survey	Ongoing survey to verify the characteristics of a pest population	FAO (1996)
Survey	An official procedure conducted over a defined period of time to determine the characteristics of a pest population or to determine which species occur in an area	FAO (1990) (revised CEPM, 1996)
Delimiting survey	Survey conducted to establish the boundaries of an area considered to be infested by or free from a pest	FAO (1990)
Detection survey	Survey conducted in an area to determine if pests are present	FAO (1990) (revised FAO, 1996)
Occurrence	The presence in an area of a pest officially recognized to be indigenous or introduced and not officially reported to have been eradicated (formerly ‘occur’)	FAO (1990) (revised FAO, 1996; ISPM 17; FAO, 2002)
Pest record	A document providing information concerning the presence or absence of a specific pest at a particular location at a certain time, within an area (usually a country) under described circumstances	CEPM (1997)
Pest status (in an area)	Presence or absence, at the present time, of a pest in an area, including where appropriate its distribution, as officially determined using expert judgement on the basis of current and historical pest records and other information	CEPM (1997) (revised ICPM, 1998)

efficacy of risk management (preventative or control) measures, as noted in Box 2.2.

These definitions are detailed and precise and establish the various aspects of surveillance, which is a combination of targeted surveys and ongoing monitoring to: (i) detect new introductions or incursions of pests; (ii) delimit any occurrences which are being contained; (iii) provide official judgement of the pest status; and (iv) be the basis for records. These records, in turn, affect decisions regarding the risk from international trade. The need to set parameters of time and space is included, without indicating the appropriate values.

While most of the surveillance actions as defined in Table 2.2 are conducted by national authorities, regional and international entities and programmes are crucial to successful surveillance. Figure 2.1 showing Cuba's national surveillance system in plant health (taken from IPPC Secretariat, 2012), illustrates the range of inputs into a surveillance system more graphically. For example, pest alerts are a critical component of the overall surveillance programme. Both the European and Mediterranean Plant Protection Organization (EPPO) and the North American Plant Protection Organization (NAPPO), both Regional Plant Protection Organizations under the IPPC, provide early warning systems (including an Alert List, a monthly bulletin of resources and news, and a list of invasive alien plants) to facilitate the identification of potential pest risks (MacLeod, 2010).

For animal health, FAO carries out the Emergency Prevention Scheme (EMPRES) to address prevention and early warning across the entire food chain, including animal health, plant protection and food safety (FAO, 2013). On the regional level, the European Food Safety Authority (EFSA) was established by the European Union (EU) in response to the food crises in the 1990s such as bovine spongiform encephalopathy (BSE) and dioxin in food products (Deluyka and Silano, 2012).

In earlier studies, regional and global initiatives were considered critical, because national-level surveillance and advance alert systems have often been weak (Convention on Biological Diversity (CBD) Secretariat, 2001b), despite the available international guidelines. Historically there has been a lack of conclusive or comprehensive information about pest status (presence or absence) and inadequate data management systems. Emergency actions, coming before an organism is officially recognized (e.g. nationally as a quarantine pest or internationally as a notifiable disease), were not always supported by legal authority and political will has had a significant influence

Box 2.2. The importance of surveillance in biosecurity programmes.

Surveillance is considered one of the primary activities in any biosecurity programme. Three steps in a biosecurity programme have been proposed (adapted from Cock, 2003) as:

- **Problem formulation**: identification of objectives, time frames and spatial boundaries; identification and assessment of risks; agreement on roles and responsibilities; agreement on methodologies for each of the three steps; identification of decision points and indicators of success; development of contingency plans to establish financial, human and infrastructural needs and access.
- **Surveillance**: biological monitoring of the targeted threat; general monitoring for unanticipated changes, such as development of invasiveness or contagiousness over time; system monitoring to ensure that the procedures for detecting a threat are functioning correctly and fulfilling the purpose (the latter point may be considered part of management).
- **Management**: implementation of the chosen response activities, such as for containment or eradication; evaluation of success over time and, in the event of failure, actions to redress or mitigate the situation. This relies on post-invasion surveillance to continually inform the management.

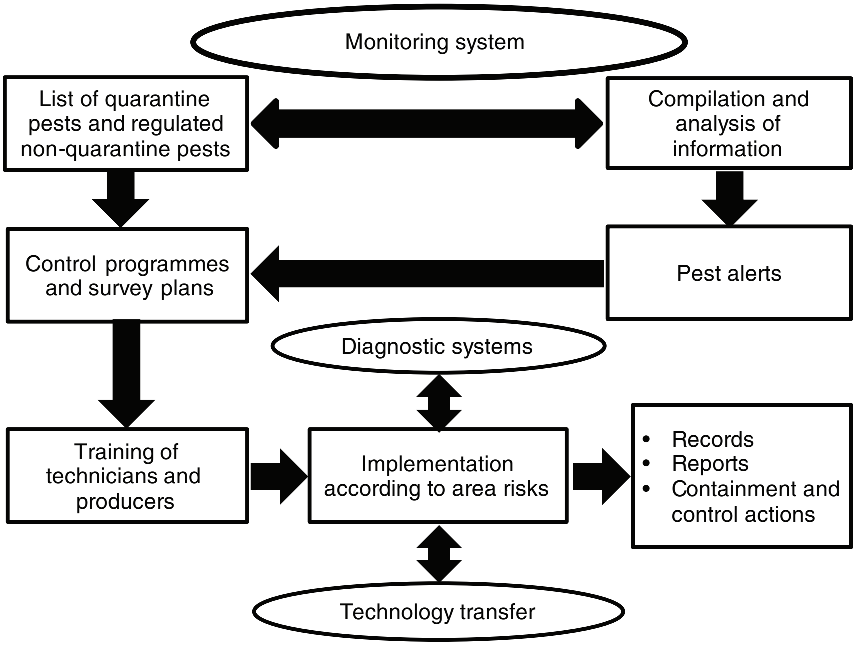

Fig. 2.1. The Republic of Cuba's Phytosanitary Surveillance System [Sistema de Vigilancia Fitosanitaria en la República de Cuba] (as reported in IPPC Secretariat, 2012).

on stopping trade (Convention on Biological Diversity (CBD) Secretariat, 2001a).

2.2.2 Recent enhancements in plant and animal health surveillance

The IPPC Secretariat discovered the importance of the factors shown in Fig. 2.2, which influence national pest surveillance, in a recent survey of implementation of International Standards for Phytosanitary Measures (ISPM) 6 (IPPC Secretariat, 2012). The influence of such factors will be magnified in a biosecurity programme in most cases, unless the programme is established under new authorities with additional financial and human resources (the two highest priority factors identified in plant health surveillance).

Concurrent with the development of the concept of biosecurity, several organizations have been working to enhance the use of risk analysis and management along with the closely linked surveillance in plant and animal health sectors. This has taken place through the global leadership of the OIE and IPPC, as well as FAO and numerous regional entities such as the InterAmerican Institute for Cooperation in Agriculture (IICA). It has also been pursued by many of the national authorities. Some progress has been made through regular funding avenues, and other advancement has arisen from special funding opportunities such as projects or technical programmes.

One example of advances from a national initiative is a phytosanitary risk-based rating for individual countries, developed by the United States Department of Agriculture/Animal and Plant Health Inspection Service/Plant Protection and Quarantine (USDA/APHIS/PPQ) Center for Plant Health Science and Technology's Plant Epidemiology and Risk Analysis Laboratory (CPHST PERAL) (USDA/APHIS, 2010).

A regional project to enhance pest risk analysis (PRA), nicknamed PRATIQUE and funded under the EU Framework Programme

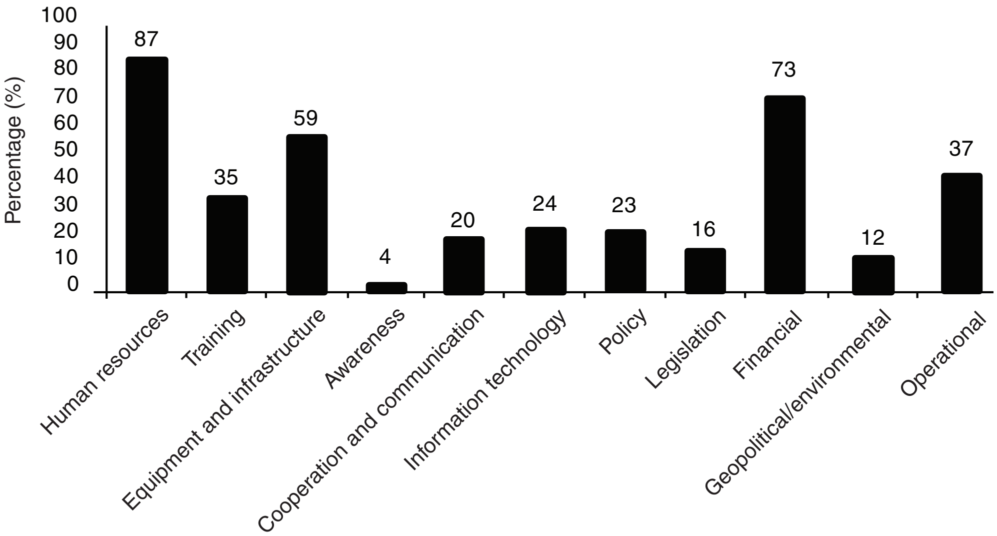

Fig. 2.2. Priority areas affecting capacity to conduct effective pest surveillance (compiled from a survey by the IPPC Secretariat, 2012).

7, reviewed methodologies for the detection of pests in trade and surveillance of exotic pests (Baker *et al.*, 2009; Baker, 2012). A major output of the project was a comprehensive review and rationalization of various types of data available for pest risk assessment, in particular, for Europe.

The intergovernmental treaty organization CABI (www.cabi.org) is one of the leading sources of scientific expertise on distribution and occurrence of pests, and an important source of taxonomic identification and diagnostics. The interactive databases for this information have greatly supported the national surveillance programmes. Over time, however, in addition to using literature review, informal and official sources, a more novel source for data has been developed. CABI is one of the founding members of the Global Plant Clinic (GPC), now under the banner of Plantwise (www.plantwise.org), which has created a new paradigm for plant disease surveillance. This initiative has been accessing on-the-ground observations through farmers' queries at local market stalls, manned by GPC partners, which are then reported to the global data bank. Any unusual or unclear diagnosis is also confirmed by a 'chain of science' that combines national and international expertise. Boa and Reeder (2009) describe how this system had, by that year, produced 40 new disease records (NDRs), confirmed by the GPC and published in peer reviewed journals, from 22 countries in Latin America and the Caribbean, Africa, Asia and Europe. This is, of course, in addition to the valuable advice for treatment of previously known diseases and the confirmation of distribution of these diseases, for national and international authorities.

2.3 Characteristics of Biosecurity Surveillance Programmes

Surveillance plays an integral part in biosecurity programmes, as with animal and plant health programmes, as indicated in Box 2.2. The characteristics of surveillance programmes for biosecurity, in relation to those discussed in the section above, are outlined here.

2.3.1 Integration of sectors

Challenges to surveillance, specifically the detection, identification and monitoring of animal, plant and even human diseases, were reviewed by a high-level Foresight programme in the UK to consider the likely and possibly enhanced scenarios for 2015 and 2030 (Office of Science and Innovation, 2006). Improvements in technology were considered key to addressing the increasing threats in each field. Limited resources demand coordination to achieve any possible synergies (Barker *et al.*, 2006), similar to the biosecurity approach. In the same programme, Quinlan *et al.* (2006) concluded from studies in the UK, sub-Saharan Africa and China, that most of the challenges would require integrated responses, with sensitivities to culture and governance.

Some important areas for integration include standardizing approaches to data collection and analysis, when cross comparisons are possible. A framework for risk assessment and estimates of impact of any type of regulated non-native species (mammal, fish, insect, etc.), for example, was designed in the UK to facilitate decisions on priorities and feasibility for management (Baker *et al.*, 2007).

This approach was presented in a case study of the then newly formed Finnish Food Safety Authority (EVIRA) by FAO (2007), again emphasizing the need for integration, not harmonization. EVIRA reportedly maintained the key sectors as separate departments and accessed cross-cutting expertise, such as risk assessment and communication, from departments external to theirs, but in the same Ministry. Other relevant Ministries provided policy input directly to EVIRA on a case-by-case basis.

In the process of integration, however, one must guard against restructuring without purpose and must support the transition over time. The Norwegian Food Safety Authority (2004) report on institutional changes to the food safety noted that: ‘In the aftermath of the first wave of inspiration, one has identified a sense of personal loss.’

2.3.2 Broader participation

Public awareness contributes to monitoring efforts and has been harnessed more systematically under the biosecurity approach (Convention on Biological Diversity (CBD), 2012).

