Chapter 4

Crop protection in organic agriculture

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Introduction

Organic farming systems are challenged by many of the same crop protection issues as conventional farming systems. Approaches to crop protection in organic agriculture differ widely among growers globally and regionally. At one end of the spectrum, organic growers use substitution-based approaches in large-scale operations to capture premium prices in a niche market. At the other end, resource-poor farmers producing subsistence crops use, by default, pest regulation tactics based on traditional knowledge. Organic growers at both ends of the spectrum are less motivated by environmental and public health considerations than are those growers that have formed the philosophical centre of organic agriculture movements in various parts of the world. For these growers, organic agriculture differs fundamentally from conventional agriculture, not in terms of the pest and disease challenges that face crop production or solely in the range of tactics used by growers, but in the conceptual approaches that frame crop management strategies.

Too often, descriptions of the conceptual approaches in conventional and organic agriculture are overly simplified (Trewavas 2004). Conventional pest control can no longer be characterised as the reliance on scheduled applications of broad-spectrum pesticides (biocides, insecticides, fungicides, herbicides). Best practices in conventional agriculture incorporate a wide range of tactics, including pest monitoring and judicious use and timing of selective pesticides, selection of insect and disease-resistant cultivars, and cultural controls such as crop rotation and crop residue destruction. By the same token, organic agriculture is more than conventional agriculture minus synthetic fertiliser and pesticide inputs. While some organic growers do simply substitute manure for fertiliser and botanically derived pesticides for synthetic pesticides – more often, organic practices involve a wide range of soil management and cropping practices that maintain ecosystem health and foster ecosystem services (Altieri 1986 1999, van Bruggen and Semenov 2000).

For the purpose of this chapter on pest and disease management, organic agriculture is defined as plant and animal production systems managed with an emphasis on sustainable and renewable biological processes: nutrients supplied at rates needed to maintain nutrient balances through decomposition of nitrogen (N)-fixing green manures and plant or animal-based soil amendments, and pest management relying heavily on promoting plant health, vegetation management and biological control. Curative pest treatments include application of microbials, botanicals, soaps, oils and minerals and augmentative releases of predators; synthetic fertilisers or pesticides are generally not applied, unless exemptions are granted.

We will use a theoretical approach to the characterisation of pests and diseases in agricultural systems, based on some of the ideas from invasion ecology. Invasion ecology is a complex and dynamic intellectual conversation often focused on exotic plants, mammals and birds. Here, we don't consider only exotic species as invaders but also any pathogen or pest species not yet present in a crop in a particular growing season. To apply some basic concepts of invasion ecology to crop protection, we consider three phases of invasion:

1 colonisation
2 establishment, and
3 population outbreak.

We explore whether certain invasion trends may be distinguished for herbivorous arthropods, nematodes, fungi, and bacteria in organic versus conventional farming systems. By borrowing the term *invasibility*, we can examine how organically managed crops may present barriers against the invasion by pests and pathogens, and compare them, when possible, with conventionally managed crops. In natural ecosystems, low invasibility has often been related to high biodiversity depending on the scale of observation (Peterson *et al.* 1998), and this relationship may also hold for managed agroecosystems (Knops *et al.* 1999). Organically managed agroecosystems are generally more diverse than their conventional counterparts. This has been shown for above-ground natural plant and crop species, insects and birds, as well as for below-ground arthropods, nematodes, fungi and bacteria (e.g. Mäder *et al.* 2002, Aude *et al.* 2004, Asteraki *et al.* 2004, Oehl *et al.* 2004). The reasons for this difference in biodiversity are manifold, but in particular, the:

1 absence of herbicides reduces detrimental effects on various microbial species;
2 absence of synthetic nematicides and insecticides reduces broad-spectrum effects on beneficial fauna;
3 absence of general fumigants reduces broad-spectrum activity on all soil life;
4 absence of easily available plant nutrients reduces the selective enhancement of fast-growing microorganisms, and
5 addition of various plant and animal-derived organic materials enhances the soil food web and, indirectly, the above-ground food web.

In addition, organic farmers frequently purposefully plant strips of controlled natural vegetation, which affects not only above-ground biodiversity, but also soil biodiversity. If higher biodiversity in agroecosystems reduces invasibility, then we can expect a reduced spread of pests and diseases in organic compared to conventional farms. We suggest that this expectation is largely met, but that there are exceptions.

We compare the range of pests and diseases that challenge crop productivity in organic and conventional farming systems around the world. Our emphasis here is on arthropod pests and diseases, but we include some observations on vertebrate and other invertebrate pests. We then describe organic and conventional strategies for pest and disease management, including the three elements:

1 prevention of colonisation or establishment;
2 population regulation through biological processes; and
3 curative interventions.

To illustrate these elements of pest and disease management in practice, we critically review comparative research programs on conventional and organic pest control in many parts of the world, and illustrate the constraints and opportunities of organic crop protection under different farming conditions. We conclude by providing suggestions on future research directions that will advance our knowledge and capacity for effective crop protection in organic agriculture.

Pests and diseases in organic versus conventional agriculture

Pests and diseases that plague conventional farming operations, causing yield loss or the application of costly inputs, are often the same species that challenge organic growers producing the same crops. One significant difference is that organic growers avoid the use of broad-spectrum synthetic pesticides, which severely disrupt natural controls in the system and promote the occurrence of secondary pests (Johnson and Tabashnik 1999). Well-known secondary pests in pesticide intensive systems include spider mites in temperate orchards treated for codling moth, rice brown planthopper in pesticide-treated tropical paddy rice, *Rhizoctonia* black scurf in potato after nematicide applications that reduce fungi-feeding collembola (Hofman 1988), and apple scab as a result of decimation of earthworm populations by the fungicide benomyl (slowing down decomposition of infected leaves). A substantial number of major pests in conventional systems, then, are regulated at low levels in organic systems by virtue of the conservation of their natural enemy complex.

Natural pest and pathogen controls are not only conserved (not disrupted) but are also promoted in organic farming conditions. Most soilborne plant pathogens causing root and foot rots in older plants are usually less prevalent in organic than in conventional farms (van Bruggen and Termorshuizen 2003). This kind of disease suppression has frequently been associated with higher microbial activity and diversity, with higher microfaunal numbers and diversity, and/or with lower soil and crop N concentrations in organic than in conventional soils. Attacks by some airborne diseases (in particular many powdery mildew and rust diseases) and by sucking insect pests (aphids and whiteflies) can also be less severe in organic than in conventional crops due to lower nitrogen concentrations in foliar tissues or phloem on organic than on conventional farms (van Bruggen 1995).

Some arthropods are favoured under conditions of organic farming practices, however, particularly below-ground pests that are fostered by rich organic matter such as the garden symphylan, cutworms, wireworms (Jansson and Lecrone 1991, Peachey *et al.* 2002) and slugs or hardy pest insects that have few biological controls and are not effectively controlled with allowable organic inputs such as the strawberry weevil or *Lygus* bug. Similarly, damping-off causing pathogens such as *Pythium* species can wreak havoc in organic crops, since these can multiply quickly in fresh organic materials incorporated into soil (van Bruggen 1995). Certain foliar diseases that can spread quickly and are controlled by frequent fungicide sprays in conventional farms, such as potato late blight and onion downy mildew, can be devastating on organic crops in humid climates (Piorr and Hindorf 1986, van Bruggen 1995). Stored products pests should also be a particularly challenging problem for organic agriculture, since synthetic insecticides are prohibited. However, it seems that stored products pests are a universal problem posing challenges for conventional and organic farmers alike. Haines (2000) describes many problems with synthetic chemical approaches in the past decades to long-term storage pest control, and proposes new innovations in alternative control strategies. These control strategies include those used by organic growers (Table 4.1).

