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Plant Diseases and Management Approaches in Organic Farming Systems

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Abstract

Organic agriculture has expanded worldwide. Numerous papers were published in the past 20 years comparing plant diseases in organic and conventional crops. Root diseases are generally less severe owing to greater soil health, whereas some foliar diseases can be problematic in organic agriculture. The soil microbial community and nitrogen availability play an important role in disease development and yield. Recently, the focus has shifted to optimizing organic crop production by improving plant nutrition, weed control, and plant health. Crop-loss assessment relating productivity to all yield-forming and -reducing factors would benefit organic production and sustainability evaluation.

INTRODUCTION

Organic agriculture (OA) has increased in importance worldwide over the past 20 years, with growth rates of more than 10% per year in many countries. By 2014, approximately 2 million certified organic producers farmed more than 43 million hectares of certified organic agricultural land (142).

Organic crop production is partially characterized by the absence of synthetic pesticides and fertilizers, but practices that promote ecosystem health are even more important (33, ch. 1, 2.1). The effects of fundamentally different management practices of organic and conventional crop production on agroecosystem functioning and the occurrence of diseases and pests have been reviewed (70, 126, 135); however, many additional publications on diseases in OA have appeared since then, and a comprehensive book on plant diseases and their management in OA was recently published (33). Therefore, for most publications prior to 2000, the reader is referred to earlier reviews (33, 70, 126, 135).

The aim of this review is to present differences in disease incidence and severity in relation to differences in management practices and to provide options for improved plant disease control in organic farming systems (OFSs). We first give a brief description of OFSs. Next, we give an overview of the differences between soilborne and airborne plant diseases (fungal, bacterial, viral, and nematodal) in organic and conventional farming systems (CFSs), and discuss possible reasons for these differences. The practices used by organic farmers to manage diseases have been recently described in detail (129); we focus on the important principles behind disease management in the second part of this review. We conclude with some suggestions for research on crop loss and disease management in OFSs.

ORGANIC FARMING PRACTICES

Organic agricultural practices are guided by standards as formulated by the International Federation of Organic Agricultural Movements (IFOAM) and regulated by (inter)national certification agencies (30, 124). Several objectives outlined in the IFOAM standards affect plant diseases and their management, in particular: (*a*) to work with natural systems rather than seeking to dominate them; (*b*) to encourage and enhance biological cycles within the farming system; (*c*) to work as much as possible in a closed system with regards to organic matter and nutrients; (*d*) to avoid all forms of pollution from agriculture; (*e*) to maintain the genetic diversity of the agricultural system and its wild surroundings; and (*f*) to consider the wider social and ecological impact of the farming system (**http://www.ifoam.org/about_ifoam/standards/index.html**). OA is governed by the idea that all processes within an agroecosystem are interdependent. It aims at achieving and supporting self-regulation through natural processes by utilizing the ecological possibilities of the farming system. The emphasis is on prevention of problems, including plant diseases (33, ch. 1, 2.1).

Compared to intensive CFSs, OFSs generally have (*a*) higher plant diversity in time and space; (*b*) higher soil organic matter content and microbial biomass and activity; (*c*) a higher diversity of microorganisms and fauna in the soil and aboveground; (*d*) enhanced water-use efficiency via a demonstrated increase in water-holding capacity, reduced run-off, and increased rooting depth; and (*e*) improved cation-exchange capacity and increased internal nutrient cycling (3, 38). These intrinsic differences between OFSs and CFSs are likely the reason for differences in the occurrence and intensity of plant diseases, which in turn require a different approach to disease management.