There is a growing body of literature on *biosecurity surveillance* as a distinct activity, within the broader domain of biosecurity (Froud *et al.*, 2008). For example, New Zealand defines biosecurity surveillance to be ‘the collection, collation, analysis, interpretation and timely dissemination of information on the presence, distribution of prevalence or risk organisms and the plants or animals that they affect’ (Acosta and White, 2011). This definition itself has been slightly modified by the New Zealand Ministry for Primary Industries to be ‘an activity that occurs inside the border that is not part of an NPMS [National Pest Management Strategy]’ (as reported by Prime Consulting International Ltd, 2002) and now comprises four subcategories of surveillance:

- **Passive surveillance**: the detection of exotic species through haphazard, unplanned and unsolicited observations by the general public, farmers, orchardists, gardeners, veterinarians, plant pathologists and others.
- **Enhanced passive surveillance**: used in situations where there is a requirement to improve the sensitivity of passive surveillance processes through the removal of barriers to the more detailed examination of situations in which particular pests might be present.
- **Active surveillance**: a planned process targeted to find and identify a particular new pest.
- **Sentinel surveillance**: uses targeted groups of the population to monitor for a specific pest or disease.

Examples are provided for each of these subcategories. Passive surveillance is illustrated by a person, working in the office of an industrial site, noticing strange caterpillars and sending them to an entomologist for identification. An example of enhanced passive surveillance is the reimbursement of laboratory fees and the payment of a sum to veterinarians submitting material from cattle with clinical signs that could possibly be associated with BSE, or the use of publicity campaigns to encourage target groups to find and notify authorities of the discovery of any exotic species. Active surveillance is illustrated by an active surveillance programme for fruit flies that might use pheromones in traps to attract the target species. The example for sentinel surveillance is bluetongue virus surveillance in New Zealand, which involves the regular testing of blood samples of cattle from sentinel herds.

In addition to governmental support of public participation in surveillance, participation from interest groups may enhance biosecurity. The International Union for the Conservation of Nature (IUCN) has an Invasive Species Specialist Group (ISSG), which comprises almost 200 members from over 40 countries and 'aims to reduce threats to natural ecosystems and the native species they contain by increasing awareness of invasive alien species, and of ways to prevent, control or eradicate them' (www.issg.org). The IUCN provided expert analysis and advice for marine invasive species biosecurity plans in a cooperative agreement with the US Environmental Protection Agency (US EPA) (Waugh, 2009) and has worked with other governments in many instances.

2.3.3 Additional drivers and objectives

Outbreaks of plant and animal pests occur for a variety of reasons. In the case of animal biosecurity, some of these include human-assisted movement of pests and pathogens, range extension of vectors and new vectors (Waage and Mumford, 2008), whether intentional or by accident.

These drivers provide the motivation for biosecurity surveillance. The aim of the activities undertaken as part of biosecurity surveillance, and the corresponding benefits of these activities to the industry and community, depend on the actual programmes undertaken and the scale of the operation. This is illustrated in Table 2.3.

From the animal health and plant health sectors, the concept of surveillance is to look for signs of diseases or pests (versus to determine the level of health or well-being, per se, as one might when working for conservation of biodiversity). In that context, health, then, might be considered high with the absence of detections of diseases or pests, although proving a negative status of no disease is always harder than proving the presence of a disease.

It is possible that some of the objectives for a good biosecurity programme are not easy to articulate, as they may evolve and appear as part of the process of discovery in the new paradigm of cooperation.

2.3.4 Cultural shifts towards collaboration and synergy

Cook *et al.* (2010) discuss adaptive governance as needed for invasive species which lie outside the historic division of animal and plant health. Some entire categories of disease and pests have passed through the metaphorical 'net' even when potentially covered by a public authority. This was the case with multiuse woody species and new sources of forage introduced in the 1980s, shrimp disease and diseases introduced through fish stock (Murray and Peeler, 2005), serious aquatic weeds in the first decade of 2000, and several severe tree pests over the past decade (Brasier, 2005). Although some of these were addressed by existing authorities, the responses were reactive and of limited impact.

A major obstacle is the lack of information about new threats to biosecurity. Even as a threat is identified, the probabilities surrounding its occurrence and possible economic consequences make the decision process difficult and seemingly indefensible. Cook *et al.* (2010) make the bold statement that: 'In the face of uncertainty and ignorance, effective risk management requires that institutions change their behavior in response to new

Table 2.3. Aims and benefits of biosecurity and biosecurity surveillance.

Organization/ country	Aims and benefits of biosecurity surveillance	Reference
Victorian Department of Primary Industries	..it 'develops policy, standards, delivery systems and services that reduces the threat of invasive plants and animals to agriculture and the natural environment, protects animals and plants from pests and diseases, enhances food safety, ensures minimal and effective chemical use, protects the welfare of animals and preserves and expands market access for Victoria's primary industries'.	State Government of Victoria, Department of Primary Industries (2010)
Western Australia DAF	Benefits of biosecurity: • minimization of the risk of exotic diseases and agricultural pests; • eradication of diseases; • minimization of costs to producers by keeping pests, diseases and weed out of the State; • increased access to markets by ensuring that produce is as free as possible from pests and chemicals; and • customer confidence in clean, safe products.	Government of Western Australia, Department of Agriculture and Food (2010)
New Zealand	Post-border surveillance is undertaken for a variety of reasons, some of the most important being: • to give evidence that a pest or disease is absent from a country, region or defined area, thus enabling access to particular export markets; • to detect new pests and diseases early enough to enable cost-effective management; • to establish the boundaries of a known pest or disease incursion; and • to monitor the progress of existing containment or eradication programmes.	MAF Biosecurity New Zealand (2009)
Canada (animals)	Looking beyond the direct economics of disease reduction, the benefits of implementing on-farm biosecurity practices are significant. For producers, they include: • improving animal health and welfare; • keeping out new diseases; • cutting the cost of disease prevention and treatment; • reducing the use of medication, such as antibiotics, with an associated reduction in the risk of emergence of resistant pathogens; • producing safe, wholesome, and high-quality products; • increasing consumer and buyer confidence; • protecting human health; • minimizing the potential for farm income losses; • enhancing the value of the herd; and • maintaining and accessing new markets for genetics. A Biosecurity Plan provides overall benefits to the dairy industry in that it: • decreases economic losses from some diseases that cannot be treated or controlled using vaccinations or other management strategies (e.g. mastitis, Johne's disease); • helps to prevent the introduction of foreign diseases; • controls the spread of infection from region to region and farm to farm; • facilitates early recognition of emerging disease threats; • prevents zoonoses; • produces safe wholesome milk and meat; • negotiates more favourable global trade policies; and • maximizes genetic export markets by the prevention of disease.	CFIA (2013)

understandings about how the world operates.' They argue that rather than the pre- to post-border continuum, biosecurity must rely on active networking across all nodes of data collection, analysis and policy formulation and risk management.

The shift towards biosecurity may require additional expertise and resources to support a consultative and iterative approach, such as for increased communications. Greater agility and responsiveness, as well as the willingness to incorporate new information, is part of the changes needed (Cook *et al.*, 2010). The hallmark of a good biosecurity programme is the ability to understand, 'live with' and, at all opportunities, address the uncertainty and lack of information typical of these topical areas and previously lost in legislative gaps, or left unaddressed due to resource limitations.

These cross-sectoral interactions provide greater opportunity for replicating successful strategies or methodologies in one sector, to another. For risks to aquaculture resources, Murray and Peeler (2005) created a framework combining risk-analysis methods and virulence theory with historical examples (mainly from salmonid production) to identify key disease-emergence risk factors. They proposed treating hatcheries and slaughterhouses and other points of possible cross contagion, with strict biosafety-type procedures for prevention of disease emergence.

2.3.5 Systematic analysis of risks and risk management

We have already touched on the inherent need for systematic analysis as a cornerstone to biosecurity, and the following sections elaborate this theme.

The lack of ongoing surveillance of wild populations of animals is considered a serious weakness to the early alert of new human diseases, because so many new epidemics arise from zoonoses (Office of Science and Innovation, 2006). This study in future synergies between human, animal and plant surveillance names three principles for improvement:

- making better use of existing data;
- focusing monitoring better; and
- ensuring that the mandates and resources of key organizations match the need.

2.4 Biosecurity Surveillance Activities

Agricultural and environmental biosecurity surveillance programmes include both legislative and collaborative programmes operating at multinational, regional, national and local levels. The growing importance of biosecurity both conceptually and operationally has meant that it is now not only a priority of government agencies, but also a political priority. This is reflected in the appointment of Ministers for Biosecurity (e.g. New Zealand, Australia, Bhutan, the Gambia), the emergence of national biosecurity strategies (New Zealand, Australia) and the development of biosecurity legislation (e.g. New Zealand, Fiji, Samoa) (Frampton, 2010). Many countries have national legislative and agency programmes for biosecurity surveillance. In the context of plants, examples include USDA/APHIS (USDA/APHIS, 2013), Biosecurity Australia (Biosecurity Australia, 2007), the New Zealand Ministry for Primary Industries (New Zealand Government, Ministry for Primary Industries, undated), the National Biosecurity Commission and Biosecurity Policy of the Kingdom of Bhutan (Frampton, 2010) and so on.

The scale of operation of agricultural and environmental biosecurity surveillance programmes may be defined by the area where a disease or pest outbreak has been contained, or conversely, an area free from the outbreak, or it may be defined by the area of importance to the stakeholders, such as protected areas, national parks or areas of high biodiversity (hot spots) or genetic centres of origin.

A number of research organizations and a wide range of individual researchers have focused on these issues. Two such research groups include the Australian Centre of Excellence for Risk Analysis

(ACERA; www.acera.unimelb.edu.au) and the UK-based Food and Environment Research Agency (FERA; www.fera.defra.gov.uk), formerly Central Science Laboratory (CSL).

FERA's key areas of statistical capability include uncertainty, modelling and risk assessment. The types of activities listed by FERA include: (i) wildlife rabies contingency modelling for use in an outbreak; (ii) modelling potential badger management strategies for the reduction of bovine tuberculosis in cattle herds in England, Wales and Northern Ireland; (iii) a computer simulation study to evaluate resistance-delaying control strategies with novel anthelmintic products on UK sheep farms; and (iv) modelling European foul brood in the honeybee.

In addition to a comprehensive set of reports that contribute substantially to knowledge and practice of statistical modelling, design, and risk and uncertainty in environmental biosecurity, ACERA also has a focus on the elicitation of expert information and the incorporation of this information into risk assessment (Burgman, 2005; Low Choy *et al*., 2009).

Large national programmes that address agriculture and environmental biosecurity have also been established. An example is the Australian Cooperative Research Centre (CRC) on National Plant Biosecurity (NPB) which was established in 2005 and renewed in 2012. The CRC comprises around 25 entities drawn from government, research organizations, universities and industry groups. The original CRC produced a number of web-based applications, three of which are: (i) the Plant Biosecurity Toolbox, which provides detailed diagnostic information (biology, taxonomy, detection, identification) about exotic pests and diseases; (ii) the Pests and Diseases Image Library (PaDIL) which provides high-quality image and information tools to facilitate research and management in biosecurity and biodiversity; and (iii) the Remote Microscope Network (RMN) (Thompson *et al*., 2011) system, which links field officers with national and international experts to speed up the identification of potential biosecurity threats. The renewed CRC has four main programmes focusing on: (i) tools, technologies and strategies for early warning of new and emerging plant pest threats; (ii) monitoring and surveillance for effective detection and response; (iii) safeguarding international trade and managing established pests; and (iv) working with community, government and industry to safeguard Australia for a secure future.

A similar CRC was created in Australia to address animal biosecurity. The three programmes of the CRC were Technologies to Enhance Detection, Ecology of Emerging Infectious Diseases, and Advanced Surveillance Systems. The key highlights of the Advanced Surveillance Systems programme included: (i) the development of an internet-based epidemiological calculator for estimating disease prevalence from pooled prevalence (www.ausvet.com.au); (ii) a bovine syndromic surveillance system (www.ausvet.com.au); (iii) a new sugar 'lure' for mosquitoes; (iv) software that analyses disease surveillance data to provide an estimation of a country's confidence in freedom from disease (www.ausvet.com.au); and (v) an electronic system for linking livestock movements to property data using the National Livestock Identification System (NLIS).

2.5 Statistical Issues and Approaches in Biosecurity Surveillance

This book focuses on statistical issues and corresponding statistical approaches to biosecurity surveillance. In this chapter we provide an overview of some of these issues as a prelude to the more detailed discussions that follow.

Many of the key statistical issues can be described under three broad headings:

- **Modelling**: building models to describe and predict pest introductions, spread and outbreaks.
- **Design**: designing surveillance programmes, determining necessary survey effort, optimal allocation of resources in surveillance and response.

- **Risk and uncertainty**: characterizing risk and uncertainty in these model-based descriptions and predictions.

A range of approaches have been used to underpin the statistical models suggested for agricultural and environmental biosecurity surveillance. These range from control charting techniques (Fox, 2006) to hierarchical models (Stanaway *et al.*, 2011) and systems models (Mengersen *et al.*, 2012).