Vertebrate pests, such as deer and other ungulates, fruit-eating and seed-eating birds, rodents, rabbits and squirrels colonise or intermittently visit both organic and conventional farms, potentially reducing yields and/or affecting food quality. Some of the practices more common on organic farms such as cover cropping, farmscaping with non-crop vegetation, and mixed cropping encourage beneficial fauna and repel some vertebrate pests, but may also improve the habitat for other vertebrates, such as gophers, voles and noxious birds. Organic practices overlap with those of conventional farming for control of these pests, including

Table 4.1 Relative reliance on different crop protection practices in organic and conventional agriculture to reduce crop invasion by pests and pathogens

Examples of specific practices are included in Altieri 1989, Lampkin 1999, Gliessman 2001, Litterick *et al.* 2004, van Bruggen 1995.

Invasion stage/ approach	Specific practices	Organic	Conventional
Colonisation prevention			
Sanitation	Pathogen-free seed, debris destruction, flaming, steaming (fumigation in conventional farming)	Common	Common
Temporal asynchrony	Late or early planting or harvest with respect to pathogen, vector or pest arrivals	Common	Common
Inconducive conditions	Crop rotation, repellent cultivars, soil suppressiveness by organic amendments, temperature control and repellents in storage facilities and greenhouses	Common	Common
Synthetic chemical barrier	preventive foliar sprays with synthetic insecticides, nematicides, acaricides, anticoagulants, fumigants, fungicides or bactericides; botanical pesticides containing petroleum derivatives	Absent	Common
Spatial isolation	Crops sown distant from pest or pathogen hosts, weeds, non-crop hosts removed, barrier crops or natural strips, physically distant from all coloniser pools	Occasional	Rare
Disrupt colonisers	Mating confusion, trap cropping, sterile male releases, and low voltage 'soft electrons' for insects, fences, trapping, netting for birds and mammals, sealant, reflective tape and startling sound for birds and rodents	Occasional	Occasional
Population regulation			
Host plant resistance	Suboptimal plant quality (low fertilisation), resistant cultivars, crop spacing, plant extracts or other repellents or hormones applied to stored products	Common	Common
Genetically modified resistance	Genetically modified crops with *Bacillus thuringiensis* toxins, proteinase inhibitors, various forms of resistance against diseases	Absent	Common in some countries
Intercropping	Mixed cultivars, mixed cropping, strip cropping, green manures, incorporation of repellent plants	Common	Occasional
Competition	Enhanced herbivore and microbial diversity to reduce the proportional representation of injurious taxa	Common	Rare
Insectary vegetation or predator resources	Flowering plants in field margins, strips, islands, hedgerows, cover crops, bat and owl nesting sites, bird perches to attract and retain natural enemies in the crop field	Common	Occasional

Invasion stage/ approach	Specific practices	Organic	Conventional
Conservation	Avoid use of biocides that disrupt natural enemies and competitors	Common	Occasional
Unsuitable environment	Ventilation, humidity, and temperature control (greenhouses and storage facilities), humidity control by irrigation, irradiation	Common	Common
Curatives[A] (at population level)			
Synthetic pesticides	Various systemic and contact insecticides, molluscicides, acaricides and fungicides, pyrethroids	Absent Exceptional	Common Common
Organics	Soaps, oils, compost teas	Common	Rare
Inorganics	Sulfur dust and sprays, diatomaceous earth, micronutrients (Si or Zn), iron phosphate, CO_2, N_2, copper hydroxide, Bordeaux mixture	Common In some countries	Common
Botanicals	Plant extracts without petroleum-based synergists (pyrethrum, rotenone, nicotine, neem, horsetail)	Rare	Rare
Inundative biological control	Predators (e.g. ladybirds, predatory mites), parasitoids (e.g. egg parasitoids, larval parasitic wasps and flies), bacteria (e.g. *Bacillus thuringiensis, B. subtilis*), entomopathic and nematopathic fungi (e.g. *Entomophthora, Trichoderma, Beauveria* and *Verticillium*), viruses (e.g. arboviruses)	Occasional[B]	Occasional
Physical removal	Trapping, vacuuming, handpicking, hunting	Occasional	Rare

[A] In the plant pathology literature, only systemic fungicides with kick-back action are considered curative, but here, we include any pesticides that limit further spread of pests and diseases in the plant population. [B] Provided no petroleum-based synergists or carriers are used.

sanitation, exclusion, trapping and the use of a variety of repellents (visual, vegetation management, auditory) but exclude the use of many fumigants, anticoagulants and toxins.

Organic growers may therefore expect to encounter most of the same pests and pathogens as conventional growers in their fields. However, the dynamics of these organisms depend on the extent to which the organism's resource requirements are met and degree to which natural controls are functioning in the management system. Therefore, for many pests and pathogens, organic practices reduce the probability of establishment and spread in the crop field despite the presence of the same crop host. For other pests and pathogens, organic practices promote suitable conditions for population growth, resulting in particular challenges for growers with limited agrochemical options.

Pest and disease management in organic versus conventional agriculture

Crop protection in organic agriculture is accomplished through three general approaches, by:

1 preventing colonisation by pests and pathogens;
2 regulating the abundance of pests and pathogens at low levels through biological processes; and
3 employing curatives that are allowed under organic agriculture guidelines.

The first two approaches tend to be prophylactic control measures and the latter involves the substitution of synthetic chemical inputs used in conventional crops once pest or disease levels begin to rise. Because prophylactic crop protection in organic systems is based on ecological processes, the crop is seen as a host, the crop field and surroundings as a biotic community with its abiotic conditions, and the pest or pathogen as an invader that colonises the crop habitat, establishes and erupts. Barriers to pest outbreaks include various means of isolating the crop from pest/pathogen source pools and regulating pest and pathogen populations once established through community resistance (Table 4.1). Community resistance comprises those factors that cause the habitat to be unsuitable for proliferation of invaders, such as resource limitation, competition, and predation. Community resistance compensates for synthetic pesticides in conventional agriculture (Drinkwater *et al.* 1995, Lampkin 1999). Above-ground, community resistance involves the conservation and enhancement of beneficial fauna, either directly or via diversified vegetation. In soil, community resistance can be enhanced by activation of the soil food web through amendment with slowly decomposing organic materials. Enhancement of biodiversity is the key element in these efforts. Curative measures, taken as pest or pathogen populations begin to rise, include application of organically approved biocides or behaviour-modifying compounds derived from natural sources or inundative releases of other organisms (competitors, predators, or parasites). Curative measures may substitute for synthetic pesticides in conventional agriculture (Guthman 2000), and can complement other tactics, such as biodiversity enhancement. Successful crop protection in organic systems relies on prophylactic measures that prevent pest and pathogen colonisation, establishment or build up sometimes in combination with curative measures when needed.

Prevention of colonisation or establishment of pests and pathogens in organic agriculture

Colonisation of the crop field, orchard, vineyard, storage facility or other agricultural environment by pests and pathogens is prevented through sanitation, source isolation, and other protective measures. Practices to prevent colonisation and establishment of pests and pathogens, namely sanitation, clean seeds or vegetative propagating materials, crop rotation, adjustment of planting time, removal of certain weeds, fencing or netting against vertebrates, sealing or repelling against storage pests, hold for both organic and conventional agriculture. However, they are even more important for organic farming, because curative measures are restricted here. The use of various crop protection practices to prevent colonisation of the crop by pests and pathogens are at least as common in organic agriculture as in conventional agriculture (Table 4.1). To illustrate some of the particular problems facing organic growers, we consider seed sanitation and crop rotation.

EU regulation 2092/91 for organic farming requires that all inputs in organic agriculture, including seeds and vegetative materials, must originate from the organic production chain when available (Lammerts van Bueren *et al.* 2003). Officially registered seeds and vegetative material must be true to type, pure and healthy (in terms of percentage germination and freedom from plant pathogens and pests). It is sometimes assumed that seed produced under organic conditions would have a greater 'vitality' than conventionally produced seed, but there is no scientific evidence for this assumption. It is more likely that the germination and emergence capacity of seeds is primarily determined by the pathogens that become associated with the seeds in the seed production phase and during seed storage. In conventional seed production firms, seed samples are tested for pathogen infection, and infected seed batches are culled so that seeds can be marketed as certified disease-free, but organic seeds are (still) frequently produced in small companies that lack those facilities. Thus, organic growers may face problems with seed-borne diseases as long as inspection of organic seed is less stringent than that in conventional seed production (see *Chapter 5*).