PLANT DISEASES IN ORGANIC VERSUS CONVENTIONAL AGRICULTURE

Root Diseases

Many root diseases are caused by soilborne pathogens. The interaction between these pathogens and saprophytic microorganisms in soil and on the root surface has a large influence on the development of root diseases. Therefore, comparisons of root diseases in organic and conventional farming systems are strongly affected by soil quality and health (33, 126, 128, 133, 134). Many comparative studies of root diseases in OFSs versus CFSs have been published (1, 6, 33, 42, 44, 45, 48, 70, 73, 78, 83–85, 99, 118, 126, 128, 130, 135, 147). These comparisons of root diseases are rather straightforward and are less confounded by the movement of pathogen propagules between neighboring OFSs and CFSs than are foliar diseases.

Soil health and root disease. Soil health characteristics and measurable indicators were described, and management practices for the promotion and maintenance of soil health and root disease suppression were discussed in an extensive recent review on soil health and root disease management, including the importance of soil health for ecosystem functioning and agricultural sustainability (64). Therefore, our discussion of this topic is limited to certain points that may need additional attention.

Attributes of a healthy soil are high organic matter, good soil structure, high water-holding and drainage capacity, balanced nutrient cycling, sufficient rooting depth, and diverse populations of ecologically beneficial microorganisms, resulting in resilience to adverse events and stress and low pathogen and pest populations (33, ch. 3.2; 64, 132). Analogous to ecosystem health, soil health is characterized by biological diversity, functional connectedness, stability, and resilience (132–134, 150). Soil health is promoted by judicious management of organic matter aimed at reducing easily available carbon and nitrogen sources, i.e., the creation of more oligotrophic conditions to stabilize biological communities (33, ch. 3.2; 108, 133). To maintain a stable soil community, soil tillage needs to be minimized (6). No-till farming is difficult without herbicides (as required by organic standards), but considerable progress has been made to reduce tillage in OA (76). Attributes typical of a healthy soil that provides a variety of ecosystem services are generally more common in diversified OFSs than in CFSs (3, 58). Soils in long-term OFSs are generally considered healthier than similar soil types in high-input CFSs.

A healthy soil has often been associated with root disease suppression (44, 64, 133, 134). Two kinds of disease suppression have been distinguished: general and pathogen specific (82). General suppression is mostly a function of biological factors, such as competition between microorganisms, and physical-chemical factors, such as the nutrient and energy supply available for growth of the pathogen through the soil and on the root surface. Pathogen-specific suppression is due to a specific interaction between a plant pathogen and its antagonist, for example an antibiotic producer or parasite, as sometimes found in monocropping situations (48). This specific kind of disease suppression does not likely occur in organically managed soils, where a great variety of crops is grown in space and time.

Root and foot diseases in monocotyledonous field crops. Surveys in neighboring or nearby organic and conventional farmers' fields with similar inherent soil characteristics, as well as several long-term farming systems experiments, have shown that most root diseases of cereal crops are less severe in OFSs than in CFSs (48, 70, 126, 135). A lower incidence of *Fusarium* infections (*Fusarium* *graminearum* or *Fusarium culmorum*) was related to higher soil biodiversity and lower nitrogen contents in organically managed soils (**Table 1**). Increased competition for nutrients between pathogenic and antagonistic *Fusarium* species is also likely, as nonpathogenic *Fusarium* species are often dominant over pathogenic ones in OFSs (135). In addition to *Fusarium* foot rot (*F. culmorum*) and snow mold (*Fusarium nivale*), eyespot (*Pseudocercosporella herpotrichoides*) and sharp eyespot (*Rhizoctonia cerealis*) severities were positively correlated with total nitrogen application rates (135). Take-all (*Gaeumannomyces graminis*) incidence was higher in recently converted organic fields than in conventional fields (**Table 1**) but lower in longer-term organic fields (135). The apparent but temporary initial increase after conversion may be due to a change from monocropping (with specific take-all suppression) to crop rotation. In bioassays, take-all severity was similar or lower in soil from OFSs than from CFSs (48).