Control charts can be used to monitor processes such as counts of pests or pest presence/absence, or related measures of interest such as time to detection. They provide signal or alert systems if the process exceeds a predetermined threshold or exhibits non-random patterns. Potential reasons for the signal can then be investigated. The broader range of quality monitoring techniques can also be used to determine the capability of a surveillance system to meet specified requirements. An example of their use is for syndromic surveillance and anomaly detection (Fox, 2006).

Hierarchical models allow the explicit description of observation-level and process-level characteristics of pest introduction, spread or outbreak. An example of this is a Bayesian model for surveillance of spiralling whitefly in Australia (Stanaway *et al.*, 2011), in which surveillance and ecological information are used to estimate invasion extent and model parameters for invading plant pests spread by multiple dispersal modes, in particular by people. The model explicitly incorporates uncertainty in the observation process by allowing for local natural spread and population growth within spatial units.

Systems models typically take a broader perspective of the biosecurity surveillance process. A Bayesian network (BN) is a form of systems model that has been increasingly widely used in biosecurity. A BN is a type of graphical model that describes the factors that impact on or are associated with a response of interest (such as absence of a pest), and their (often complex) interactions. The model is then quantified, often using information drawn from a range of sources including observations, literature, expert judgement, and so on. The quantified model then allows an assessment of the overall probability of the outcome (e.g. probability of pest freedom), identification of major factors contributing to the outcome and scenario ('what if') assessment (Johnson and Mengersen, 2012). BNs are currently being used for pest risk management in the Beyond Compliance project, an international project based in South-east Asia (Mengersen *et al.*, 2012).

There have been a variety of approaches to biosecurity surveillance design. These include designs constructed to meet specific constraints (Barrett *et al.*, 2009; Hester *et al.*, 2012), simulation-based approaches (Potts *et al.*, 2012) and model-based designs.

Constraint-based surveillance designs, also sometimes known as risk-based designs, ensure conformance to specific requirements such as a cost threshold or a guaranteed power to detect a species if it is present. An example of such a design for detecting the introduction of exotic plant and animal pests on Barrow Island in Australia is provided in Chapter 11, this volume. Software such as EpiTools (Sergeant, 2009) can also be used for this purpose, as demonstrated in the design of a surveillance system for citrus canker in the Northern Territory of Australia (Hester *et al.*, 2012). This tool can also be used for animal surveillance designs, for example to estimate disease prevalence or demonstrate freedom from diseases in animal herds (Sergeant, 2009).

Simulation-based approaches can provide a way of evaluating the potential outcomes of a proposed surveillance design, such as the predicted risk of non-detection, pest spread or outbreaks. The simulation models are also for evaluating the impact of different design assumptions. The efficacy of this approach has been evaluated for the citrus canker surveillance problem mentioned in the previous paragraph.

Many of the approaches described above are discussed in more detail in subsequent chapters of this book. For specificity here, we focus on a review of a range of statistical modelling approaches to agricultural and environmental biosecurity surveillance.

2.6 Statistical Modelling Approaches

2.6.1 Statistical requirements

Biosecurity aims to manage the risks of invading arthropod and disease pests by carrying out pre-border, border and post-border control activities. Mitigation of risks is a bioeconomic management issue and the strategic decision-making process has benefited from modelling both the probabilities and the consequences of pest invasions (Myers *et al.*, 1998; Cook, 2005; Waage and Mumford, 2008; Carrasco *et al.*, 2010a,b; Epanchin-Niell and Hastings, 2010). Ideally, risks are managed before pests breach the border but once an incursion has occurred, the task becomes one of eradication, minimizing spread or reducing the consequences in invaded areas. From a tactical point of view, post-border management of incursions requires spatial inference to manage pests at an operational level. Post-border surveillance provides the data used to infer the likely extent of invading pests over time so that regulators can confidently manage movement pathways and pest control strategies.

Post-border surveillance activities that feature in plant biosecurity risk management include early detection, area freedom and response surveillance (McMaugh, 2005). Early detection surveillance aims to detect pests in an area before they become too widespread to eradicate (Hulme, 2006). These programmes target surveillance at areas with a predetermined high probability of a pest being present (Wotton and Hewitt, 2004; Stark *et al.*, 2006; Hadorn and Stark, 2008). Managers are interested in how to best deploy early detection surveillance over space and time, while balancing the cost of surveillance against the expected benefit of timely eradication or control (Myers *et al.*, 1998; Prattley *et al.*, 2007).

Once an exotic pest is detected, the major economic threat facing producers is the suspension of access to international and domestic markets until the extent of the incursion can be demonstrated. Area freedom surveillance aims to provide sufficient evidence to satisfy the importing markets that the probability of moving the pest through trade from particular areas is low (Aluja and Mangan, 2008; Plant Health Australia, 2010). Guidelines for establishing areas of low pest prevalence have recognized that area freedom is not a necessary requirement for market access negotiations (IPPC, 2008; Lloyd *et al.*, 2010). However, they have rarely been implemented due to concerns over ecological (and operational) uncertainty within quarantine systems (Aluja and Mangan, 2008).

Delimiting extent is not only necessary for maintaining trade but is also needed for managing eradication or long-term containment programmes (Cacho *et al.*, 2010; Carrasco *et al.*, 2010c). Ongoing surveillance provides information about the extent of pests over time so that movement restrictions and control measures can be regulated most effectively. Each of these applications requires the spatial extent of the pest to be reliably estimated over time (Cacho *et al.*, 2010). While inference on the probability of pest extent provides the foundation for decision making, the spatial statistics for analysing the dynamic extent of invaders are generally not available to the agencies that manage incursions.

The initial design of any biosecurity investigation needs to consider the spatial units used for decision making, data collection and ecological modelling (Graham *et al.*, 2004). In continuous space, a bounding polygon can be constructed around a population. For incursions, where non-contiguous satellite populations are common, some meaningful ecological or management resolution is needed to define the functional boundaries (Burgman and Fox, 2003). More commonly, species distribution models seek to assign a value for presence or absence to discrete cells. These cells may be arranged on a continuous regular grid (Argaez *et al.*, 2005; Royle *et al.*, 2007) or may consist of an irregular patchwork (Gumpertz *et al.*, 2000).

At fine resolutions, the effective extent of an invading plant pest is restricted to those individual hosts that are capable of sustaining the pest throughout its life cycle. Hosts may be logically arranged for the purposes of analysis into fields, farms or other landholdings. Alternatively, arbitrary areas may be related to pest habitat based on the density of hosts. Environmental constraints, such as weather conditions and soil types that operate at broader scales may also be used to restrict the area at risk. As host landscapes are all fragmented on some scale (With, 2002), it may be necessary to break the spatial domain down into discontinuous habitat patches for a particular analysis (Leung *et al.*, 2004; Moilanen, 2004). Statistics that estimate the extent of an incursion need to accommodate the choice of spatial scale on two fronts. First, the model outputs need to be at a spatial resolution that is useful for making management decisions. Secondly, models that include invasion ecology must be at a resolution that can adequately represent the dynamics of spread over time. The choice of a geographic model is therefore integral to the modelling process and the parameterization of these models.

Ultimately, the managers of invading pests seek to map the probable spatial extent of a pest at the current time (or at some time in the future) based on all of the information available. These maps can: (i) define containment lines for pest control (Plant Health Australia, 2010); (ii) help negotiate access to markets for produce from areas considered free of pests (Jorgensen *et al.*, 2004; Martin *et al.*, 2007; Lloyd *et al.*, 2010); and (iii) be used to deploy surveillance resources to maximize the information required to make decisions (Prattley *et al.*, 2007; Barrett *et al.*, 2009; Davidovitch *et al.*, 2009). Biosecurity programmes generally seek to simplify the population characteristics of an incursion into the presence or absence of pests over space and time. Even low populations of a pest represent a threat to the future management of an incursion. As the location of each organism comprising the invasion is not known, the process of delimiting the extent becomes one of estimating the hidden or latent extent at a particular time (Clark, 2005). Typically, visual inspection of hosts backed up by diagnostic tests provides the data, which are used to demonstrate that areas are pest free. However, these data are far from complete. The sites or areas to which observations of presence or absence are attributed may only be partially examined and even at a single plant scale, pests may be overlooked if the symptoms are not apparent to the observer (Bulman *et al.*, 1999; Fitzpatrick *et al.*, 2009; Gambley *et al.*, 2009). In order to infer the probability of pest absence for an area, an observation process must be modelled to accommodate potential false absence records that apply to the spatial unit of interest (Kery, 2002; Tyre *et al.*, 2003; Meats and Clift, 2005).

If a pest is present in an area, false absence records are, to a large extent, dependent on the density of the pest population in that area (Royle and Dorazio, 2006; Kery *et al.*, 2006; Cacho *et al.*, 2010). Observation models alone can only be used to provide evidence against presence at a particular population intensity. It is the loss of power for observations to detect pests at low levels that challenges the delimiting of pest extent (Delaney and Leung, 2010). To infer pest absence in an area, additional information about a pest's likely intensity must be introduced into the analysis. Information about pest intensity needs to be derived from the particular reproductive and spread characteristics of a pest. Statistically, this is expressed by the intrinsic spatial and temporal correlation within a pest population (Wintle and Bardos, 2006). Dynamical models for the invasion process can mathematically specify spread mechanisms (and parameter uncertainty) to allow structured ecological information to be incorporated into the statistical analysis (Gibson *et al.*, 2006; Hooten *et al.*, 2007).

Inference on the geographic distribution of an invading pest over time is operationally impossible without combining information from observations and the ecology of the pest. Observational data collected by surveillance for different pests could have quite different interpretations for management depending on the reproduction and dispersal dynamics of the organisms. Similarly, while the distribution of a pest is governed by its intrinsic ecology or epidemiology, quite diverse incursion scenarios could unfold, given any particular introduction event. It is the role of biosecurity surveillance to tie the process of invasion to the landscape so that appropriate management decisions can be made. Quantitative modelling of surveillance data and invasion dynamics provide a way forward to assimilate this information and embed it into biosecurity decision making.

2.6.2 Pest observation models

Statistical interpretation of biosecurity surveillance requires an observation model that describes the imperfect signal that an observer receives about the true pest population when visiting a site. Traditionally, surveillance focuses on the visual inspection of hosts or sampling of material, but similar models can be applied to other signal detection data such as background passive surveillance (Cacho *et al.*, 2010), trapping (Barclay and Hargrove, 2005; Meats and Clift, 2005) and remote sensing (Wang, 2009). In most plant health surveillance systems, false positives are unlikely and so observation of the pest (and subsequent diagnostic confirmation) is considered sufficient evidence that it is truly present. Therefore the primary goal of observation models in plant biosecurity applications is to analyse evidence for pest absence at a site.

Biosecurity surveillance data typically consist of observational outcomes, generally presence/absence, attributed to a geographic area that is usually referred to as a site. The spatial definition of a site is somewhat arbitrary, where the area may consist of a single plant, a field, a farm or some other functional management area. A site may be subdivided into counted units that are assumed to be independent and identically distributed so that standard statistical models can be applied. The spatial definition of a site is integral to the construction of the observation model (MacKenzie, 2005). The analyst must be mindful of the relationship between the outcome recorded, the latent state inferred and the effect of spatial aggregation of information within the model components.

The probability that a pest is observed within a site can be considered a function of the search intensity (e.g. plants inspected, time spent, area covered) and the expression of the pest within the sampling frame (Kery, 2002). Consider a pest that is present on a particular number of plants at a site and is perfectly observed. If the proportion of plants inspected from the area is relatively small, the probability of not detecting the pest may be adequately modelled by the binomial distribution. Under the assumption that the plants selected are exchangeable, this model can be used in the frequentist form to arrive at a confidence level for a predetermined prevalence (Cannon and Roe, 1982). If the proportion of plants inspected is large, the observation model may instead be based on a hypergeometric distribution (Cameron and Baldock, 1998; Hanson *et al.*, 2003). Where the measure of search intensity is the proportion of the area surveyed, or search time, a Poisson distribution provides a further option. These basic statistical functions for modelling count data from observations can be implemented in frequentist analyses or they can be used to provide the likelihood component of a Bayesian approach (Hanson *et al.*, 2003; Johnson *et al.*, 2004).

Imperfect examination of those units that constitute the measure of search intensity is commonly referred to in the epidemiology literature as test sensitivity (Cannon, 2001; Bohning and Greiner, 2006; Gambley *et al.*, 2009) and in ecological studies as detectability (Wintle *et al.*, 2005; Royle, 2008). Overestimation of detectability will result in underestimates of pest distribution that can severely compromise population management decisions (Myers *et al.*, 1998; Wintle *et al.*, 2004). The simplest approach to imperfect detection is to use a point estimate of detectability to reduce the search intensity in the observation model (Martin *et al.*, 2007).