Pathogens and pests can also be avoided by adapting the crop planting time or rotating crops that harbour different suites of pests and pathogens (temporal isolation). The time between rotations of a particular crop is usually longer in organic than conventional field crop production (5–8 years v. 2–3 years). Successive planting of the same crop is not permitted according to organic standards in the EU, but rotation times are minimised in organic greenhouse production as only high value crops with similar cultural practices can be grown such as tomato, sweet pepper and cucumber in rotation. Organic growers practicing short crop rotations in greenhouses can face severe problems with root knot nematodes in soil-bound production of these high-value crops.

Organic growers can avoid diseases and pests by planting susceptible crops at times of the year when certain pests are less pervasive. For example, to avoid severe damage from late blight, organic farmers plant early maturing potato varieties early in the growing season so that tubers have grown to a reasonable size by the time late blight becomes pervasive (Tamm *et al*. 1999). Asynchrony of dispersing insect pests and susceptible crop stages is a tactic used commonly by organic and conventional growers worldwide. For example, winter wheat production in the northern US can be timed to avoid infestation by Hessian fly (*Mayetiola destructor*), which lives as an adult for only a few days. The US Department of Agriculture provides estimates of fly-free dates for growers sowing varieties that are otherwise susceptible to the pest. Subsistence farmers in Malawi avoid devastation of their bean crop by sowing with the first rain. Later crops are attacked heavily by bean fly (e.g. *Ophiomyia spencerella*), which can kill the plant. Planting crops before peak aphid vector flights can reduce virus infection in US lettuce production. The next generation of aphids is often wingless and is less likely to move between plants. Planting dates can also be used to reduce vertebrate pest damage, such as January plantings of sunflower crops in India, planned to reduce the synchrony of sprouting plants and mature seeds with the incidence of harmful birds (house crows and rose-ringed parakeets) (Mahli 2000).

Invasion biology and metapopulation theory claim that organisms can be prevented from spreading into patchy islands when the distance between patches is large. Therefore, crop fields can be isolated from source pools by keeping large distances between fields with the same crop. In northern California, organic production of kiwi fruits is successful in part because of sparse cultivation of this specialty crop. In organic agriculture with longer rotations, the patch sizes (fields with a certain crop) are frequently smaller than in conventional agriculture. Moreover, fields are often separated by strips of natural vegetation on organic farms. Thus, crop plants can be pathogen-free and herbivore-free as a consequence of locating fields distant from coloniser pools (Letourneau 1999). However, small-scale organic farmers cannot always take advantage of this method to avoid pests and diseases, since all plots may be located very close together. For example, fields on some small-scale organic farms are organised as 'pie-pieces' in a circle, where all crops shift to the next small 'pie-piece' in the following season. Although this circular arrangement is appealing to customers who buy produce at the farm, risks of pest and disease problems are enhanced through movement of pathogens and pests from plant residues to neighbouring seedlings of the same species. Finally, the source pool itself can be removed by destroying weeds that act as carriers or alternate hosts of crop pests and pathogens. Weeds and natural vegetation surrounding cropping areas may harbour various diseases, particularly viral and bacterial diseases (Thresh 1982, Wenneker *et al*. 1999). Also, poplar trees may harbour lettuce root aphids, which move to adjacent lettuce crops (Phillips *et al*. 1999). On the other hand, non-crop vegetation can host various parasitoids and predators that contribute to insect pest control (Barbosa 1998, Pickett and Bugg 1998), and a judicious approach to weed control is needed. Many organic farmers remove weeds selectively and maintain natural surroundings carefully to avoid the spread of pests and diseases into their crops.

Storage pests are a particularly difficult problem; although storage facilities are often patchy, pests and pathogens tend to either move with the produce from the crop field to the storage facility or reside in the storage facility, making isolation difficult for many pest taxa in both organic and conventional farming operations.

Regulation of established pests and pathogens in organic agriculture

Once a pest or pathogen becomes established in a crop, field or storage facility various processes act to either enhance its abundance and spread in the system (invasion occurs) or to suppress its abundance and spread (persistence at low levels). These processes involve either host or product quality or the presence of suppressive agents in the community that regulate population growth of the pathogen or pest in the crop environment. In addition, physical impedance to spread by enhanced distances between hosts or physical barriers contributes to pest and pathogen regulation. Host plant quality can be optimised for minimal disease severity or reduced success of herbivorous insects (Scriber 1984). Indeed, crop resistance to pests and pathogens is a mainstay of organic agriculture. Resistance to pest and pathogen exploitation is brought about by selecting varieties with genetically based resistance traits, managing the phenotype, health and nutrient concentration to reduce its suitability for pests and pathogens, or managing crop and non-crop vegetation to reduce the concentration of food plants for herbivores (see *Community resistance*). Suppressive agents include competitors (neutral herbivores and microbes avirulent or less damaging to the crop) and natural enemies (predators and parasitoids of the pestiferous and pathogenic organisms). Included in this arsenal of crop defences are tactics that can be used together to protect the crop from yield loss either in the field or in the storage facility (Table 4.1). Integrative strategies are a cornerstone of successful crop protection in organic agriculture. In the following sections we explore the tactics available in organic agriculture, their effectiveness and limitations.

Host plant resistance

Host plant quality is optimised for crop protection when:

1 adequate nutrient status for plant productivity and health is maintained, without excess nutrients or imbalances that support high levels of herbivores or pathogens; and
2 toxic or repellent properties are sufficient to directly reduce pest or pathogen exploitation and survival.

The first approach is somewhat flexible, allowing for a grower to respond to pest and pathogen dynamics. However, the decision to use a resistant variety is set for the season. Its use will be determined by the probability of invasion, the severity of the pest or pathogen, any associated loss of yield quality or quantity, marketability, complementarity with other crop protection tactics, and the effectiveness of the resistant cultivar against the target and other possible exploiters. A caveat to these generalisations is that ‘one organism’s famine is another organism’s feast’, that is, very high nitrogen may attract an insect and deter a plant parasitic nematode (if ammonia is released from the nitrogen source). High mustard oil content deters insects that find it toxic, and attracts those that specialise on mustard family crops.

Depending on the target pests or pathogens, plant quality-based resistance can be induced by regulating the type and quantity of nutrients and moisture applied to the crop. For example, high N levels can enhance the population growth of certain aphids, but when potassium (K) is in ample supply, the amount of soluble N circulating in the phloem tissue is reduced, thus retarding aphid fecundity (van Emden 1966). Water shortage, in contrast, accelerates the breakdown and mobilisation of proteins and enriches the phloem nutrient quality for aphids, whereas excess moisture may predispose the crop to root-rotting pathogens. Sometimes nutrient sources used by organic growers can produce mineral balances that reduce the suitability of crop plants for pests and vectors, such as European corn borer (Phelan 1997) or the bean fly (Letourneau and Msuku 1992, Letourneau 1994). Thus, management practices can enhance or reduce host plant resistance by regulating the quality of food source for insects or pathogens (but see Letourneau 1997). Likewise, certain physiological conditions increase the incidence and severity of disease, and can be mitigated by management practices. For example, high N concentrations in soil and plant tissues may predispose a crop to diseases like powdery mildew, rust and certain root-rotting pathogens (Daamen *et al.* 1989, Tamis and van den Brink 1998). However, shortages of some elements may also enhance the susceptibility to certain diseases; for example, K shortages increase the risk of *Verticillium* wilt in cotton, and calcium (Ca) shortages enhance susceptibility to *Pythium* root rot (Engelhard 1989).