Several plant-parasitic nematodes (**Table 1**) were more numerous on cereal crops and corn in conventional fields than in organic and low-input fields at various locations (6, 70, 126, 135). The nematode structure index, a measure of the number of trophic layers and of the potential for regulation of other nematodes, was higher in organic long-term experimental plots than in the accompanying conventional plots (6). Thus, predatory omnivorous nematodes could have been responsible for reduced plant-parasitic nematode populations in the organic plots. Omnivorous nematodes were more numerous in organic than conventional plots in another long-term experiment comparing biodynamic (D), organic (O), and conventional (K) agriculture in Switzerland (a.k.a. the DOK experiment), but plant-parasitic nematodes were also more numerous in soil from the organic plots in that experiment (9; 33, ch. 3.3).

Root diseases in dicotyledonous field and vegetable crops. There is a large body of literature demonstrating suppression of many root diseases in organic vegetable production fields (**Table 1**). Nevertheless, addition of fresh organic matter may temporarily increase the risk of damping-off, as facultative saprotrophic pathogens such as *Pythium* spp. can multiply in this new substrate. After the initial increase in damping-off, the incidence may decrease and increase again in an oscillatory fashion, depending on the time of planting since incorporation of the organic materials (44, 45). Thus, seedling damping-off can be either reduced or enhanced in OFSs, depending on the time of planting since incorporation of fresh organic matter (23). For example, seedling damping-off of tomatoes was either similar (*Pythium aphanidermatum*) or reduced (*Rhizoctonia solani*) in organically managed compared with conventionally managed soils after incorporation of fresh plant debris into the soils (42, 79). Nevertheless, damping-off of *Brassica* spp. by *R. solani* was reduced in OFSs (111).

Root diseases on older plants are very often reduced in OFSs compared with CFSs. This was the case for club root (*Plasmodiophora brassicae*) and stalk rot (*Sclerotinia sclerotiorum*) of *Brassica* spp. in Nepal (**Table 1**), probably owing to mixed cropping and proper residue management in OFSs (111). Mulching and cotton gin trash amendments resulted in high soil populations of *Trichoderma* spp. and increases in water-holding capacity, mineralizable nitrogen content, and microbial biomass and diversity, reducing southern blight (*Sclerotium rolfsii*) of tomatoes (**Table 1**) (13, 73). Composted manure application led to a lower incidence of *Fusarium* wilt in organic melons compared with conventional melons (147). Similarly, *Fusarium* wilt on flax (*Fusarium oxysporum* f. sp. *lini*) was reduced in soil samples from organic field or greenhouse plots compared with their conventional counterparts. This was associated with the use of plant- and animal-derived composts or manure in the organic plots that led to relatively high soil pH and total carbon content, and composition of ammonia-oxidizing bacteria (109, 134). The organic greenhouse soil had not yet stabilized at the time of soil sampling, and the soluble carbon and nitrate levels were higher than in the conventional plots (134). However, *Fusarium* wilt was suppressed more in the organically

Table 1 On-farm, field experiment, and greenhouse comparisons of soilborne plant pathogen and/or disease levels in organically and conventionally managed soils