Detectability on an infested unit may be influenced by a number of factors, for instance, observability due to tree architecture (Gambley *et al.*, 2009), terrains (Hauser and McCarthy, 2009) or differences in observer experience (Gambley *et al.*, 2009; Christy *et al.*, 2010). Variation in individual pest behaviour may also result in mixtures of detectability (Royle, 2006; Christy *et al.*, 2010), as can spatial clustering on units within the site (Gschlossl and Czado, 2008). Where there is epistemic uncertainty surrounding the detectability parameter, or detectability is expected to vary between units, the data can be treated as being overdispersed (Potts and Elith, 2006). The beta-binomial distribution is one analytically tractable form for estimating detectability in a Bayesian framework that has led to its widespread use (Clark, 2003; Gelman *et al.*, 2004; Thebaud *et al.*, 2006; Hooten *et al.*, 2007). Data from overdispersed Poisson processes may likewise be modelled using a negative-binomial distribution (Royle, 2004; Gschlossl and Czado, 2008).

Another class of models for dealing with overdispersion in presence/absence analyses are the zero-inflated binomial and zero-inflated Poisson models (Hall, 2000; Branscum *et al.*, 2004; Wintle *et al.*, 2004; Martin *et al.*, 2007). For pest count data in a binomial setting, the models consider the outcomes of the observation process to be either zero or binomial depending on the pest status. Royle (2006) recommends caution when using zero-inflated models to infer population sizes at low densities. Therefore, despite their simplicity, these models may have limited value in estimating pest absence for biosecurity applications. Most biosecurity surveillance programmes are limited to the collection of presence/absence data, suggesting that logistic regression models to predict the status of sites are given some additional covariate data such as host status or environmental favourability (Kery, 2002; Gelman *et al.*, 2004).

In a Bayesian setting, the foundation observation models discussed so far provide the likelihood function for analysis. Uncertainty in detectability can be defined by specifying a prior distribution on the hyperparameters for overdispersed models or for random effects and parameters in logistic regression. Priors may be derived from plausible values provided by experts, or from existing empirical evidence (Hooten *et al.*, 2007).

In addition to uncertainty about detectability, it is also necessary to consider the potential expression of the pest in the context of the invasion process. A major source of variation in detectability will be the size of the population within the observation unit (Royle, 2006; Harwood *et al.*, 2009). As an area is invaded, both the number of infested units and the probability of detection on individual units will increase. At the margins of the range, pest expression is expected to be poor and therefore models will lack inferential power (Barrett *et al.*, 2009). The evidence for absence used for mapping extents is therefore sensitive to the way in which the observation model processes the pest signal at low population levels.

Pest observation outcomes recorded at some point in space and time are generally interpreted as applying to some spatio-temporal vicinity (Yoccoz *et al.*, 2001). Observations taken at a site at one time are expected to reflect the true status at times in the recent past and future. Temporal discounting of surveillance data has been examined for herd-based sampling in veterinary epidemiology given continued exposure to infection (Schlosser and Ebel, 2001). In a similar way, observations in one area are expected to contain information about nearby or connected areas.

Autocorrelation of the pest status in space and time is a function of the invasion ecology of the organism. It is recognized that the assumptions required of simple inferential probability models are usually violated in the face of spatial autocorrelation (Legendre, 1993; Wintle and Bardos, 2006). To delimit extent, the observation process must be modelled in relation to internal processes within the observation unit, but this must also be supported by the external processes that give rise to interdependencies with other units. In the following section, invasion process models are introduced to define some ecological processes that give rise to spatial and temporal correlation.

2.6.3 Invasion process models

General reviews on invasion ecology can be found in Mack *et al.* (2000), Puth and Post (2005), Liebhold and Tobin (2008), Simberloff (2009) and With (2002). The spatial realization of an invasion process over time is the result of the birth, dispersal and death of many individual organisms. As the extent of an invasion evolves as a dynamic process, considerable heterogeneity and spatial dependence is displayed in the distribution patterns (Hastings *et al.*, 2005). Spatial correlation can be due to similar underlying environments as well as being intrinsic to the dispersal process itself (Wintle and Bardos, 2006). The probability of a pest being present in a particular area can be modelled as a function of the dispersal-mediated connections with infested sites and the time over which those connections exist (Jerde and Lewis, 2007).

Invasion processes can be broken down in different conceptual ways, depending on the components of interest to particular applications (Simberloff, 2009). Component processes of interest can include introduction (entry), colonization, establishment and spread (Mack *et al.*, 2000; With, 2002; Hennessey, 2004; Lockwood *et al.*, 2005; Hulme, 2006; Drake and Lodge, 2006). For brevity, we lump the first three processes under the heading of colonization and then look at dispersal. In this simplified framework, colonization deals with the internal processes within a defined area while dispersal deals with the exchange of organisms between areas.

In simplest terms, colonization is the process of a defined area going from uninfested to infested. As any infested area poses a biosecurity risk, estimating colonization events is fundamental to the spatial management of invasive pests. Much work has focused on colonization across national borders (Drake and Lodge, 2006; Holmes *et al.*, 2009; Simberloff, 2009). The IPPC adopts the terminology of endangered areas to identify a region that favours the establishment of a pest of concern, while establishment is defined as the perpetuation of a pest in an area for the foreseeable future (FAO, 2012). Here we consider the colonization process as applying to any area of interest for which the pest status is sought. The process encompasses the introduction of the pest into the area, followed by successful reproduction and leading to permanent establishment. Considerable work has gone into identifying the intrinsic biological characteristics of successful invaders (Johnson *et al.*, 2006). However, the most reliable indicators of invasion success across taxa appear to be extrinsic factors such as climate/environment similarity and the number of pest propagules introduced (Jarvis and Baker, 2001a; Rouget and Richardson, 2003; Hayes and Barry, 2008).

Habitat suitability, in particular the availability of suitable host plants and climatic requirements, has a major impact on the probability that an area will be colonized. Climate matching has proved to be one of the most useful estimators for the ultimate distribution of an invading organism (Sutherst and Maywald, 1985) but comes with some caveats. Biogeographic predictive models based on environmental covariates in the native range of a pest can lead to erroneous estimates of final extent, either due to genetic differences in the invading population or due to different relationships between the pest and unidentified covariates (Fitzpatrick *et al.*, 2007). It also needs to be recognized that the destination areas encompass both spatial and temporal environmental variation (Jarvis and Baker, 2001b; Simberloff, 2009).

The exposure of an area to the risk of pest introduction is commonly referred to as propagule pressure (Leung *et al.*, 2004; Lockwood *et al.*, 2005; Carrasco *et al.*, 2010b). A propagule is a group of one or more organisms that enters an area at a particular time, while the propagule pressure is the total exposure of an area to these over some period of time (Simberloff, 2009). Exposure assessments for environmental pollutants have used epidemiological risk characterization techniques at a sophisticated level (Nieuwenhuijsen *et al.*, 2006) but these are yet to be investigated rigorously with respect to colonization in invasions (Stohlgren and Schnase, 2006). Of interest to biosecurity are estimates of the probability that an area is free of a pest at some time. One approach is to implement discrete time models for the number of propagules arriving at a destination and surviving. Jerde and Lewis (2007) adopt a Poisson model for the survivors as the sum of movements from all pathways into the destination and use a geometric distribution to estimate the waiting time for a colonization event in discrete time. A similar approach was used by Leung *et al.* (2004).

The fate of organisms between entry and establishment is one of the great unknowns of invasion biology (Puth and Post, 2005), and is perhaps the most difficult process to parameterize. Early stages of the colonization processes are poorly understood, most notably because they are rarely observed and there is little empirical evidence on processes that lead to establishment (Simberloff, 2009). A handful of studies have attempted to quantify the number of propagules being moved along pathways (Stanaway *et al.*, 2001; McCullough *et al.*, 2006; Lee and Chown, 2009), however, these are difficult to relate to the establishment of populations in new areas.

Successful establishment is based upon the fates and reproductive success of what is generally a small founding population (Kawasaki *et al.*, 2006). Therefore, stochasticity plays a central role in understanding and modelling the colonization process. In particular, there is potential for initially low rates of population increase and spread, known as Allee effects, that can cause local extinction after the introduction (Hastings, 1996; Foley, 2000; Keitt *et al.*, 2001; Dennis, 2002; Drake and Lodge, 2006). While Allee effects may contribute significantly to the success and expression of the colonization process, prohibitively intensive collection of data from populations at low densities may be needed to quantify this effect (Kramer *et al.*, 2009). In order to define the hierarchical link between observations and pest status, models of colonization need to represent the population states within the area over time. Given that it is difficult to collect empirical information on the colonization phase, much of the burden for providing prior ecological knowledge falls upon dispersal models.

Invasive pests can spread by a number of natural dispersal mechanisms, including along drainage lines, wind-assisted flights (Reynolds and Reynolds, 2009) or active flight (Guichard *et al.*, 2010). Additional human-mediated dispersal pathways may also exist on nursery stock (Smith *et al.*, 2007), produce (Areal *et al.*, 2008) or simply as incidental hitchhikers (Ward *et al.*, 2006). Spatial connectivity processes for natural dispersal and human-mediated dispersal underpin biosecurity management problems (Diggle, 2006).

Several spatial frameworks have been used to provide the scaffolding for modelling invasions and pest dispersal. On continuous space and time, the classic deterministic reaction–diffusion models of Skellam (1951), based on random movements of individuals, formed the basis of invasion research for decades. Integro-difference equations (IDE) offer a discretized methodology for implementing invasive dispersal with the flexibility of different dispersal kernels (Neubert and Parker, 2004). Dispersal kernels model the probability of movement between two areas as a function of Euclidean distance. While Gaussian kernels are commonly used (Havel *et al.*, 2002; Wikle and Hooten, 2006; Chapman *et al.*, 2007), other distributions used for dispersal kernels include Laplace (Lewis and Pacala, 2000; Neubert and Caswell, 2000), Cauchy (Mayer and Atzeni, 1993), exponential (Havel *et al.*, 2002) and negative exponential (Chapman *et al.*, 2007). Dispersal kernels with exponentially bounded tails lead to asymptotically constant rates of spread through continuous space, while others, for example the Cauchy distribution, can lead to accelerating rates of spread (Kot *et al.*, 2004). One of the drawbacks of IDEs is that they are deterministic and provide for a continuous distribution of organisms rather than a discrete distribution of individuals. Incorporating stochasticity on discrete individuals can slow the rate of spread (Kot *et al.*, 2004) so that even fat-tailed kernels can lead to asymptotic rates of spread (Clark *et al.*, 2001, 2003).

While continuous space models can have attractive mathematical properties, their application to heterogeneous environments can be problematic. As biosecurity programmes frequently deal with spread through geographically fragmented host landscapes, another option is to look at the transfer rates of propagules between discrete areas. Connectivity models provide a more tractable framework for working with discrete patches that may exchange propagules (Urban and Keitt, 2001). Rates of exchange may again be modelled as a function of distances to known infested sites using the same dispersal kernels as for continuous landscapes. Gravity models to predict the colonization rates of lakes by zebra mussels have been one successful application of this approach (Bossenbroek *et al.*, 2001). Similar approaches on lattices that define connectivity as bond strengths between neighbouring areas are commonly used in epidemiology (Sander *et al.*, 2002; Dybiec *et al.*, 2004, 2005; Otten *et al.*, 2004; Shirley and Rushton, 2005; Gibson *et al.*, 2006; Zhou *et al.*, 2006). As these models deal with the links between individual ecological units of interest, they offer readily interpretable statistics for the management of spread between areas (Urban and Keitt, 2001; Shirley and Rushton, 2005).

Incursions typically spread through adjacent areas at both fine and coarse scales (Scherm *et al.*, 2006). Most invasive species arrive in countries due to the activity of people and continue to travel on similar human-mediated pathways after arrival as well as by natural dispersal. Invasion processes can be highly stochastic with the colonization of satellite sites outside of the contiguously infested area, a major driver of the overall spread (Lewis and Pacala, 2000; Neubert and Caswell, 2000). Empirical evidence for the dispersal distances of individuals is difficult to collect but can be used to estimate dispersal kernels (Kareiva, 1983; Hawkes, 2009). Where long-distance movement is a prime contributor to invasions, uncertainty about rates of spread can prohibit meaningful inference about distribution (Clark *et al.*, 2003).

Plant biosecurity surveillance is deployed and evaluated according to some (generally informal) underlying mechanistic model of pest ecology (Plant Health Australia, 2010). While mechanistic models may be formulated differently, the spatial realization of these models may be similar (Wikle, 2003). What is more important for managing high-priority plant pests is that the model can be translated into operational use for the appropriate management units, whether they are countries, districts, farms, blocks within a farm, trees within a block or a continuous landscape of wild hosts. Pest spread across a landscape of plant host material requires critical examination as a spatial model (With, 2002). Whether it is for early detection, incursion management or to justify pest-free areas, these ecological models provide the dynamic context for interpreting surveillance data.