Inherently resistant cultivars have been available for many crops, providing resistance against diseases caused by fungi, bacteria, viruses and nematodes as well as certain insect pests. The mechanisms underlying the resistance range from physical features such as tough leaves, and hairy or waxy tissues to deterrent or toxic secondary plant compounds in the foliage, fruits or seeds. Some of the resistance features have a broad activity against many pests and diseases and are based on multiple genes. For example, leaf toughness forms a significant impediment to insect herbivore feeding and pathogen ingression on many crops (Bergvinson *et al.* 1994, Agrios 1997). Alkaloids such as nicotine, glucosinolates and cyanogenic glycosides, found in tobacco, cabbage and cassava respectively, are not only toxic to most herbivores but also to many plant pathogens (Rosenthal and Janzen 1979, Agrios 1997). The inhibiting agents can be present continuously (constitutive resistance) or can be induced by stress, insect feeding or infection by pathogens and symbionts.

If a single gene governs resistance to pest exploitation, a cascade of biochemical reactions is usually triggered by a particular elicitor of a pathogen or pest, resulting in strong resistance. In many cases a pathogen or pest population can adapt relatively easily to this kind of resistance through heavy selection pressure (Riggs 1959), while counter-resistance is not so easily selected against multiple, mild resistance factors. For this reason, organic growers prefer to use plant cultivars and animal breeds with broad resistance based on multiple genes (see *Chapters 5* and *6*). Although this means that a limited level of infection or feeding may occur, organic growers take this for granted, since they value a greater genetic variation and the associated yield stability. For the same reason, many organic growers prefer open-pollinated varieties over hybrids. Moreover, mild resistance based on multiple genes can still be effective, when combined with other tactics such as biological control of pests, pathogens or vectors, even when it is insufficient to control a pathogen or pest on its own (Wyss *et al.* 2001, Vaarst *et al.* 2003).

Plant resistance traits may work indirectly through their effects on natural enemies. For example, certain maize plants (*Zea mays*), when fed upon by caterpillars, release a mixture of volatile compounds that attract parasitic wasps. Varieties known to produce these induced odour emissions will likely maximise biological control by being particularly attractive to parasitoids (e.g. Degen *et al.* 2004). Varietal selection for maximum effectiveness for biological control is in its infancy, and is often targeted for the discovery of gene sequences that can be transferred to conventional cultivars. The production of varieties particularly suited to organic production systems is progressing in recent years, but the choices are limited compared to varieties for conventional conditions (Jahn 2003, see *Chapter 5*).

Community resistance – vegetation

A key characteristic of natural plant populations is their genetic and phenotypic heterogeneity. Individual plants tend to occur in natural habitats displaying a mosaic of resistance levels due to genetic variability (Whitham and Slobodchikoff 1981) and induced responses. Such heterogeneity inherently reduces the probability of counter-resistance in rapidly evolving pathogens and phytophagous arthropods, and increases the durability of plant defences over time. A mixed cropping or mixed varietal scheme reduces the concentration of suitable food plants for insects and pathogens that specialise on a subset of the plants or varieties grown in the mixture (Finckh 1997, Mundt 2002). Herbivores, particularly specialised feeders, have a lower probability of finding their host plant under these conditions, and tend to leave the field at greater rates than when suitable hosts are concentrated in monocultures. However, the searching efficiency of parasitoids may also be reduced (Bukovinszky 2004), while indirect effects through plant quality and emission of volatiles may also have a role in the effects of crop mixtures on herbivore suppression (Bukovinszky *et al.* 2004). Spread of plant pathogens is inhibited by resistant components in the mixture forming obstacles and traps. Andow's (1983, 1991) reviews of the literature on pest population densities in mixed cropping versus monoculture showed that 56% of the herbivores had lower population densities, 16% had higher population densities, and 28% had similar or variable densities in polyculture compared to monoculture. Intercropping is an integral part of many low-input, traditional cropping systems in the tropics, but is only occasionally used for products destined for the organic market, especially in temperate regions.

Community resistance – pathogens and herbivores

The degree to which competition among herbivores or among microbes ultimately reduces plant injury in natural systems is debated. In agroecosystems, where the reduction of target pest numbers is often the goal, it is conceivable that the guilds of plant exploiters could be shifted to include more neutral invaders and prevent the build up of the few most injurious species. Theoretically, organic practices that promote the richness of plant-supported microbes and herbivores in the community can cause such a 'dilution effect' of the pestiferous taxa, thus reducing crop injury levels and yield loss. However, innovative practices aimed at specific taxa have not always been successful. For example, supplemental feeding of rodents aimed at increasing the numbers of competing, non-pestiferous species in Canada did not reduce vole densities or damage (Sullivan and Sullivan 2004).

Community resistance – biological control

Organic crop production relies on the suppression of pathogens and pests through the introduction, conservation or enhancement, or augmentation of predators (or parasitoids). Natural biological controls of pests and pathogens are enhanced in organic systems that foster and maintain biodiversity through limited use of disruptive curatives coupled with vegetation management (Barbosa 1998). Plants growing within and near the crop field offer resources for natural enemies such as alternate prey or hosts, pollen or nectar, as well as microhabitats that are not available in weed-free monocultures (Letourneau and Altieri 1999) or extensive cropping operations with little non-crop vegetation. Non-crop vegetation serves to increase faunal biodiversity, which increases the potential for ecosystem services to growers. Because organic growers tend to rely more on ecosystem services for crop health than do growers employing chemical input intensive schemes, vegetation management and farmscaping have become key crop protection tools in some areas. The challenge is to encourage natural enemies without overly favouring pest organisms. Detailed knowledge of animal behaviour, resource use and movement patterns with respect to non-crop vegetation can aid in vegetation management schemes for biological control and biodiversity conservation. For example, studies of bird communities in riparian strips in Quebec suggested that woody vegetation increased richness of some insectivorous birds, but did not increase pestiferous red-winged blackbird densities in adjacent crop fields (Deschenes *et al.* 2003). Microbial communities in organically managed soils are often highly diverse compared to simpler systems managed with low vegetational diversity and synthetic chemical inputs. Consequently, plant pathogens are frequently suppressed in organic farming systems by enhanced microbial complexity and activity, brought about by regular soil amendment with recalcitrant organic materials like mature composts and manure (Mäder *et al*. 2002, van Bruggen and Termorshuizen 2003, Litterick *et al*. 2004).

Curative control

There are limited options for curative control allowed under organic agriculture guidelines, which vary from country to country. Curatives are inputs to the crop production system that are applied after a pest or pathogen has established in the crop, and threatens to reduce yields if action is not taken. Table 4.1 provides a representative list of botanically derived pesticides, microbial agents and other naturally available materials typically approved under organic standards. These materials vary in their toxicity levels and non-target effects.

In many countries, copper fungicides are allowed for persistent problems such as the control of late blight on potatoes and downy mildew on grapes. Similarly, sulfur fungicides are used to control powdery mildew on various crops and scab (*Venturia inaequalis*) on apples and pears. The number of sulfur sprays may even exceed that of synthetic fungicides in conventional apple production, but the environmental impact may still be lower (Spruijt-Verkerke *et al*. 2004). The environmental impact of copper can be significant, considering the broad impact spectrum and the tendency to accumulate in soil. Finally, some synthetically produced curatives, such as pyrethroids, are allowed for certain uses as an exception to the rule. However, the organic regulations are adjusted constantly, and curative applications are becoming more restricted. For example, copper fungicides are already banned in many countries.

Various plant extracts are allowed under most organic guidelines, provided that they are not formulated in petroleum-based synergists or carriers. However, they are only rarely used, primarily as insecticides (Table 4.1). Compost extracts are used more frequently, and are commercially formulated these days (Litterick *et al*. 2004). They can be very effective in disease control, depending on the starting material, the composting and fermentation procedures, and the final microbial activity.

Curative biological control can be accomplished by inundative release of selected biocontrol agents. Although many specific biological control agents against plant pathogens, insect and nematode pests have been identified, relatively few species have been registered for field use, primarily parasitoids and predators for insect and mite control, and some fungi and bacteria for insect and pathogen control. Biocontrol of soilborne pathogens has been successful under controlled environmental conditions using simplified potting mixes, but has often failed when selected microorganisms were added to field soil (Fravel 1999). This is also the case, even more so, for foliar microbial biocontrol agents due to the increased exposure to the elements. We recently noticed that the bacterial biocontrol agent *Pseudomonas fluorescens* did not survive as well in organically as in conventionally managed soil (Hiddink *et al*. 2005). It may be more difficult to get a biocontrol agent established in a microbially diverse organic soil than in a microbially impoverished conventional soil, as could be expected from invasion biology theory.