Crop	Management practices in organic crops	Disease intensity in organic as compared with conventional systems	References
Monocot field crops			
Corn or sorghum in rotation with soybean and oat	Farming systems comparison; organic according to National Organic Program guidelines	Lower populations of *Pratylenchus* spp. in organic farms	Neher & Olson (1999) in Reference 135
Cereals: wheat, barley	Replicated field experiment; organic management according to EU guidelines; organic plots were located in a lower lying and wetter area than conventional plots	Higher incidence of damping-off by *Bipolaris sorokiniana*; less severe *Fusarium* foot rot; similar or more severe root rot and take-all by *Gaeumannomyces graminis* in organic plots	Hannukala & Tapio (1990) in References 126 and 135; 70
Cereals: wheat, barley, rye, triticale	Organic and conventional farm fields; shallower tillage, lower N, no pesticides in organic fields	Reduced incidence and severity of various foot and root rots (*Fusarium* spp., *Rhizoctonia*), similar or less severe eyespots (*Pseudocercosporella* and *Rhizoctonia*); similar or reduced take-all[a] (*G. graminis*) Declining *Rhizoctonia* bare patch in long-term, no-till farms Reduced severity of root rot and take-all (*G. graminis*) in organic field plots and in bioassays with soil from organic farms	Pior & Hindorf (1986), Daamen et al. (1988), Kloch (1991), and Tamis & van den Brink (1998) in References 126 and 135; 94, 103; 47
Cereals: wheat, oats	Replicated long-term farming systems experiment; organic and low-input plots with winter cover crops; manure in organic plots	Plant-parasitic nematode populations (*Heterodera avenae*, *Ditylenchus dipsaci*, and *Pratylenchus thornei*) lower in low-input and organic plots; root-knot nematode galls were similar	Clark et al. (1998) and Jaffee et al. (1998) in Reference 135; 6
Dicot field/vegetable crops			
Brassica spp.	Survey of organic and conventional farms; mixed cropping, residue management, botanical pesticides in organic fields	Stalk rot (*Sclerotinia sclerotiorum*) and damping-off (*Rhizoctonia* sp.) less severe; club root (*Plasmodiophora brassicae*) similar	111
Flax	Bioassays with soil from organic experimental plots with different amendments	*Fusarium* wilt (*Fusariam oxysporum* f. sp. *lini*) more suppressed in soil from organic field plots with complex amendments and from an organic greenhouse than in conventional counterparts	109, 134

(*Continued*)

Table 1 (*Continued*)

Crop	Management practices in organic crops	Disease intensity in organic as compared with conventional systems	References
Lettuce	Organic and conventional fields; longer crop rotation and compost in organic; Cu fungicides in organic and conventional	Corky root (*Rhizorhapis suberifaciens*) less severe in organic fields with higher microbial activity	128
Melon	Bioassays with soil from organic and conventional fields; composted manure in organic fields	Lower incidence of *Fusarium* wilt (*F. oxysporum* f. sp. *melonis*) in organic fields, associated with higher microbial activity	147
Potato	Bioassays and greenhouse experiments with soil from organic and conventional fields; organic according to EU regulations	Reduced brown rot incidence and survival of *Ralstonia solanacearum* race 3 biovar 2 in organic sandy soil, increased brown rot incidence and pathogen survival in nutrient-rich organic clay loam soil	84, 85
	Field experiments on effects of compost, rapeseed as precrop, and biocontrol agents at one organic and one conventional farm	No clear differences between farms in black scurf (*Rhizoctonia solani*), common scab (*Streptomyces scabies*), and silver scurf (*Helminthosporium solanii*); some reductions in disease severity by rapeseed or compost at both farms in either year; minor effects of biocontrol agents	7
Soybean	Bioassays with soil from organic and conventional field plots; organic transition from pasture, grain rotation, or vegetable crops; with or without amendments	*R. solani* became progressively more suppressed during transition to organic field management in field plots and bioassays. Sudden death syndrome (*Fusarium virguliforme*) became more severe over time in bioassays.	80
Tomato	Comparison of organic and conventional farm fields; organic certified according to California regulations	Lower severity of corky root (*Pyrenochaeta lycopersici*) and *Phytophthora* root rot (*Phytophthora parasitica*) in organic fields; *P. lycopersici* suppressed in organic soil in bioassays, associated with high microbial activity, low N content, and high actinomycete diversity	Workneh et al. (1993), Workneh & van Bruggen (1994) in References 70 and 135

(*Continued*)