2.6.4 Statistical models

Statistical approaches to inferring extent commonly rely on generalized linear models to relate species distribution to environmental covariate data, however, such models ignore the intrinsic spatial correlation that is a feature of where individuals are found (Latimer *et al.*, 2006; Wintle and Bardos, 2006; Dormann, 2007a; Hoeting, 2009; Beale *et al.*, 2010). Auto-models provide an extension to regression models to allow the spatial covariance between sites within a neighbourhood to be admitted to the analysis (Besag, 1972, 1974). This autocovariance term may be based on Gaussian, binomial or Bernoulli distributions.

In the broader class of auto-models, conditional autoregressive (CAR) models have been increasingly used for disease mapping applications (Lawson, 2009), particularly as the algorithms to implement these models within Markov chain Monte Carlo (MCMC) software are freely available (Thomas *et al.*, 2004). For the analysis of presence/absence data, autologistic models have become a mainstay of species distribution problems (Augustin *et al.*, 1996; Huffer and Wu, 1998; Hoeting *et al.*, 2000) although their performance under conditions of strong spatial association has been questioned (Dormann, 2007b; Carl and Kuhn, 2007). It is uncertain over what range of scenarios a predominantly spatial model can implicitly incorporate the temporal processes of invasions. Spatio-temporal extensions to the autologistic model have been applied to pest outbreaks under the assumption that the spatial and temporal components of the autocovariance are separable (Zhu *et al.*, 2008). As dynamic processes in space and time may not be separable, explicitly modelled space–time processes must be developed for greater power of inference and interpretation of management strategies (Wikle and Royle, 1999). One of the main limitations of spatio-temporal auto-models for biosecurity applications is their inability to accommodate the dynamic nature of a pest invasion as it unfolds.

Wikle (2003) introduced reaction–diffusion equations for pest spread and reproduction into a hierarchical Bayesian framework to estimate arrival times of invading house finches. This and related studies (Wikle and Hooten, 2006; Hooten *et al.*, 2007; Hooten and Wikle, 2008), used integro-difference equations with spatially varying diffusion coefficients to structure the spatial transition of populations in discrete time steps. As the parameter of interest was the spatially varying rate of spread, these authors specified a log-normally distributed population process, but with the population set to zero according to some reasonable boundary conditions. While the hierarchical Bayesian modelling framework they developed marked a major advance in the analysis of invasion data, further extension of their models is required to focus the inference on the estimation of pest boundaries.

To delimit pest extent in a Bayesian model, inference on the pest status of each area of interest from the surveillance data requires some underlying invasion process. Gibson *et al.* (2006) describe a percolation model to estimate the disease infection times of plants on a lattice by considering the difference in colonization times between neighbouring plants to be exponentially distributed. A feature of biosecurity data is that often thousands of spatially referenced data points are collected but when detection probabilities are low, the information available to distinguish parameters can lead to poor convergence properties for highly parameterized models (Webster *et al.*, 2008). Furthermore, incorporating the space–time information contained in these points into MCMC models becomes computationally prohibitive. Banerjee *et al.* (2008) and Latimer *et al.* (2009) propose predictive process models that may overcome some computational hurdles by modelling invasion processes at a manageable number of points in space and time.

The dimensional complexity of space–time models makes evaluation computationally intensive and requires research to determine workable incursion management scenarios. Some level of spatial and temporal model aggregation is required to partition the system into computationally (operationally) manageable components for which conditional probabilities of absence can be determined.

Quantitative analysis of biosecurity surveillance data faces some significant hurdles for interpreting the distribution of invading species. Ecological complexity must be captured by process model such that they adequately portray uncertainty over space and time. On the other hand, assimilation of information from large data sets into high-dimensional models also imposes computational challenges for estimating extent and other parameters. Biosecurity managers need to make pest management decisions based on information from expert ecological opinion and from large spatio-temporal surveillance data sets. Moreover, decisions are often required urgently in the face of uncertainty. The adoption of quantitative techniques will only occur when they directly support the management aims of biosecurity agencies within their operational decision-making environments.

2.7 Discussion

We opened this chapter with a discussion of two issues that impact on the future of biosecurity surveillance: (i) the definition of the term itself; and (ii) the activities that the term encompasses.

As indicated in the Introduction, the definitions of biosecurity, and even of biosecurity surveillance, are quite broad and the scope of these terms is evolving and expanding. While plant and animal health practitioners relate well to the term as familiar within their respective frameworks, they may drop the 'plant and animal' preface when discussing biosecurity, thereby recognizing it as different from simply a combination of the previously existing two sectors. Biosecurity-related decision making depends critically on reliable evidence. A key source of such evidence is through surveillance. This requires not only careful design and implementation of surveillance schemes, but also appropriate statistical modelling and analysis of the surveillance outputs. This chapter has presented an overview of these approaches. Most of them are focused on the evaluation of risk, that is, the synthesis of the probabilities and consequences of pest entry, establishment and spread.

Effective analysis of surveillance data requires careful attention to the development of appropriate statistical models at both the design and the analysis stages of the surveillance activity. At the design stage, a geographic model can describe the spatial and temporal scales and units required for decision making, data collection and ecological modelling, as well as the potential area of pest risk, the hosts and pathways of the pest, and other key considerations. The geographic model must be complemented by an observation model that describes the presence/absence data obtained, or to be obtained, in the surveillance study. This needs to take into account the survey and sampling design, the population characteristics of the pest, its potential pattern of incursion, the probability of missing the pest if it is present, and so on. Since the observation model can only provide evidence about presence at a particular population density, it must in turn be complemented by a spread or invasion model that describes the pest's likely spatial and temporal intensity.

These geographic models, observation models and invasion models are themselves comprised of sub-models that describe important components of the problem. For example, an observation model requires sub-models for pest detectability and for the status of the pest over space and time. Similarly, an invasion model requires sub-models that describe the spatial process of pest dispersal, which may include one or more deterministic reaction–diffusion representations, continuous space–time representations, connectivity or gravity representations, or fully Bayesian stochastic representations. These sub-models require careful choices of parameters and associated statistical distributions, which in turn inform the statistical analysis of the surveillance data. For example, the sub-model of pest detectability determines the manner in which overdispersion is dealt with in the resultant data, while space–time correlations will determine the method for temporal discounting of the surveillance data.

Not only must decisions be made about the form of the geographic, observation and invasion models and sub-models, but the statistical representations of the model components must also be carefully considered. A number of relevant statistical models have been described in this chapter, including generalized linear models and spatial autoregressive models to infer extent, reaction–diffusion and difference equations for pest spread and reproduction, and percolation models to infer pest status at an area of interest. These models can be cast in deterministic, frequentist or Bayesian stochastic frameworks, or a combination of both.

The geographic, observation and invasion models are not independent. Components of one model are necessarily linked to components in the other models. For example, the sub-model that describes space–time correlations in the geographic model is strongly linked to the description of the dynamic processes of pest spread of space and time required in the invasion process model. Similarly, the geographic model will inform the component processes of entry, colonization, establishment and spread considered in the invasion model, as well as the habitat suitability sub-models that underpin these processes. The spatial and temporal scales determined in the surveillance design phase impacts on all of the models and the resultant analyses.

There are many difficulties in constructing and employing these types of surveillance models. These include: (i) the availability of required information in a timely manner; (ii) the decision making required to decide on the appropriate biological and statistical descriptions of the model components and processes; (iii) the computational implementation of the statistical analyses; and (iv) the practical interpretation of the analytic results. It is important that these difficulties are seen as an opportunity for improvement of the methods and tools used for biosecurity, rather than as an unassailable obstacle in evidence-based biosecurity decision making. Moreover, the development of these models can be viewed as an avenue for creating closer links between the various sectors and corresponding organizations involved in biosecurity. It is hoped that the summary provided in this chapter, along with the statistical issues and methods described in other chapters of this book, motivates further consideration and uptake of these approaches, as appropriate.

In this chapter we have reviewed the various definitions and characteristics of biosecurity surveillance and its place in the broader picture of plant and animal biosecurity. It is evident that while the general intent of biosecurity surveillance is consistent, there are differences among international, national and regional organizations with respect to the particular definitions of biosecurity surveillance and the corresponding activities undertaken under its auspices. This is natural given the different focal areas of these organizations and the environments in which they operate. However, as illustrated in this chapter, it has the potential to induce confusion and misalignment among stakeholders. This chapter thus serves the purpose of providing both a review and a clarification of biosecurity surveillance, to assist in creating a more consistent understanding of this field.

This shared understanding of the definition of biosecurity surveillance leads naturally to an agreed understanding of the activities that it encompasses. This depends on a combination of intrinsic and extrinsic factors. Intrinsic factors include the organizational and operational aspects of biosecurity surveillance itself. Maintaining flexibility and longevity in biosecurity surveillance programmes is a constant balancing act, since both are essential to effective surveillance. Moreover, sharing of information, including data and results, across organizations and programmes will become an increasingly important feature of future surveillance, particularly in light of globalization, climate change and new data sources. These extrinsic factors also include population growth and trends, industrialization and new pathways such as the internet. These will all influence how biosecurity surveillance is conducted in the future.

Importantly, a key extrinsic factor is the placement of biosecurity surveillance in the broader biosecurity regime. For example, we have found that biosecurity goes much farther than the combination of animal and plant health, to provide more holistic coverage of biological threats, addressing naturally occurring, and accidental and intentional man-made threats to biodiversity, health, food and even public safety. It is therefore important to identify the role that surveillance plays in the context of the other dimensions of this broader regime, in order to appreciate its value, optimize resources and improve outputs and outcomes.

These current and future challenges in biosecurity surveillance, and the current differences in biosecurity definitions and activities identified in this chapter, motivate the argument for a unifying epidemiological framework and a harmonization of approaches to biosecurity surveillance. This has the potential to lead to a more proactive than reactive approach to the field of agricultural and environmental biosecurity in general (Waage and Mumford, 2008).

We close this chapter with the remark that one of the defining features of the body of effort in biosecurity surveillance reviewed here is collaboration. Not only is this collaboration required between geographic areas, but it is also needed between governments, producers, processors, communities and other stakeholders. This is explicitly stated in the 2010–2013 Biosecurity Strategy developed by the state of Victoria in Australia which is 'encapsulated in a vision of collaboration between government, industry and community to manage the state's biosecurity risk profile' (State Government of Victoria, Department of Primary Industries, 2010). This strategy document states one of the primary drivers for biosecurity to be a scientific, regulatory and political priority: 'No one entity, no matter how well resourced or prepared, can effectively act alone in responding to biosecurity threats' (State Government of Victoria, Department of Primary Industries, 2010).

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Invasive Species and Global Climate Change

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14 Global Identification of Invasive Species: The CABI Invasive Species Compendium as a Resource

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Abstract

The number, spread and impact of invasive species in the latter half of the 20th century has been without historical precedent. Now, as human activity causes a precipitous rise in greenhouse gas emissions (e.g. CO_2), there is growing concern that climate change may also be a significant, long-term driver enhancing invasive species introduction and spread. New and more powerful tools that facilitate linking invasive species and climate change are required to identify and manage these consequences. One such tool, which exploits a wide range of traditional and social media, is the Invasive Species Compendium, or ISC. The ISC is a scientific, web-based encyclopedia that compiles the latest information on the invasive species that have the most negative impacts on the environment, the economy and/or animal or human health. The information in the ISC, updated weekly with the latest scientific findings, can be used; to infer future climate change impacts on an invasive species; to understand the potential environmental and/or economic impacts of the species, and to identify ways to control and manage the species in question. This chapter discusses the value and efficacy of the ISC, with a particular emphasis on its application in a globally warmed future.

Introduction

As climate change and rising CO_2 levels impose additional risks regarding the introduction and spread of invasive species (Mooney and Hobbs, 2000), new and effective management methods are needed. Chief among these is the strategy of detection and prevention, i.e. to keep track of invasives through visual recognition and assess their potential for environmental or economic harm. The introduction and demography of invasive species is tied to global trade (Hulme, 2009), with consequences for ecology and agriculture (Pimentel *et al*., 2005; Ziska *et al*., 2011). To manage invasive species, a comprehensive means to identify, track and, if possible, eliminate them is needed. It is from this perspective that the global Invasive Species Compendium (ISC) was developed. Previously, knowledge about a given invasive species was often sporadic, specific to a given region, and not integrated spatially or temporally. Increasing international trade, in combination with changes in climate, lend urgency to the need for an integrated, publically accessible, continuously updated invasive species resource at no cost to the user. Such a resource may be especially relevant to developing countries that may lack technical information on invasive

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species management or in countries/regions where trade and climate are undergoing rapid changes. To develop such a resource, the global ISC was initiated as a means to provide scientific information on invasive species that was widely accessible, region specific and temporally accurate.