One might expect that organic growers would use biological control proportionally more than conventional growers, but surveys indicate that biological control agents are rarely applied on organic farms (Langer 1995), with the exception of *Bacillus thuringiensis* (Bt) for caterpillar control and various parasitoids and predators in greenhouse production. In most countries, organic regulations allow the application of biological control agents, provided that no petroleum-based synergists or carriers are used in the formulation. It is possible that the greater biodiversity in organic agroecosystems (in the open air) reduces the effectiveness of inundative biological control agents through intraguild predation or competition.

Pest and disease management case studies in organic versus conventional agriculture

Relatively few replicated, on-farm studies compare the relative effectiveness of organic and conventional crop protection practices. This is particularly true for vertebrate pests. Table 4.2 lists recent examples of field comparisons between organic and conventional agriculture in different crops and location. These studies show that biodiversity is generally higher on organic farms, that pests and pathogens are usually regulated by organic practices, but that there are exceptions in either case. Few studies monitor pest levels and related yield losses. Even fewer studies are integrative for crop protection, monitoring both pests and pathogens. We provide two detailed, integrative case studies selected from European agriculture and commercial operations in the western USA to illustrate some constraints and benefits of organic agriculture practices. These examples and those listed in Table 4.2 illustrate many of the general themes described above, including:

1 holistic approaches that characterise organic agriculture;
2 the kinds of pests and pathogens affected by different management practices;
3 the possibility of different, but equally successful, routes to crop protection; and
4 the importance of diversity in promoting ecosystem services for organic agriculture.

Table 4.2 Recent on-farm and field-experiment comparisons of pest or disease levels under organic or ecological versus conventional management

Crop	Management practices in organic crops	Crop protection consequences as compared to conventional	Reference
Almond	A mixed cover crop, no fertilisers or pesticides	Shot hole disease more severe, almond scab on leaves and fruits similar; no differences in fungal communities	Teviotdale and Hendricks (1994)
Apple	Organic soil amendments that promote soil microbial diversity	Higher growth scores and lower colonisation by root pathogens (*Pythium* sp., *Rhizoctonia solani*)	Manici *et al.* (2003)
	Organic soil amendments that promote soil microbial diversity	Less *Pythium* root rot, more non-pathogenic *Pythium* spp.	Mazzola *et al.* (2002)
	Sulfur sprays	More severe apple scab (*Venturia inaequalis*), similar orange tortrix (*Argyrotaenia citrana)*	Vossen *et al.* (1994)
	Weed-, disease-, nutrient management	Lower abundances of predaceous beetles, lower diversity of non-predaceous beetles	Pearsall and Walde (1995)
Carrot	Biological pest control, soil management	Higher diversity of predaceous arthropods	Berry *et al.* (1996)
Cereals (wheat, barley, triticale, rye)	Organic practices (lower fertility, no pesticides)	No difference in epigeic collembolan composition	Alvarez *et al.* (2001)
		No difference in species richness of butterflies, rove beetles, spiders, lower richness of carabids	Weibull *et al.* (2003)

Crop	Management practices in organic crops	Crop protection consequences as compared to conventional	Reference
Cereals (wheat, barley, triticale, rye)	Organic practices (lower fertility, no pesticides)	Lower densities of aphids, higher densities of weevils, leaf beetles, spiders, plant hoppers, plant bugs and sawfly larvae	Moreby and Sotherton (1997)
		Lower infection with ear blight (*Fusarium* spp.) and lower mycotoxin contamination	Birzele *et al.* (2002)
	Organic practices (lower fertility, no pesticides)	Reduced incidence and severity of foot rots and root rots, eyespot, and take-all; similar or less powdery mildew (*E. graminis*); similar, less or more leaf spot and glume blotch (*S. nodorum*); similar or more leaf rust (*Puccinia* spp.); less stripe rust (*P. striiformis*); less leaf blotch (*M. graminicola*)	Various authors cited in van Bruggen and Termorshuizen (2003) (root diseases) and in van Bruggen (1995) (root and shoot diseases)
	Organic with red clover as pre-crop	Higher numbers of total predators	Basedow (1991)
	Organic experimental fields, sulfur applications	More severe *Septoria* leaf blight at end of season; more severe powdery mildew at beginning of season	Higginbotham (1996)
Grape	Organic management; cover crops	No difference in *Phylloxera*, but reduced severity of secondary fungal root infections	Lotter *et al.* (1999)
Maize	Organic management, winter cover crops, composted chicken manure	Aphids, mites and corn ear worm fluctuated from year to year, but were similar in organic and conventional field plots; more seed corn maggot in 1 of 8 years	Clark *et al.* (1998)
Olive	No synthetic pesticides	Low mortality and higher fecundity of lacewing adults	Corrales and Campos (2004)
Pepper	Organic management, compost, cover crop	Corn borer (*Ostrinia nubilalis*) larval populations similar, beneficial insect populations greater in 1 year; fruit damage by insects or diseases less or similar	Delate *et al.* (2003)
Potato	Absence of fungicides or only copper fungicides	Much more severe late blight (*Phytophthora infestans*)	Piorr and Hindorf (1986), Zwankhuizen *et al.* (1998)
Rice	Ecological agriculture practices	Similar or higher arthropod abundance, with no decrease in yield	Hossain *et al.* (2002)
	Organic practices	Similar abundance of major pests, damage and species richness of arthropods	Hesler *et al.* (1993)
Straw-berry	Organic, no insecticides	Higher tarnished plant bug density and damage	Rhainds *et al.* (2002)
	Mulch, no fumigation	*Cylindrocarpon* root rot greater in organic	Rosado-May *et al.* (1994)

Crop	Management practices in organic crops	Crop protection consequences as compared to conventional	Reference
Strawberry	Straw mulch, no fumigation or fungicides, low fertility	Less fruit rot by *Botrytis cinerea*, variable grey mould severity depending on cultural practices	Gliessman *et al.* (1996), Daugaard (1999)
Tea	No synthetic pesticides	Greater abundance and diversity of carabid beetles	Mukhopadhyay *et al.* (2003)
Tomato	Biological insecticides and living mulch	Higher level of thrips and caterpillar damage.	Hummel *et al.* (2002)
	Cover crops, composted manure, insecticidal soap, Bt	Same levels of potato aphids, army worm and tomato fruit worm, wild fluctuations; more stinkbug injury in 1 of 8 years	Clark *et al.* (1998)
		Lower severity of corky root, *Fusarium* and *Pythium* root rot, *Phytophthora* root rot	Clark *et al.* (1998), Workneh *et al.* (1993)
		Reduced Southern blight	Bulluck and Ristaino (2002)
	Organic, cannery waste compost	Reduced anthracnose (*Colletotrichum coccodes*) on fruits	Abbasi *et al.* (2002)
Various crops	Alternative soil amendments	Higher *Trichoderma* and lower *Phytophthora* and *Pythium* propagule densities	Bulluck *et al.* (2002)
	Organic practices, habitat diversification	Higher species richness, abundance and activity of nocturnal insects insectivorous bats	Wickramasinghe *et al.* (2003)
	Organic management: cover crops, composted chicken manure	Reduced populations of *Pratylenchus* spp., *Rhizoctonia solani* and *Verticillium dahliae* in soil	Clark *et al.* (1998), Berkelmans *et al.* (2003), Neher and Olson (1999), van Bruggen and Termorshuizen (2003)
	Biodynamic mixed farm with 6 years grass-clover in a 10 year rotation	Carabid abundance and species richness generally higher (except in potato) Staphylinid and spider abundance and species richness generally similar	Booij and Noorlander (1992)
	Organic practices	Greater abundance and lower diversity of predaceous beetles	Shah *et al.* (2003)

Case study 1 – pest and pathogen regulation in organic versus conventional cereal crops in Europe

Since the 1980s, the proportion of cereal crops (wheat, barley, oats, rye) has steadily dropped in conventional agriculture in north-western Europe (except for France). The main reason is a reduction in price supports, resulting in such low prices that it is not profitable to grow cereals as intensively as was commonly done in this region (with straw shorteners, high fertilisation, and frequent fungicide and insecticide applications). On organic farms, cereal crops are still profitable as they are grown less intensively. Moreover, they are essential crops in the longer rotation schemes. Some of these crops (oats, rye, triticale) are also used as winter cover crops to reduce nitrate leaching. Because of the large differences in production practices for cereal crops at organic versus conventional farms in Europe, many comparative studies of farming systems have focused on these crops. Most comparisons have involved single (experimental) farms side by side (Rabbinge and Zadoks 1989). In a few cases, replicated experimental treatments were compared (Hannukala and Tapio 1990), and even fewer publications covered large surveys on many farms (Tamis and van den Brink 1998 1999).