Table 1 ***(Continued)***

Crop	Management practices in organic crops	Disease intensity in organic as compared with conventional systems	References
Tomato	Replicated long-term farming systems experiment; organic and low-input plots with winter cover crops, composted manure, and wider rotations in organic plots	Lower severity of corky root (*P. lycopersici*), *Fusarium*, *Pythium*, and *Phytophthora* root rot; lower soil populations of *Verticillium dahliae* and *R. solani*; similar damping-off (*Pythium* or *Rhizoctonia*) in bioassays with residue amended soils Populations of *Meloidogyne* sp. and root-knot symptoms not consistently lower in organic plots; juveniles of *Meloidogyne javanica* more suppressed in organic than conventional soil	Clark et al. (1998) in Reference 135; Clark et al. (1998) and Jaffee (1998) in Reference 135; 6
Tomato	Bioassays with soil from organic and conventional field plots, according to California organic regulations	Similar or reduced damping-off incidence (*Pythium aphanidermatum* or *R. solani*) in growth chambers	Grünwald et al. (1997) in Reference 135; 42
Tomato	Replicated experiment with conventional, low-input, and organic treatments in solarized soil in plastic greenhouses; humic acid as fertilizer, organic pesticides, sulfur, and copper sprays in organic plots	Incidence of damping-off (*R. solani*) reduced	79
Tomato	Survey of organic and conventional farms; mixed cropping, residue management, and botanical pesticides in organic fields	Bacterial wilt (*R. solanacearum*), damping-off (*R. solani*), and root-knot nematode symptoms (*Meloidogyne* spp.) less severe	111
Tomato	Field experiments with synthetic or organic fertilization; organic treatments received mulch and various soil amendments	Reduced Southern blight (*Sclerotium rolfsii*) in plots with organic amendments and mulch	13, 73
Perennial crops			
Apple	Conventional and organic apple orchards; organic soil amendments that promote soil microbial diversity in organic orchards	Lower colonization by root pathogens (*Pythium* spp., *R. solani*); less *Pythium* root rot, more nonpathogenic *Pythium* spp.	78, 83

(Continued)

Table 1 (*Continued*)

Crop	Management practices in organic crops	Disease intensity in organic as compared with conventional systems	References
Avocado	Surveys in organic and conventional orchards; green manure, manure, and straw mulch in organic orchards; greater soil microbial activity and fauna	*Phytophthora* root rot (*Phytophthora cinnamomi*) reduced	Malajczuk (1983) in Reference 126; 144
Grape	Comparison of organic and conventional vineyards; bare soil in conventional and cover crops in organic vineyards	No difference in *Phylloxera* but reduced severity of fungal root infections (*F. oxysporum*, *Cylindrocarpon* sp.)	Lotter et al. (1999) in Reference 135
Strawberry	Replicated on-farm study of organic and conventional fields; straw mulch and no fumigation in organic fields	Various root rots (*Cylindrocarpon*, *Fusarium*, *Pythium*, *Rhizoctonia*) similar or greater and *Verticillium* wilt similar in recently converted organic field plots	Rosado-May et al. (1994) in Reference 135
Various crops in rotation or in bioassays	Field experiments with synthetic or organic fertilization; organic treatments received mulch and various soil amendments	Higher *Trichoderma* and lower *Phytophthora* and *Pythium* propagule densities in soil	13
	Replicated long-term farming systems experiment; organic and low-input plots with winter cover crops, composted manure, and wider rotations in organic plots	Reduced populations of *Pratylenchus* spp., *R. solani*, and *V. dahliae* in soil	6, 135
	Long-term organic, biodynamic, and conventional (DOK) experiment	In bioassays: damping-off (*Pythium ultimum*) of garden cress least in organic soil at low fertility and in conventional soil at high fertility Total herbivorous nematode counts higher in organic than in conventional plots with mineral fertilizer	118; 9; 33, ch. 3.3

[a]More severe take-all in recently converted organic fields but similar or reduced take-all in established organic farms.

managed soil, where the relative oscillations in microbial populations after a disturbance were less intense (indicative of greater soil health) than those in the conventionally managed soil.