The Invasive Species Compendium: An Overview

The ISC is a multimedia encyclopedia that includes information regarding several thousand invasive species (available at http://www.cabi.org/isc/). The ISC is, at present, the most extensive and authoritative compilation on all taxa of invasive species. It includes, globally, known invasive organisms across all ecosystems – aquatic, marine or terrestrial – that cause the most harm. Since its release in 2012, the tool has been updated weekly and is available on an open-access basis.

The ISC was developed by a consortium of organizations from 12 countries that contributed financially to its development. The effort to develop the ISC was led by CAB International (CABI) in association with the US Department of Agriculture (USDA). They are partnered by expert organizations including the European and Mediterranean Plant Protection Organization (EPPO) and the World Organisation for Animal Health (OIE). CABI, an international, non-profit, science-based, knowledge organization, has a mission to provide information and apply scientific expertise to solve problems in agriculture and the environment (CABI, 2012).

The objective of the ISC effort was to provide an international resource with respect to invasive species. In that regard, the ISC covers the identification, biology, distribution, impact and management of thousands of invasive species. Invasive species of all taxa are covered, including plants, fungi, bacteria, viruses and animals. Subcategories of animals are further distinguished into insects, nematodes, molluscs and vertebrates.

The impacts of these organisms on natural ecosystems and on biodiversity are considered, as well as their impacts on systems managed for agriculture, agroforestry, aquaculture and animal health. Economic impacts are documented, as well as potential adaptive uses (see Chapter 20, this volume). While an underlying goal is to ingrate global knowledge, a geographic information system (GIS) is also used to display distributions of invasive species at the country, state and province levels. The ISC also includes information the invasive species' pathways and vectors, as well as available methods regarding control and management. Extensive reference materials are included, including images, library documents (including peer-reviewed journal articles), conference papers and reports, bibliographic abstracts and a glossary of technical terms, as well as comprehensive links to relevant identification keys and image libraries. As of June 2013, there were over 1682 full invasive species data sheets and over 7291 abbreviated data sheets in the ISC.

Data Sources for the ISC

The content for the ISC data sheets is derived globally from thousands of expert scientists. The ISC's veracity derives from their expertise, from corroboration through peer review and through rigorous editing for quality control.

Additional content is derived from existing compilations of knowledge on invasive species, including expert organizations such as the Inter-American Biodiversity Information Network, the currently inactive Global Invasive Species Programme and the Smithsonian National Museum of Natural History. Content is presented dynamically in the ISC through an advanced web-based platform combining databases, text and images. GIS, taxonomic relationships and data suitable for decision-support tools, such as risk analysis data, are also provided by the ISC in an interactive framework.

Any user accessing the ISC can also link to information both within the ISC and with other local or remote knowledge bases. The content is updated weekly, and the ISC will be maintained, enhanced and updated regularly into the foreseeable future.

Management and Financing of the ISC

The ISC Consortium, a group of supporting organizations (Table 14.1), provides the strategic direction and scientific leadership for the ISC project, as well as financial resources. The Consortium's goal is to provide a ubiquitous resource that: (i) is easily accessed; (ii) is relevant at different biogeographical scales; (iii) is biologically accurate; and (iv) provides control and management options for invasive species. Because such a resource must be temporally relevant, the ISC continues to be updated regularly as new information becomes available.

A primary goal of the ISC is accessibility. It should be widely available to an extensive group of stakeholders. To make the ISC free to its users, development costs are shared among Consortium Members. At present, the budget for the development and

Table 14.1. Consortium members of the Invasive Species Compendium.

- Australia, Group Membership
  - Cooperative Research Centre for National Plant Biodiversity, CRCNPB
  - Grains Research and Development Corporation, GRDC
  - Horticulture Australia Limited, HAL
  - Invasive Animals Cooperative Research Centre, IACRC
  - Australian Centre for International Agricultural Research (ACIAR)
- Canadian Food Inspection Agency; Forest Service; and International Development Agency
- Caribbean Island Countries (sponsored by European Union DGDEV)
- France, Ministry of the Environment
- Forum for Agricultural Research in Africa (sponsored by DFID)
- India, Ministry of Agriculture
- Malaysian Agricultural Research and Development Institute
- Mexico
  - National Health, Safety and Quality Service for Agri-Food, SENASICA
  - Comisión Nacional para el Conocimiento y Uso de la Biodiversidad, CONABIO
- Monsanto Corporation
- Netherlands Ministry of Economic Affairs, Agriculture and Innovation
- Secretariat of the Pacific Community (SPC)
- Swiss Agency for Development and Cooperation
- Syngenta Crop Protection
- UK
  - Department for Environment Food and Rural Affairs, DEFRA
  - Department for International Development (DFID)/CABI/FARA
- US Agency for International Development (USAID)
- US Department of Agriculture:
  - Agricultural Research Service (ARS);
  - Animal and Plant Health Inspection Service (APHIS);
  - Foreign Agricultural Service (FAS);
  - Forest Service (USFS);
  - Invasive Species Coordination Program;
  - Natural Resources Conservation Service (NRCS);
  - Rural Development (RD)
- US Department of Commerce, NOAA's National Ocean Service (NOS)
- US Department of the Interior, U.S. Fish and Wildlife Service (FWS)

Note: New Members are expected from Latin America, Asia, Australasia, Europe and North America. Any country, non-governmental organization, private company or industry can become a member; most members are in the environment or agriculture arena, and work on invasive species issues. Participation is voluntary and by invitation.

maintenance of the ISC is US$4.75 million over an 8-year period until 2016. Contributions from more than 29 Members of the Development Consortium, based in 12 countries, have amounted to more than US$4.75 million to date. Of this, US$3 million covered the phase of development and release of the definitive ISC. The remaining US$1.75 million covers the task of updating, maintenance and enhancement. Additional funds are sought continuously, to include emerging invasive species and to enhance the current information base. Such funds are also critical in extending the period of updating, maintenance and enhancement beyond 2016.

New Consortium Members are asked to make a one-time contribution of US$175,000 (US$130,000 for developing country organizations), paid over 1 or 2 years. Each new Member makes an essential contribution towards the development target. No distinction is made regarding when a member joins the Consortium.

Organizations that join the Consortium benefit in several ways. Participants have the opportunity to leverage the contributions of all the other Members and to receive the benefits of a multi-million dollar development based on global expertise. Membership allows participants to ensure that their own priorities are duly considered in the ISC's development, ongoing maintenance and enhancement. Membership presents a visible token of participation and leadership in a project that is positioned to reduce the economic and environmental impact of invasive species globally. Members have an opportunity to discuss and influence common interests in an international forum of like-minded representatives of public and private sector organizations and development assistance agencies.

Development of the ISC

The development of the ISC has taken place in phases. The first phase was completed after 18 months in 2008 and delivered an alpha version covering work to document 1000 invasive species. This was made available to the development Consortium Members for use and feedback. During the second phase, information on 500 more species was added, with enhanced development of the IT platform and with the development of advanced search tools. The beta version, with extended content and enhanced functionality, was released in October 2010. A revised beta version was released to the public in June 2011, with the final, definitive version in April of 2012 (see Table 14.2; CABI, 2012).

Table 14.2. Features of the Invasive Species Compendium.

The April 2012 version of the ISC includes:

- Full data sheets on more than 1500 invasive species and related topics prepared by 1000 specialists from throughout the world, peer-reviewed and edited by CABI. A single data sheet for an invasive species includes:
  - Identity: including names, taxonomy, description
  - Images
  - Distribution: including global and regional maps
  - Biology and Ecology: including habitat, host species, genetics, physiology, environmental requirements, epidemiology, vectors, natural enemies
  - Impact: including economic, environmental, cultural
  - Management: including diagnosis, detection and control (regulatory, genetic, cultural, chemical, biological)
  - Gaps in knowledge/research needs
  - References: linked to abstracts and, where available, to full text
- Additional data sheets on a further 7000 species
- 4000 images
- More than 75,000 abstracts of the published literature on invasive species (added to weekly)
- Full text of more than 1085 relevant published documents (added to weekly)
- Powerful search and browse facilities

The third phase of the ISC relates to sustainability. Specifically, the ISC will be updated continually, both in regard to information and also to accessibility and use. This process will involve the input and participation of Consortium Members, as well as feedback from users. At present, the business plan covers these additional costs until 2016, with the intention of indefinite continuation.

How can the ISC be improved for the future? Proposed actions for Stage 4 of the ISC include: better GIS tools for assessing the impact of climate change on invasive species biology; training people to use the ISC; linking population decline or the extinction of native, threatened species to specific invasive species and documenting it in the ISC; expanding information on biological mechanisms that enhance invasive species establishment; developing new scientific tools for extinction vulnerability (population and habitat viability analysis and meta-model analysis); establishing and extending the capacity of the ISC to communicate and exchange data with national invasive species databanks/inventories; enhancing/updating information on the biological control of invasives (updated global database on biological control); and augmenting the number of invasive species with full data sheets.

Use and Access

Open access, free at the point of use, was proposed and agreed at the ISC Inception Workshop in 2006. The costs of ISC maintenance are covered by the ISC Consortium contributions.

The ISC is freely available for use as a global knowledge base to address practical issues concerning the impact of thousands of invasive species – on the environment, on biodiversity and on agriculture, forestry and fisheries, and on animal health. In June 2012, the Compendium content was licensed under a Creative Commons Attribution-NonCommercial-NoDerivs 2.0 UK: England and Wales Licence. It spans the boundary between invasive species' impacts on food security (through the productive use of land and water) and concurrent impacts on the environment and biodiversity.

The ISC has intrinsic value for preventing the introduction of invasive species (including providing data for tools with predictive capability) by providing timely access to information on potential introductory pathways, as well as the management and containment of established invasive species. In addition, it has utility in extension, training, public awareness and research and development, and may provide a scientific tool for policy decisions. The ISC is especially valuable in the local production of educational materials – for example, public information notices and training techniques specific for a given biogeographical region. All information, text and photographs in the ISC can be downloaded to prepare educational materials specific to local needs.

Application of the ISC for the Detection and Prevention of Invasive Species with Climate Change

Anthropogenic increases in atmospheric carbon dioxide, and the resultant increases in climatic variation, are among the most challenging issues in global biology (IPCC, 2007).

These changes have a number of implications for the biology of invasive species. For example, increased carbon dioxide could favour weedy invasive species such as cheatgrass, exacerbating the environmental damage from large, cheatgrass-fuelled fires in some regions (Ziska *et al*., 2005). Although additional data are needed, initial studies have suggested that, on average, invasive species may show a stronger response to both recent and projected changes in carbon dioxide relative to native plant species (Song *et al*., 2009). Climate change, particularly warmer temperatures, could also result in shifts of invasive species' ranges, sometimes leading to net expansions or contractions (Parmesan, 1996; Bradley *et al*., 2009).

Clearly, there is a need to have tools that can assist in predicting the behaviour of invasive species under different climate change scenarios. The ISC can provide a first assessment. Here are some examples on how the ISC can be used for purposes related to climate change.

Assessing the future range of an invasive species

The ISC contains information on the preferred climate for a species: temperature, rainfall, soils (of a plant species), etc. These data are contained in tables in the Biology and Ecology section of the ISC's Invasive Species data sheets. The optimal climate data relative to optimal growth and fecundity of an invasive species can be exported via text or table formats, enabling them to be used for specific and sophisticated climate models. The ISC can also export distribution data to a Google map using a KML (Keyhole Markup Language; a map file format that can display distribution data) download tool. Layering freely available present-day climate data under the distribution of a species could be used to explore, using maximum entropy or other techniques, the range change of the species predicted by future-climate-change models.

What are the invasives in my country?

The ISC can make a list of the invasive species present (those that have a full data sheet) for any country. For some countries, the information can be obtained at the state or province level. This can serve as a starting point for land managers, scientists and others to examine the regional threats posed by invasive species for their area. Such an assessment may also identify adjoining invasives that could potentially migrate in response to climate change (McDonald *et al*., 2009).

Assessing the threat of new invasives

A list of known invasive species can be requested from other geographically close countries; or, alternatively, from countries with similar climate and/or soils. Cross-comparisons can be made in order to elucidate new threats or to assess the economic or environmental vulnerability of a given country or region to proximate invasive species. The ISC can then provide a list of invasive species that may present a risk. The GIS capability of the ISC can be used to do this task. As a result, any country can prepare prevention actions and early detection and rapid response (EDRR) programmes as management tools to cope with new invasive threats.

This assessment can be a two-step process. The ISC search capability can be deployed to compile a list of invasive species in country X that are not in country Y at present. Extrapolating the ISC data using the ISC search capability can be used with other resources such as WorldClim (www.worldclim.org) climate projection models to investigate the invasive species of a country (country X) with a climate that is the same as or similar to that predicted for another country (Y) some time in the future. Those species identified as present in X but not in Y could then be prioritized in national invasive species prevention and management programmes in country Y; programmes which could also be informed by other data in the ISC such as those relating to known pathways of introduction.