From all these studies it is apparent that fungal root and foot rots caused by *Fusarium* species are similar or reduced in organic cereal crops. The same holds for take-all disease caused by *Gaeumannomyces graminis* and for eyespot and sharp eyespot caused by *Pseudocercosporella herpotrichoides* and *Rhizoctonia cerealis*, respectively (van Bruggen 1995). In some studies, the lower disease levels at organic farms were associated with lower N application rates (van Bruggen and Termorshuizen 2003), higher microbial activity and diversity (Hiddink *et al.* 2005), or greater populations and/or diversity of soil microfauna (Mäder *et al.* 2002, van Bruggen 1995). Another reason for suppression of root diseases in organic cereal crops could be enhanced competition by arbuscular mycorrhizae, which are generally more abundant in organic than in conventional crops, due to the lower available N and P in organically managed soils (Oehl *et al.* 2004).

The lower N application levels in organic cropping systems also have a tremendous influence on above-ground diseases and pests. Powdery mildew, snow mould and stripe rust of wheat were less severe in a long-term organic than in a neighbouring conventional experimental farm in the Netherlands, despite regular fungicide applications in the conventional system (Daamen *et al.* 1989). This was attributed to lower N levels in the organic wheat tissue, but could also be due to a more open canopy structure and less conducive microclimate. In an extensive survey of 150 Dutch wheat fields, most above-ground diseases (snow mould, powdery mildew, *Septoria* leaf and glume blotch, *Fusarium* scab) were less severe in the organic than in the conventional and integrated farming systems (Tamis and van den Brink 1998). The differences were significant for snow mould, glume blotch, and *Fusarium* scab. Contrary to the two-farm study mentioned above (Daamen *et al.* 1989), there was no significant difference for stripe rust, while leaf rust and powdery mildew on the ear were significantly more severe in organic than in conventional farms (Tamis and van den Brink 1998). Incidences of diseases that were higher in conventional farms than in organic farms were again positively correlated with N application rates (Tamis and van den Brink 1998). The higher severity of leaf rust and powdery mildew on the ears of organic than on those of conventional wheat plants may also have been related to N concentrations, since N is released from soil organic matter in the summer time, and can be higher in organic than in conventional farms at that time.

Plants high in N can also support large aphid populations (van Emden 1966, Thresh 1982) and are often more susceptible to virus infection. Thus, when high soil nitrate concentrations coincide with aphid flights, the population may grow explosively. Unfortunately, organic farmers have little control over the time when N is released in soil, and in some seasons aphid populations may be as high in organic as in conventional farming systems (Daamen *et al.* 1989, Piorr and Hindorf 1986). Leaf miners and cereal leaf beetles were generally more numerous in the conventional farming system and were associated with high N application rates (Daamen *et al.* 1989). In an extensive field survey, no significant differences were found in populations of aphids, leaf miners and cereal leaf beetles between organic and conventional farms, but there were enormous variations among years (Tamis and van den Brink 1998). Nevertheless, it is important to try to keep mineral N concentrations minimal, also at organic farms. This can be done by focusing on organic matter build up over many years, and minimising applications of additional organic fertilisers during crop growth.

The absence of fungicide use in organic cereal production has given rise to concerns about grain moulds and mycotoxins on organic cereals. These concerns are not always justified. *Fusarium* scab of wheat was less severe in organic than in conventional farms in the Netherlands (Tamis and van den Brink 1998). In several German studies, *Fusarium* contamination of grains and concentrations of deoxynivalenol (DON) were also lower in organic than in conventional farms (Birzele *et al.* 2002, Schollenberger 2002), while in some French studies *Fusarium* head blight severity and mycotoxin levels were similar in organic and conventional wheat production (Champeil *et al.* 2004). DON concentrations were also similar in organic and conventional grains in a British study (Berlath *et al.* 1998), but were below the European threshold level. Average levels of ochratoxin A contamination (from *Penicillium* and *Aspergillus*) were similar in rye and barley grains from organic and conventional farms, but significantly lower in organic than in conventional wheat grains (Czerwiecki *et al.* 2002). Thus, there is no reason to believe that mycotoxins would constitute a problem in organic cereal products (Schollenberger *et al.* 1999). The main reason for lower contamination levels at some organic farms may be the lower N contents and greater diversity of non-pathogenic fungi on the ears of unsprayed plants (Lemmens *et al.* 2004). Moreover, mycotoxin production per unit mycelium can be enhanced by the stress of certain fungicides (Felix D'Mello *et al.* 1998).

Insect pests can often be kept in check by a greater diversity of non-herbivorous arthropods. Piorr and Hindorf (1986) noticed an increase in beneficial insects during the conversion period on a biodynamic farm. Reddersen (1997) also observed a higher diversity of arthropods in organic cereal fields, accompanied by a lower arthropod abundance compared to conventional cereal fields. In many other studies, a relatively high arthropod abundance in organic compared to conventional wheat fields was associated with a higher arthropod diversity in organic wheat fields (Moreby *et al.* 1994, Basedow 1995, Pfiffner and Niggli 1996). Feber *et al.* (1997) measured similar levels of pest butterflies in organic versus conventional farmland, but found significantly more non-pest butterflies in organic farmland. Total numbers of epigeic predatory arthropods were also highest in organic farming systems compared to pesticide intensive agricultural production systems (Basedow 1991). Among epigeic predators, carabid abundance and species richness were higher in organic cereal fields, while staphylinid and spider abundance and species richness were generally similar in different management systems (Booij and Noorlander 1992). The reasons for the frequently greater arthropod diversity in organic farms can be found in the greater variety of food sources associated with greater plant diversity within fields and in surrounding habitats (Booij and Noorlander 1992, Holland and Fahrig 2000, Asteraki *et al.* 2004).

Greater plant diversity in the field can also have benefits for disease control in cereal crops. Different cereal crops, for example barley and wheat, have sometimes been grown in mixtures resulting in a reduction in barley powdery mildew by increasing the distance between susceptible plants (Burdon and Whitbread 1979). However, mixtures of wheat and field beans resulted in higher powdery mildew severity on the wheat crop as the bean density increased (Bulson *et al.* 1997); this was probably as a result of the greater N content of the wheat plants. Cultivar mixtures with different resistance genes have also been very effective in controlling different barley powdery mildew pathotypes (Finckh *et al.* 2000). The use of cultivar mixtures was a very effective and widespread practice in the former Eastern Germany (Finckh *et al.* 2000) and is now practiced on a large scale in rice production in China. Unfortunately, organic growers have not yet widely adopted this practice. Another form of mixed cropping, relay cropping of clover between cereal plant rows, is gaining popularity in Europe. This practice helps control weeds, supplies N to the next crop, and contributes to disease control, particularly of take-all caused by *Gaeumannomyces graminis* (G.A. Hiddink, A.J. Termorshuizen, J.M. Raaijmakers and A.H.C. van Bruggen, unpublished data).