Phytophthora root rot (*Phytophthora parasitica*) severity of organic field tomatoes was primarily associated with soil physical factors, such as high clay content and low aggregate stability, and to a lesser extent with low microbial activity, whereas corky root (*Pyrenochaeta lycopersici*) severity was positively correlated with high nitrogen levels in soil and tomato tissue, and low nitrogen mineralization potential and microbial activity (70, 135). In contrast, tomato production in commercial organic greenhouses often suffers from a buildup of corky root due to limited crop rotation (33, ch. 2.4; 43, 130). Longer rotation and organic management both reduced severity of corky root and other root diseases in organically managed plots (**Table 1**). The use of manure and cover crops, better water penetrability, and lower nitrogen availability in the organic plots all contributed to disease suppression (70). In addition, soil populations of *R. solani* and *Verticillium dahliae* were significantly higher and had greater fluctuations in the conventional treatments than in the organic treatments (135).

Few comparisons are available for bacterial plant diseases (**Table 1**). Corky root of lettuce (*Rhizorhapis suberifaciens*) was less severe in organic fields than conventional fields (128). Corky root severity was enhanced by low microbial activity, inorganic nitrogen applications, and herbicides in CFSs (128). Survival of *Ralstonia solanacearum* race 3 biovar 2, causal agent of potato brown rot, was shorter in organic soils than in conventional sandy and clay soils from Egypt but not in those from the Netherlands (84). Decline rates of the pathogen were positively correlated with bacterial diversity (84, 137). The incidence of brown rot infection was similar in organically and conventionally managed soils from Egypt (although the number of latently infected plants was higher in conventional than in organic sandy soil), but organic management significantly increased disease incidence in Dutch sandy and clay soils because survival was related to dissolved organic carbon (DOC) content, which was highest in Dutch organic and conventional farms, where large amounts of manure were applied annually. Amendments with manure or synthetic fertilizer decreased survival and disease incidence in some cases, likely due to release of ammonia (65).

Populations of *Meloidogyne* spp. were not consistently lower in organic plots than in conventional plots of a long-term field experiment (6). Root-knot symptoms on tomatoes were rare and differences were not consistent among treatments (135). However, suppression of *Meloidogyne javanica* juveniles in a bioassay was greater in soil from the organic plots and was positively associated with the bacteria-dominated food web in those plots (6). Root-knot nematodes were considered less of a problem by organic tomato producers than by conventional tomato producers in Nepal (111). In contrast, tomato production in organic greenhouses can be severely affected by root-knot nematode problems owing to relatively short rotations in those production systems (130). Steaming of organic greenhouse soils resulted in only temporary relief, as suppression of *Meloidogyne* juveniles was reduced in soils that had been steamed (R. Berkelmans, unpublished results).

Root diseases in perennial crops. Replant diseases on young trees can be caused by a variety of pathogens, ranging from fungi and oomycetes to nematodes, depending on the organisms that were associated with the roots of trees that were removed. In organic apple orchards, pathogenic *Pythium* species were less frequently isolated from roots of young trees than were nonpathogenic *Pythium* species, whereas that was not the case in conventional orchards (83). Reduced colonization of organic apple roots compared to conventional apple roots by *Pythium* and *Rhizoctonia* species was also observed in another study (78). On older fruit trees, *Phytophthora* root rot is commonly suppressed in OFSs. For example, suppressiveness against *Phytophthora cinnamomi* on avocados evolved after many years of mulching, resulting in enhanced microbial activity and lysis of *Phytophthora* hyphae (126, 144).

Despite soil fumigation in conventional strawberry fields, the incidence of root rot caused by various fungi (**Table 1**) was similar in recently established organic and conventional plots (91, 135). However, in well-established organic strawberry fields with appropriate soil management practices, incidence of root diseases can be reduced to below the level found in conventional fields (135).

Increased biodegradation of soil fumigants has made these fumigants ineffective against nematodes in bananas, and organic amendments have become the most effective means of nematode control (33, ch. 5.8). Similarly, organic amendments are most effective against nematodes in coffee (33, ch. 4.9). Organic mulches also help with the decomposition of fallen berries, reducing the initial inoculum on infected berries.