Analysing pathways for invasive species' introductions with climate change

The ISC will have a data sheet for over 50 pathways used by invasive species. For a particular proposed climate change scenario, pathways that might be used by an invasive species to enter a country can be identified, and as a result, management strategies to mitigate or prevent introductions can be developed and implemented.

Analysing invasive species by habitat under climate change

In the near future, over 45 habitat data sheets will be included in the ISC, providing lists of associated invasive species and collating information on the specific risks, threats and management challenges invasive species pose to each of those habitats. The name of the habitats in the ISC is contained in the 'Advanced Search Help'. Some of the habitats included are agricultural lands, forests, grasslands, roadsides, mangroves, salt marshes, lakes, streams, coral reefs, etc. For example, if we are interested in knowing the invasive species that are found in the habitat called 'terrestrial-managed, forests', we can query the ISC to list those invasive species associated with such a habitat.

If there is particular concern about the range expansion of an invasive species habitat under climate change, the ISC can also help. In our example, we might wish to pursue how invasive species within the habitat, 'terrestrial-managed, forests', might be impacted for a given IPCC scenario. The ISC can be queried for a list of invasives in that specific habitat throughout the world. The list can then be refined by the specific climate parameters (e.g. change in minimum temperature) that are projected for the climate model in question. Identification of the invasive species associated with that habitat will also generate a list of species in neighbouring countries or regions with strong trade links. That way, in conjunction with other techniques described above, an estimated list of all of the potential invaders within that habitat and the range that habitat might occupy between regions or countries, can be examined.

Summary

Anthropogenic carbon dioxide and associated changes in global climate will influence the distribution and biology of invasive species. Given the economic and environmental damage inflicted by invasives, it is imperative that management tools that can track, discern and help to prevent the establishment of invasive species become a global priority. In this regard, the Invasive Species Compendium (ISC), by initiating and maintaining a comprehensive scientific database of current and potential threats, associated movements and biological and ecological characteristics, will provide a freely available, unique, easily accessible, worldwide resource to assist with the detection and management of invasive species on a global basis.

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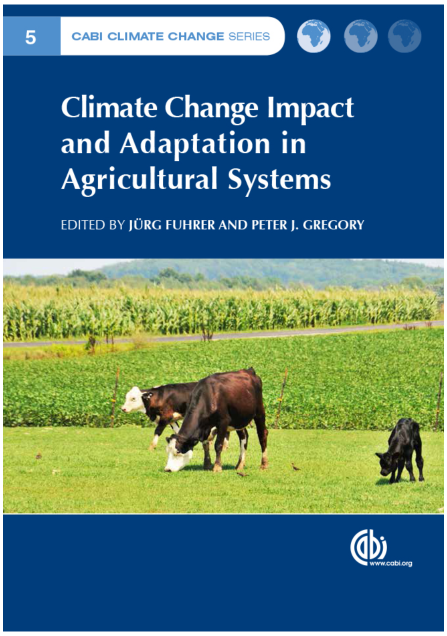

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1

Climate Projections for 2050

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1.1 Introduction

In order to assess the implications of climate change in terms of impacts and adaptation needs, projections of the future climate are needed. Climate models are the primary means of such simulations. The results are often coined 'climate scenarios' but should really be called projections, as they are built on alternative scenarios of future land-use changes and greenhouse gas emissions. The basis for climate projections is discussed in this chapter, together with a selection of general results that are of key relevance for agriculture, which stem from state-of-the-art climate projections. This chapter provides the background for the subsequent chapters in this book, and discusses climate projections for the next few decades. While the focus is on the period until 2050, it should be noted that climate change will very likely continue well beyond the middle of the 21st century. Indeed, the long-term prospects are about not only a changed climate but also a climate that is changing over time, i.e. it is about continuous change over a long time. The same is thus also true for our knowledge requirements regarding climate change impacts, as well as the motivation and need for climate change adaptation; however, these may take form.

1.2 Basis for Climate Change Projections

1.2.1 General

While we observe and experience our contemporary climate and intrinsically may expect its past behaviour to also give us a good picture of things to come, future conditions are innately unknown to us. This is especially true for the consequences of the use of fossil fuels and land-use change, which increasingly adds greenhouse gases to the atmosphere, not least carbon dioxide but also methane, nitrous oxide, etc. There are emissions that affect the tropospheric ozone, which has an effect on the climate, in addition to impacts on health and vegetation. Human activities also affect the amount of sulfate particles and soot in the atmosphere, which further compounds our impact on the climate. Land-use change, in addition to affecting carbon sources and sinks, affects the physical properties of the land surface, which further adds to the forces that the climate now responds to on global, regional and local scales (Pitman *et al*., 2011).

That we force the climate and that the climate responds is certain (IPCC, 2007). Climate change projections for the future have, however, uncertainties. This should not be confused with the view that they are left wanting; evaluation of climate models suggests that they perform well in many respects, and as they are based on physical principles, their results do have considerable credibility.

Model shortcomings are one source of uncertainty. Scenario uncertainty concerning underlying future emissions and land-use pathways is another. In addition, the climate system exhibits internal variability that arises from the complex interplay between the atmosphere, the ocean and the other climate system components. The relative importance of these sources of uncertainty is well established (e.g. Hawkins and Sutton, 2009).

Climate projection uncertainty is smaller at the global scale compared to the regional scale – and even more so, compared to the local scale. This is due largely to the ubiquitous internal variability that can simultaneously affect different regions in contrasting ways but which is largely cancelled out in the global mean. The relative importance of internal variability for climate projection uncertainty declines over time, as the forced climate change signals become greater. At the same time, the uncertainty linked to the emissions and land-use change scenarios grows. The uncertainty attributed to climate models has a more constant presence compared to the other two factors. These sources of uncertainty are discussed below.

1.2.2 Climate-forcing scenarios: fossil fuels and land-use change

Underlying climate model projections, i.e. forward-looking simulations of the evolution of the climate system, are scenarios of climate-forcing factors. In terms of the climate over the next few decades and beyond, this concerns anthropogenic emissions of greenhouse gases, particles and their precursors and the indirect greenhouse gases (see above), as well as land-use change. While today's energy systems, consumption patterns, food and fibre production do lock us on to a path of continued climate change in the short and medium term, the longer-term situation is less certain. Thus, scenario assumptions of emissions and land-use change are an important part of uncertainty in climate projections.

Knowledge of both the underlying climate-forcing scenario (emissions, land-use change) and of the climate model (cf. 'climate sensitivity', see below) is paramount when considering a specific climate change projection; for example, in terms of temperature change. Climate models, emissions and land-use scenarios have evolved over time. Early on, more or less idealized scenarios were used, which were followed by more versatile ones. Over the past 10 years or so, most global and regional climate projections have been based on the IPCC Special Report on Emissions Scenarios (SRES; Nakićenović and Swart, 2000), which span a range of possible future emissions pathways. The most recent climate projections are based on the RCP scenarios (representative concentration pathway; Moss *et al*., 2010). These are coined RCP2.6, RCP4.5, RCP6.0 and RCP8.5. The SRES and the RCP scenarios are set up in different ways. The former provides greenhouse gas emission and land-use change pathways, based on underlying assumptions regarding socio-economic drivers such as population and economic and technical development. The atmospheric concentrations of greenhouse gases are then derived from the emissions scenarios, for use in climate models. The RCP scenarios provide radiative forcing/greenhouse gas concentration scenarios for the 21st century. The number attached to each scenario designates the radiative forcing in $W\ m^{-2}$ by 2100. There is an accompanying effort with RCPs for the generation of corresponding greenhouse gas emissions, land use and socio-economic developments.

There is no one-to-one comparability of the RCPs and the SRES, but they span much of the same range of alternative future climate forcing. The RCPs, however, also include a scenario (RCP2.6) that corresponds to considerably lower emissions than any of the SRES scenarios, and as such is aligned with a considerable mitigation effort. Still, neither the SRES nor the RCPs are recommendations for policy, or forecasts. There are no probabilities affixed to them.

Overall, when interpreting climate model results, information is needed about the underlying emissions and land-use scenarios, as climate change projections largely scale with the emissions scenario. How much so depends, however, on the climate models themselves.

1.2.3 Climate sensitivity

Alongside assumptions regarding the emissions pathways and future land-use change, a second key uncertainty in climate change projections is the sensitivity of the climate system. Simply put, this is a measure of how much the climate changes when it is forced.[1] Climate sensitivity is the net measure of the direct effect of the forcing and the feedback that arises within the climate system. An example of key feedback is that a warmer atmosphere can hold more moisture; as water vapour is a greenhouse gas, this enhances the initial warming. Possible changes in clouds are another key feedback. The sign of the overall climate sensitivity is robustly known (positive, i.e. feedback enhances the change due to some initiating factor, such as emissions), but its magnitude is generally only known within a range of values. The range of climate sensitivity in climate models overlaps with the body of estimates based on historical and contemporary climate variations, which provides confidence in the models and their results.

1.2.4 Climate models

Climate models are sophisticated simulation models that build on the physical, chemical and biological understanding of the climate system, written in computer code. There are today quite a few global and regional climate models in the world, constantly under further development, evaluation and in use in research. The majority of climate models have interacting components for the atmosphere, the ocean and the land surface, but there are also models with interactive carbon cycle and vegetation components, as well as some with yet additional climate system components. The latter are today known as 'Earth System Models'. In the case of models that do not carry a vegetation component, relevant properties are prescribed.

While climate models do exhibit various biases, they also perform well in many respects (Randall *et al.*, 2007), including the overall global and regional climate characteristics and the reproduction of observed changes over time.

Global climate models are fundamental when considering the response of the climate system to forcing. Solving the equations in climate models requires, however, extensive computational power, not least as simulations span from decades to centuries and often need to be repeated with several variations. This constrains the resolution of the models. Even today, many global climate models have a resolution ('grid size') of a few hundred kilometres. This is insufficient for resolving variable landforms and other physiographical details that have a significant effect on the near-surface climate in many regions. Global model results are therefore applied to regions by various downscaling techniques (Rummukainen, 2010) such as statistical models and regional climate models. The latter is also known as dynamic downscaling.

The global climate modelling community has a long tradition of organizing coordinated simulation experiments that span many climate models and different sets of simulations. Many of the results in the Fourth Assessment Report of the IPCC (Intergovernmental Panel on Climate Change; Meehl *et al.*, 2007) came from the so-called CMIP3 coordinated study, which was followed by CMIP5 (Taylor *et al.*, 2012). Coordinated regional climate model studies are fewer but have, during the past few years, emerged for several regions, not least Europe (Christensen and Christensen, 2007; Kjellström *et al.*, 2013), the Americas (Menendez *et al.*, 2010; Mearns *et al.*, 2012) and Africa (Paeth *et al.*, 2011). Coordinated studies of course provide more information for the characterization of model-related uncertainties, either by co-consideration of all results or by allowing a specific scenario to be tested in a wider context, including how it compares with other scenarios.

Advanced climate models are based on fundamental physical laws. This enables their use in projections of the future beyond the observed period. There are limitations on model resolution, as mentioned above, meaning that small-scale processes that cannot be resolved have to be parameterized (i.e. represented with approximate descriptions). For example, cloud formation cannot be simulated explicitly in climate models as it ultimately involves very detailed mechanisms. Rather, it may be parameterized in terms of relevant large-scale ambient conditions in the models. Parameterization is, however, also based on the physical understanding of the involved processes.

Parameterizations are formulated in somewhat different ways in different climate models. This explains why climate models as a whole exhibit a range of climate sensitivities. This range overlaps observational estimates.

1.2.5 Internal variability

Finally, the climate system is non-linear. This manifests itself in ubiquitous internal variability within the climate system, resulting in inter-annual variability and also variability at the decadal scale. The global mean temperature, for example, exhibits some inter-annual variability in concert with the large-scale interaction between the ocean and the atmosphere in the Pacific, known as El Niño–Southern Oscillation (ENSO). ENSO also has various strong regional signals around the world of anomalous warmth and coolness, as well as unusually wet and dry conditions. Different variability patterns characterize yet other world regions, including the Arctic and North Atlantic Oscillations (AO, NAO; Thompson and Wallace, 1998), the Pacific-North American Pattern (PNA), as well as the more regular monsoon circulations.

The presence of significant regional-scale climate variability implies that, to begin with, while climate change is indisputably discernible at the large scale, it still may remain within regional-scale variability, meaning that it may be more difficult to identify conclusively at this scale. The same applies to climate projections and, consequently, the emergence of statistically significant change occurs later in many regions than in the global mean (Giorgi and Bi, 2009; Kjellström *et al.*, 2013). Mahlstein *et al.* (2012) find, for example, that statistically significant regional precipitation changes emerge only once global mean warming climbs above 1.4°C, which is roughly a doubling of the warming until the beginning of the 2000s. There is not, however, an absence of ongoing regional changes before clear signals emerge; rather, regional climates undergo transitions that may manifest themselves earlier as changes in, for example, the likelihood of extreme events (Stott *et al.*, 2004; Jaeger *et al.*, 2008), before the mean climate shows a significant response.