Thus, organic practices that promote biodiversity both above ground and below ground tend to enhance the resilience of the arable farming system so that many pests and diseases are controlled by natural enemies. These practices include an extensive rotation, soil organic matter management fostering high turnover rates and relatively low residual mineral nutrients with minimal fluctuations, crop or cultivar mixtures, and varied field margins. Although this is a desirable scenario for cereal production, it is not always practiced, and the great variation in organic farming practices understandably results in large variations in pest and disease intensities.

Case study 2 – pest and pathogen regulation in organic versus conventional tomato fields in California

Tomato is a relatively high input crop in Californian agriculture. Of the top 15 vegetable crops, 11 field crops, and 11 fruit or nut crops produced in the USA, Pimentel *et al.* (1981) listed tomato as having the highest percentage of acreage treated with insecticides (93%) and fungicides (98%) and the ninth highest for acreage treated with herbicides (67%). A 36% yield reduction was predicted if pesticides (insecticides, fungicides) were not applied to the tomato crop (Agricultural Issues Center 1988). To check this premise, pests, diseases and their natural enemies were monitored in two complementary comparative studies in California. Van Bruggen participated in the Sustainable Agriculture Farming Systems (SAFS) experiment in Davis, California, where irrigated conventional, low-input and organic cropping systems with 4-year rotations were compared with a 2-year conventional rotation from 1989 through 2001 (Poudel *et al.* 2001). All crops in the rotation were represented each year, and there were four replicated blocks for a total of 56 plots on 11 ha. Tomatoes were the most intensively investigated crop species in this experiment with respect to disease incidence and severity, insect pests, weed infestations and N dynamics. Letourneau and van Bruggen carried out a two-year survey of 18 organic (ORG) and conventional (CNV) commercial tomato production systems to compare:

1 the incidence of pests and pathogens;
2 injury levels and pest damage to the crop;
3 pest abundance and disease severity;
4 biodiversity of the microbial and arthropod communities associated with the crop; and
5 nutritional status of the crop.

The survey was carried out on nine ORG and nine CNV tomato fields in a 600 km^2 area, encompassing five counties in the Central Valley of California. This sample covered a representative spectrum of actual commercial farming practices, and the variability needed to identify particular practices that affect pest management. All 18 farms used the same tomato cultivar Blazer® (Drinkwater *et al.* 1995). Farms in both ORG and CNV management categories included sites bordered by various combinations of annual crop fields, orchards, oak woodland and riparian habitats. All fields were maintained reasonably weed-free within the beds during the growing season, but annual weeds were abundant along roadsides and field edges, especially where sufficient moisture was available. The cropping history of the fields, however, was not independent of management category. Most conventional farms were maintained as bare ground fallows over winter through initial tillage and subsequent herbicide applications, whereas organically managed fields had a vegetative cover with annual weeds and/or cover crops (see Workneh *et al.* 1993, Drinkwater *et al.* 1995, Letourneau *et al.* 1996, and Letourneau and Goldstein 2001 for details of sites, design and sampling methods).

Root disease incidence and microbial community structure

In both the experimental study and the field surveys, foliar diseases were not important on irrigated tomatoes (mostly by furrow irrigation) in the semi-arid climate of California. Only occasionally, diseases such as bacterial spot (*Xanthomonas campestris*) occurred when it rained early in the season (Clark *et al.* 1998). Virus symptoms were also seldom observed. There were no differences in foliar disease incidence and severity between organic and conventional farming systems. Root diseases were quite common and sometimes severe in conventional tomato fields, but were absent or only slight in low-input and organic fields.

In the SAFS experiment, corky root (*Pyrenochaeta lycopersici*) was significantly more severe in the conventional system with a 2-year rotation and only slightly more severe in the conventional system with a 4-year rotation compared to the low-input and organic systems (Clark *et al.* 1998, van Bruggen and Termorshuizen 2003). The same was true for root rot caused by *Pythium aphanidermatum*. Differences in severity of other root rots were mostly not significant. These observations were made six, seven, eight and nine years after the start of the experiment. In the last two years, there were significant differences between both conventional treatments and the alternative treatments. Both alternative systems had winter cover crops, and much better water penetration than the conventional systems, which developed a hardpan over time. The organic plots had lower nitrate concentrations in soil and plant tissues and a higher microbial biomass and associated food web (particularly bacteria-feeding nematodes) than the conventional plots (Ferris *et al.* 1996). There were positive correlations between corky root severity and N concentrations in soil and plant tissues (A.H.C. van Bruggen, unpublished data, 1998).

In the field survey of tomato-producing farms in California both the incidence and severity of corky root were lower in well-established and recently converted organic farms (ORG) than in conventional farms (CNV). The main variables explaining corky root incidence and severity levels were N concentrations in both soil and tomato tissue (Workneh *et al.* 1993). Corky root was more numerous and severe at higher N concentrations. However, N mineralisation potential and fluorescein diacetate (FDA) hydrolysis, both measures of microbial activity, were negatively correlated with disease severity. These relationships were confirmed in greenhouse experiments (Workneh and van Bruggen 1994a). In other greenhouse and laboratory experiments, corky root suppression in ORG soils was associated with larger populations and higher diversity of actinomycetes in the rhizosphere (,Workneh and van Bruggen 1994b, Drinkwater *et al.* 1995). The community composition of actinomycetes and bacteria were more similar among samples with the same soil management (CNV or ORG) than between different management types (CNV v. ORG). Phytophthora root rot (*Phytophthora parasitica*) was also more severe in CNV than ORG fields, but this difference was primarily associated with soil texture, structure and moisture content instead of microbial and nutritional factors (Workneh *et al.* 1993).

Plant-parasitic nematode populations, in particular *Pratylenchus* spp., were significantly lower in the organic and low-input systems than in the conventional systems of the SAFS experiment as early as 1993, four years after initiation of the experiment. This difference was maintained until the end of the experiment in 2000 (Ferris *et al.* 1996, Clark *et al.* 1998, Berkelmans *et al.* 2003). Populations of *Meloidogyne* spp. were not consistently lower in the alternative systems than in the conventional systems (Clark *et al.* 1998, Berkelmans *et al.* 2003). Root knot symptoms on tomatoes were rare and differences were not consistent among treatments (Clark *et al.* 1998). Bacterivorous nematodes were generally more abundant in the organic and low-input than in the conventional treatments (Ferris *et al.* 1996). Accordingly, the enrichment index, a measure of resource availability, was higher, and the channel index, a measure of domination of the fungi-based over the bacteria-based food web, was lower in the organic and low-input than in the conventional treatments (Berkelmans *et al.* 2003). Moreover, the structure index, a measure of the number of trophic layers and potential for regulation of opportunists, was generally higher in the organic and low-input than in the conventional systems (Berkelmans *et al.* 2003). Suppression of *Meloidogyne javanica* in a bioassay was negatively correlated with the channel index, indicating that suppression was associated with a bacteria-dominated food web as observed in the organic and low-input plots of the SAFS experiment (Berkelmans *et al.* 2003). A positive correlation between suppression of *M. javanica* and microbial biomass had been described earlier (Jaffee *et al.* 1998). At that time, no relationship was found between *M. javanica* suppression and management system, nor with total number of nematode trapping fungi, yet the diversity of nematode trapping fungi was greater in the organic plots (Jaffee *et al.* 1998).

Thus, the general tendency was that root infections by fungal pathogens and populations of plant parasitic nematodes were lower in organic than in conventional soils, and this was associated with either higher microbial diversity and activity, and/or a better soil structure, and/or a more complex soil food web in the organic soils. These characteristics are typical for a healthy soil that can resist disturbances by invading species (van Bruggen and Semenov 2000). Such a healthy soil is attained by organic practices such as winter cover cropping, applications of compost, and avoidance of synthetic pesticides and fertilisers.