Foliar Diseases

Although the comparison of soilborne diseases in OFSs versus CFSs is rather straightforward, comparing airborne diseases among systems is less clear, as there are often scale differences and neighboring systems may freely exchange aerial inoculum as well as vectors and their parasites. As only a small fraction of farms are following organic practices, it is sometimes thought that these may profit from an overall low inoculum because of pesticide use in the surrounding CFSs. However, an extensive spatial survey in France demonstrated that CFSs benefitted more from OFSs than vice versa, owing to the greater abundance of predators and parasitoids in OFSs (39). Despite these difficulties in comparing aerial diseases, it is possible to compare disease developmental processes and plant susceptibility as affected by the growing system (33, ch. 3.1). Plant susceptibility to both foliar and root pathogens is affected by nutrient status (24) as well as by microorganisms in the soil, rhizosphere, phyllosphere, and endosphere (33, ch. 3.1; 100, 125).

Many diseases and insect vectors are promoted by high nitrogen contents in plant tissues (33, ch. 3.4; 24). For example, some rusts, powdery mildews, and virus vectors (in particular aphids) are often less problematic in OFSs than in CFSs (**Table 2**), even though only a few pesticides are allowed in OFSs. However, diseases caused by multiple-cycle pathogens, such as late blight of potatoes and onion downy mildew, can constitute a severe problem for organic farmers in humid climates because effective control measures have not been developed (33, ch. 5.1, 5.5; 126). Virus diseases could be more or less problematic in OFSs, but there is little documented evidence (33, ch. 3.4). The complex interactions between host, vector, alternative hosts, and environmental factors make generalizations difficult. Other hosts and virus vectors may reside in the surrounding natural vegetation. Organic fields are often relatively small, and border effects may play an important role. However, natural enemies are often more abundant than in CFSs (70, 123), contributing to control of virus vectors.

Foliar diseases in monocotyledonous field crops. The farming system has important effects on small grain cereals because of changes in nutrient status and rotation management (33, ch. 5.2). Stripe rust (*Puccinia striiformis*), powdery mildew (*Erysiphe graminis*), Septoria leaf blotch (*Zymoseptoria tritici*), and *Fusarium* scab (*F. graminearum*) were often less severe in long-term OFSs than in CFSs (**Table 2**) (70, 126). This was attributed to the lower nitrogen levels in organic wheat tissues. However, the severity of Septoria leaf and glume blotch (*Parastagonospora nodorum*) was sometimes higher in recently converted OFSs than in neighboring CFSs. Transitional organic crops also had higher aphid infestations, indicating that nitrogen levels might still have been high in these crops. Glume blotch (*P. nodorum*) and leaf rust (*Puccinia recondita*) on the ear are sometimes less severe in CFSs than in OFSs in Europe, where conventional cereals receive fungicide applications until late in the growing season to delay senescence (126).

The absence of fungicide use in OFSs has given rise to concerns about grain molds and mycotoxin production in those farms (143). However, *Fusarium* scab is often less severe in organic than in conventional wheat (**Table 2**) because of the longer rotations and lower nitrogen levels, and the reported mycotoxin levels in organic cereals were the same or lower than in conventional cereals in Europe (10, 18, 25, 105). However, little maize is grown in most OFSs in Europe. The

Table 2 On-farm and field experiment comparisons of aerial plant pathogen and/or disease levels under organic compared with conventional management