1.3 Projections

1.3.1 Temperature

Temperature change is a fundamental characteristic of climate change (‘global warming’ is often used synonymously with the present-day ‘climate change’). The observed global mean change since the pre-industrial era is large compared to variability over comparable timescales, and now amounts to *c.*0.8–0.9°C. To keep the global mean temperature rise under 2°C has been agreed as the international target under the UN Framework Convention on Climate Change (UNFCCC). However, the present evolution of emissions is not aligned with emissions pathways that might provide a likely chance of meeting the two-degree goal (e.g. Peters *et al.*, 2013), suggesting that global warming may well come to exceed this UNFCCC target. The majority of climate change projections to date build on scenarios that do not include specific new climate policy measures and, consequently, result in a larger warming than the two-degree goal. The IPCC (2007) Fourth Assessment Report contained projected global warming results that ranged from around 1°C to more than 6°C for the period between the late 20th century and the late 21st century, with consideration of different emissions scenarios, climate models and information on climate change impacts on the carbon cycle. When additionally considering the observed warming since the pre-industrial until the late 20th century, the same projected change in temperature increases to *c.*1.5–7°C.

The climate system response to forcing is not uniform. While the overall pattern due to emissions is one of warming, some regions will warm more (or less) than others, and thus more (or less) than the global mean change (see Plate 1). For example, a 2°C global mean warming would imply temperature increases larger than 2°C over land regions.

Changes in the average temperature emerge over time in a relatively gradual manner. Changes in variability, and not least in extremes, can, however, manifest themselves in more complicated ways. Intuitively, and what is also evident in climate projections, is that warm extremes become more commonplace, whereas cold extremes less so (e.g. Zwiers *et al.*, 2011; Orlowski and Seneviratne, 2012; Rummukainen, 2012). It is also characteristic that in areas in which there is a reduction in seasonal snow cover, such as the high northern latitudes, the reduction of cold extremes exceeds the wintertime mean temperature change. Correspondingly, in the relatively dry subtropical areas that experience increasing dryness, changes in warm extremes exceed the average regional temperature change (e.g. Kharin *et al.*, 2013).

As extremes manifest themselves in a more or less sporadic fashion, changes in them are more difficult to pinpoint than those of climate means (Trenberth, 2012). Extremes can also change in terms of their return period or likelihood of occurrence, magnitude, geographical distribution, and so on. When posing the question of whether extreme events will change in ways that impact a specific sector or region, the vulnerability of the activity or the location needs to be specified. The use of indices may be helpful (Sillman and Roeckner, 2008; Zhang *et al.*, 2011).

1.3.2 Precipitation

Global precipitation increases with global warming. Results suggest that the increase in the global mean of precipitation is around 2% for each 1°C rise in temperature. The projected changes are non-uniform over the globe, as evident from Plate 1 (see also, for example, Solomon *et al.*, 2009). Regional changes are often larger or smaller than the global mean change. There is a distinct large-scale pattern that is coined 'wet gets wetter' and 'dry gets drier' (cf. Held and Soden, 2006). Although there are exceptions to this, it by and large summarizes the big picture well. Consequently, precipitation is projected to increase at high and middle latitudes, decrease in the subtropical regions and increase in parts of the tropics. In the transition zones between these divergent patterns, the projected change is very small or of insignificant magnitude. The exact location of the transition regions varies to some extent between models and projections. Thus, in the affected regions, while some projections may suggest an increase, others can show a decrease.

A general increase in the occurrence of heavy precipitation is, however, a typical result both for regions in which precipitation on average increases and for regions in which precipitation on average decreases. There are many measures for extreme precipitation. For example, such heavy precipitation events that at the end of the 20th century had a return period of 20 years are projected to become 1-in-15- to 1-in-10-year events by around 2050 across most of the global land area (IPCC, 2012); that is, with a rate of increase that is twice or more the rate of the global mean precipitation increase (Kharin *et al.*, 2013). The uncertainty due to climate model quality is larger for the tropics than for many other regions. Climate projections tend to exhibit large increases in extreme precipitation compared to changes in average precipitation (Rummukainen, 2012; Kharin *et al.*, 2013; Sillman *et al.*, 2013).

Precipitation is a basic measure of hydrological conditions, but does not wholly describe issues relating to water availability; information is also needed on evapotranspiration, soil moisture, drought risks, runoff, etc. For example, there are studies that indicate an increasing risk of drought in subtropical regions in the Americas, southern Europe, northern and southern

Africa, South-east Asia and Australia (Dai, 2011; IPCC, 2012; Orlowsky and Seneviratne, 2012).

1.3.3 Other aspects

Temperature and precipitation are two fundamental aspects of the climate we experience. There are also a variety of other variables and processes that intimately affect us, such as cloudiness, soil moisture, evapotranspiration, snow, glaciers and sea ice, wind and sea level. Characterization of the climate also involves the consideration of sequences of events and phenomena such as, for example, drought, flooding, storms and heatwaves. Likewise, characterization of the climate concerns, in addition to average conditions, also variability patterns and extremes (IPCC, 2007, 2012; Rummukainen, 2012). While climate projections can provide information on all of these aspects, a comprehensive account is beyond this chapter. Also, which aspects are pertinent to consider depends on the question in hand: for example, the kind of climate impact or region of interest. Seasonality related to agriculture, for example, follows temperature in Europe, while it follows the succession of wet and dry periods in Africa.

1.4 Regional Patterns of Change

Global climate model projections also provide information on regional-scale climate. Plate 1 gives a first impression of regional patterns of projected temperature and precipitation change, relative to the overall global mean warming amount.

However, the detail in global climate model projections is constrained by model resolution, which in most cases corresponds to a few hundreds of kilometres (Masson and Knutti, 2011; Räisänen and Ylhäisi, 2011). Information on the quality of the models in simulating large-scale variability is important for regions in which such variability plays a significant role in shaping the regional climate (e.g. van Haren *et al.*, 2013). Complementary regional-scale climate projections are carried out with downscaling, either by means of regional climate models (Rummukainen, 2010) or statistical downscaling (Maraun *et al.*, 2010). Downscaling attempts to capture better the influence of variable orography and land–sea distribution on the regional climate than what is feasible to achieve with global models. Consequently, for many climate change impact studies, downscaled climate projections can be a better starting point than the direct results of global climate projections.

For example, Kjellström *et al.* (2013) analysed results from 21 recent regional climate models for Europe. Even though these had been forced by different global models, the projections gave very similar patterns of change for both temperature and precipitation (see Plate 2). The largest wintertime changes occur in the north-east and the largest summertime ones in the south. Precipitation tends to increase in the north and decrease in the south. However, there are also models that show small to insignificant changes in large parts of Europe, and models that suggest a general wetting. These findings largely confirm earlier regional projection results for Europe (e.g. Christensen and Christensen, 2007; Déqué *et al.*, 2012).

A similar analysis for Africa is shown in Plate 3. In North Africa, warming is greater in the summer than in the winter. There is a similar feature in the south of Africa. Warming for most of the models here ranges from around 1°C or slightly less to somewhat above 2°C. The range of precipitation changes projected by regional climate models (RCMs) is similar to the European case (Plate 2), in the sense that it spans from a general drying to a general wetting. The RCM median result suggests drying in both the north and the south of Africa, and either an increase or no change in between these areas.

1.5 Circulation Patterns and Regional Changes

Internal variability is a ubiquitous aspect of the climate system. Its specific regional manifestations can often be analysed in terms of circulation patterns or 'large-scale variability modes'. For example, different phases of ENSO lead to significant regional temperature and precipitation anomalies in many parts of the world. Inter-annual variability in the North Atlantic, Europe and the Arctic region occurs in concert with the North Atlantic Oscillation and the Arctic Oscillation, and manifests itself as, not least, inter-annual variability in general cold-season weather. In monsoon regions, such as South-east Asia and Western Africa, the seasonally changing temperature contrast between the land and the sea generates a distinct variability of regional precipitation. Under climate change, however, some of the characteristics of circulation patterns may change. This would imply regional climate change that further deviates from the global mean, in addition to the general larger warming over land than over sea, etc. (cf. Plate 1).

While individual models may project various changes in circulation patterns as a result of climate change, global climate projections to date do not collectively suggest major shifts in ENSO, NAO and some of the other comparable modes (IPCC, 2007). Precipitation associated with monsoons is projected to increase in general, as well as the overall global area that is affected by monsoons (Hsu *et al.*, 2012), due to higher sea surface temperature and atmospheric water vapour content resulting from global warming.

More recently, it has been postulated that the retreat of sea ice in the Arctic region may affect atmospheric circulation and promote the occurrence of more persistent weather patterns, such as extreme winters and summers at the high and mid-latitudes of the northern hemisphere (Francis and Vavrus, 2012; Liu *et al.*, 2012). Climate models suggest that such a link may exist and play some role during the 21st century (Yang and Christensen, 2012). The expected continued reduction of the Arctic sea ice cover may counteract the effect of the overall warming on the occurrence of cold winter months in Europe and concurrent mild winters across North America. This does not mean an expectation of more cold winters in Europe, however, but rather that cold winters will still occur even when overall warming proceeds.

Overall, regional-scale climate in many parts of the world is shaped not only by global-scale constraints but also by the action of circulation patterns; the latter often warrant special attention in the analysis of regional climate change projections (Deser *et al.*, 2012).

1.6 Discussion and Conclusion

Climate change is of global and regional concern. In addition to general warming, changes are expected in precipitation patterns and other aspects, both on average and in terms of variability and extreme events. Changes that well exceed climate variability far back in time, and certainly over the history of modern society, are to be expected. This underlines the need for knowledge on how the future can unfold, in order to anticipate the impacts and to be able to prepare for them. Climate projections offer a means to do this.

A pertinent question for analyses and impact assessments is 'which climate model and projection to choose'. Unfortunately, there is no specific answer. Rather, one needs to recognize the sources of uncertainty and, as much as possible, look at many projections from many climate models, based on different emissions scenarios. In the case of it being prohibitive to account for large sets of scenarios, the evaluation of climate models may provide guidance for choosing a smaller set of models and projections. For example, one could perhaps exclude models which exhibit larger biases in variables that are especially crucial for the impact study in hand. For the early part of the 21st century, projections are relatively similar across many emissions scenarios; and one could consider focusing on one or at most a few emissions scenarios. In any case, consideration of the results from more than one model and/or projection is always recommended. While use of a subset of models and projections does not necessarily suffice for quantification of scenario uncertainty, it can still provide a useful reminder that scenarios and projections are possible unfolding futures that are subject to uncertainty, rather than definitive forecasts.

Climate projection results are often similar when it comes to the direction of the projected changes, be these of increase, decrease or no evident change. The size of projected change, however, varies more. This is due in part to differences in climate sensitivity, i.e. in the response to a given forcing represented in models (in other words, in the underlying process descriptions). Some of the variation across models can be attributed to the simulated internal variability. Nevertheless, the magnitude of change characteristically increases with fossil fuel emissions and land-use change, and thus also over time as long as these remain unabated.

One way to condense information from multiple models and projections is to consider multi-models (ensembles). Analysis of multi-model means helps to highlight results that are consistent across the models, although this occurs at the expense of suppressing outliers. For example, the latitude zones that border the higher latitude regions with a projected consistent precipitation increase, and the subtropical regions with a projected consistent precipitation decrease, have a 'no change' appearance, while specific projections may exhibit either increases or decreases. Outliers may need to be considered for impact assessments, as they may represent extreme responses and thus give at least a partial idea of 'best case' and 'worst case' scenarios. Thus, multi-model mean results need to be amended with consideration of either some individual projections, or the model spread. The pursuit of probabilistic projection analysis of global and regional projections is a more refined method addressing the same problem (e.g. Déqué and Somot, 2010; Alessandri *et al.*, 2011).

In the end, of course, the intended use of climate projections, such as in agricultural impact assessment, needs to guide the considerations. High-resolution information may be preferred, in which case downscaled information, be it from statistical or dynamical approaches, is probably needed. The assessment and impact model at hand may pose constraints on whether individual projections or ensemble-based results can be used. Nevertheless, proper consideration of climate projections necessarily requires insights into their basis and underlying scenario assumptions.

Note

[1] The definition of climate sensitivity refers to the long-term (equilibrium) global mean temperature rise for a doubling of the atmospheric carbon dioxide content. A specific climate scenario may feature an increase in the atmospheric carbon dioxide concentration that is either smaller or larger than a doubling. The value of the climate sensitivity should thus not be confused with a specific climate change/global warming scenario. Another concept is the 'transient climate response', which refers to the warming that manifests itself around the time when the atmospheric carbon dioxide concentration doubles. The climate sensitivity is larger than the transient climate response, which is due to the slow progression of warming signals to spread in the ocean.

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