Pest incidence, tomato injury and arthropod community structure

In the SAFS experiment, arthropod pests were monitored every two weeks by taking plant and fruit samples. Pest populations fluctuated significantly from year to year. Russet mites were occasionally problematic, and were treated with sulfur in all fields in the first few years (Clark *et al.* 1998). Potato aphids, armyworm and tomato fruit worms were severe enough to warrant insecticide sprays in the conventional treatments. Insecticidal soap and Bt were occasionally applied in the organic treatment. These were less effective than synthetic insecticides, so that aphid and armyworm populations were sometimes higher in organic plots, but in general, insect pests did not differ significantly among management treatments. The lack of significant differences among treatments was attributed to the relatively small plot size (0.11 ha per plot), necessitating an extensive on-farm field survey (Clark *et al.* 1998).

In the field surveys, arthropods were vacuum extracted from tomato foliage. The major tomato pests, such as thrips, aphids, tomato russet mite, flea beetles, leaf-eating caterpillars, leafminers, fruit-eating caterpillars and fruit-piercing insects were present in all fields. Average damage levels accruing over the season were significantly correlated with the mean abundance of the most common species of that pest group collected in vacuum samples. That is, western flower thrips *Frankliniella occidentalis* abundance was directly correlated to percent tomato leaflets damaged by thrips; flea beetle (*Epitrix hirtipennis*) abundance was positively correlated with percentage tomato leaflets damaged by pit-feeders; and tomato fruitworm (*Helicoverpa zea*) abundance and percentage of fruits with deep wounds typical of fruitworm damage were also significantly correlated.

Damage from insect pests was variable among fields and among pest groups (e.g. leaf grazers, foliage pit-feeders, fruit punctures), but the average levels of overall and specific types of damage in organic and conventional fields were not significantly different (Drinkwater *et al.* 1995, Letourneau and Goldstein 2001). The average abundance of phytophagous insects was virtually the same on organic and conventional tomato at the time of crop harvest. Although crop N levels were significantly lower in organic fields, neither pest levels nor damage was explained by tissue N levels (Letourneau *et al.* 1996).

However, community-level profiles (richness and abundance of herbivores and natural enemies) in commercial tomato fields under organic and conventional management were significantly different despite the wide range of specific farming practices and conditions represented within these management categories (Letourneau and Goldstein 2001). Organic farms had a more diverse arthropod fauna than conventional farms, with the average for five 30-s vacuum samples per farm yielding about 40 arthropod morphospecies in conventional tomato and 66 morphospecies in organically managed tomato. Natural enemies (parasitoids plus predators) were almost twice as abundant on organic compared to conventional farms.

Conventional tomato fields received seven times as many insecticide sprays as organic fields (Letourneau and Goldstein 2001), and the application frequency, spectrum of toxicity and persistence of pesticides was inversely associated with some of the prominent natural enemies. Fields managed with cover crops or annual weeds over the winter wet season had at least a magnitude higher abundance of these parasitoids and flea beetles than did fields that were kept in bare fallow (no vegetation). Vegetative fallow practices, which maintained vegetative cover during the wet season, may have perennialised the crop habitat to allow continuity of certain arthropod populations through the year. Natural enemies are often enhanced in perennial crop habitats and in vegetative fallow compared to annual crops disrupted by bare fallow (Honek 1997). However, insecticide treatments could disrupt the potential stability gained by local vegetational cover. In general, practices used more often on organic farms, such as cover cropping and low intensity pesticide treatments, were associated with increases in parasitic wasps (primary source of variability among farms) and more predators.

Clearly, the avoidance of synthetic insecticides and fungicides in organic tomato production did not reduce yields by the predicted 36% (Agricultural Issues Center 1988). Indeed, in both the SAFS experiment and the field surveys, there were no significant differences in pest damage between CNV and ORG treatments. Arthropod communities were not monitored in the SAFS experiment, but substantially different arthropod community profiles in ORG v. CNV farmers' fields (species diversity of herbivores and abundance and species diversity of natural enemies) suggested that natural biological control on ORG farms may be compensating for pesticide inputs in CNV operations. Whereas specific management practices and landscape characteristics of ORG and CNV farms were associated with abundance patterns of specific pests and natural enemies, these management schemes were generally robust to variable pest control challenges on individual farms.

Conclusions

For any given combination of crop, location, labour and capital availability conditions there are potentially several optimum crop protection strategies. Different crop production or protection strategies include schedule-based prevention, integrated pest management, organic, traditional, biodynamic, biological or ecological practices. Alternative strategies may rely on fundamentally different conceptual approaches, yet also function as viable suites of best management practices for crop production. Andow and Hidaka (1989) demonstrated the idea of such 'syndromes of production' using Shizen and conventional rice farming management schemes, and show that qualitatively different sets of integrated practices can produce favourable outcomes in terms of yields and profit. We suggest here that for most conventional crop production systems in most locales, viable alternatives, including organic agricultural schemes, either already are in practice or are possible. To support and develop alternative crop protection schemes that are economically, socially and environmentally sustainable, alternative lines of research, price supports, agricultural policies, and land-use practices may need to be embraced. To optimise crop protection in organic agriculture, research should be geared to defining and accessing suites of crop production materials and practices that work in concert as a favourable production syndrome (*sensu* Andow and Hidaka 1989). We suggest four key research areas for crop protection improvement in organic agriculture.

Future research directions

Knowledge banks from natural systems studies and comparisons with agroecosystems

The application of ecological principles to pest regulation in agroecosystems is extremely important for advancing crop protection through ecosystem services. However, the staggering amount of diversity in habitats and life histories among pests and pathogens defies any strict adherence to generalities. Therefore, technological advances in data management and expert systems can now be used to synthesise detailed results from relevant ecological studies as a basis for making specific decisions in pest management. Further, the degree to which results from ecological studies in natural systems can be transferred to understanding plant–arthropod, disease–host, and predator–prey interactions in agroecosystems is, for the most part, speculative. Future comparative studies between natural and managed habitats are needed to test common assumptions (Barbosa 1998) and create a realistic set of goals and practices for organic growers.

Development of cultivars suited to organic farming conditions and needs

Breeding for resistant cultivars under organic management conditions should be a high priority. Herbivores that exploit cultivated varieties often encounter resources that differ in fundamental ways from the plants' wild relatives. Attributes that have arisen out of a selection process for enhanced productivity and palatability under conventional conditions tend to increase the crop's suitability as a host for phytophagous arthropods and pathogens. First, compared to their progenitors, crop plants can contain lower levels and simplified suites of antiherbivore defences (Kennedy and Barbour 1992), can possess a more uniform genetic composition, and may experience lower levels of plant stress. Second, the presentation of these plants to herbivores and pathogens differs from the conditions found in most of the communities of their wild relatives in its tendency for uniformity in species composition, age distribution of the population, and structural pattern. Each of these factors contributes to the need for research into optimised plant resistance in different management contexts and cropping systems.

Optimisation of production of healthy seed and vegetative propagating materials

Organic crop production can be very successful provided that healthy seed and vegetative propagating materials are used, since the options for intervention are limited once the crop is in the field. The best option would be to produce seeds and vegetative materials in pest and disease-free areas (i.e. in isolated regions with arid climates). However, organic agriculture may not be well established in such regions, and facilities for tissue culture and seed health testing may not be available, for example in northern Africa. A combination of biological, social and economic research would be needed to optimise the production in such regions in close collaboration with local farmers. Additional research would be desirable to develop and test plant extracts and microbial communities for biological control of seedling diseases, and to formulate these products so that they can be approved by organic certification agencies.

Assessment of the role of landscape factors for colonisation of pests, pathogens and natural enemies

Vegetation at the field margin or in surrounding areas serves as coloniser sources for mobile pests, vectors, and pathogens. The degree to which organic crop fields are colonised, exploited and damaged may depend upon the quality of these source pools. Vegetation management may reduce pest and pathogen levels directly or may serve to stabilise and enhance predators and parasitoids for biological control of crop pests. Rigorous analyses of landscape-scale phenomena, though recognised as critical for decades (e.g. a 'wide-area view' *sensu* Rabb 1978), are only recently becoming feasible with new geographical information systems capabilities (e.g. Marino and Landis 1996, Letourneau and Goldstein 2001, Thies *et al*. 2003) and metapopulation dynamics models.

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