Crop	Management practices in organic crops	Disease intensity in organic as compared with conventional systems	References
Monocot field crops			
Corn	Replicated long-term farming systems experiment; organic and low-input plots with winter cover crops, composted manure, and wider rotations in organic plots	Similar incidence of common smut (*Ustilago maydis*)	Clark et al. (1998) in Reference 135
Cereals: wheat, rye	Surveys on organic and conventional farms; longer rotations, organic fertilization, lower N levels, and absence of pesticides at the organic farms	Less stripe rust (*Puccinia striiformis*), powdery mildew (*Erysiphe graminis*), leaf blotch (*Mycosphaerella graminicola*), and head blight (*Fusarium* spp.) in organic farms; similar leaf spot and glume blotch (*Leptosphaeria nodorum*) and leaf rust (*Puccinia recondita*) on organic farms; more scald (*Rhynchosporium secalis*) on one organic farm.	Pior & Hindorf (1986), Daamen et al. (1989), Hannukala & Tapio (1990), Koch (1991), and Tamis & van den Brink (1998) in References 70 and 126
Cereals: wheat	Field surveys and grain samples from organic and conventional farms; fungicides used in conventional fields, not in organic fields; lower N levels, no pesticides in organic fields	Lower infection with ear blight (*Fusarium* spp.) and lower mycotoxin contamination; lower infection in one of three years, and similar mycotoxin levels in another study	10, 18, 25, 105
Cereals: wheat, barley, rye	Grain samples from conventional and organic farms; lower N, no pesticides applied in the organic farms	Ochratoxin A (OTA) incidence on cereal grains similar in both farming systems; contamination levels higher in barley and rye samples but lower in wheat samples from organic fields	20
Rice, wheat, barley, rye, oats, and maize	Grain samples from conventional and organic farms; lower N, no pesticides applied in the organic farms	OTA incidence similar in organic and conventional samples, but contamination levels were higher on organic samples	53
Cereals: wheat	Comparison of conventional and organic experimental fields; sulfur applications in organic fields	More severe Septoria leaf blight at end of season; more severe powdery mildew at beginning of season in organic fields	Higginbotham (1996) in Reference 70
Cereals: wheat	Field surveys: comparison of diversified organic farm fields and simplified conventional fields; less tillage, lower N, no pesticides in organic fields	Leaf blotch (*Mycosphaerella graminicola*) and aphids (mainly *Metopolophium dirhodum*) lower in organic fields	39

(*Continued*)

Table 2 (*Continued*)

Crop	Management practices in organic crops	Disease intensity in organic as compared with conventional systems	References
Dicot field/vegetable crops			
Brassica spp.	Organic, mixed cropping, residue management, botanical pesticides	Leaf spot (*Alternaria brassicae*) and black rot (*Xanthomonas campestris*) severity similar in both farming systems	111
Cucurbit spp.	Organic, mixed cropping, residue management, botanical pesticides	Powdery mildew (*Erysiphe* sp.) and downy mildew (*Pseudoperonospora cubensis*) less severe; *Phytophthora* blight (*Phytophthora capsici*) and anthracnose (*Colletotrichum orbiculare*) more severe	111
Potato	Comparison of one organic and one conventional farm; organic management according to EU regulations, copper fungicides used	More severe late blight (*Phytophthora infestans*) in organic farms	Piorr & Hindorf (1986) in Reference 70
Tomato	Survey of organic and conventional farms; mixed cropping, residue management, and botanical pesticides at organic farms	Late blight (*P. infestans*) similar; Septoria leaf spot (*Septoria lycopersici*) less severe	111
Tomato	Replicated long-term farming systems experiment; organic and low-input plots with winter cover crops, manure in organic plots	Similar bacterial speck (*Pseudomonas tomato*) and bacterial leaf spot (*Xanthomonas vesicatoria*)	Clark et al. (1998) in Reference 70
Tomato	Compost experiment at an organic farm and a conventional farm; cannery waste compost at the organic farm	Reduced anthracnose (*Colletotrichum coccodes*) on fruits in the organic plots with cannery waste compost	1
Tomato	Replicated experiment with conventional, low-input, and organic treatments in solarized soil in plastic greenhouses; humic acid as fertilizer, organic pesticides, sulfur, and copper sprays in organic plots	Powdery mildew (*Leveillula taurica* and *Oidium* sp.) and early blight (*Alternaria solani*) reduced; late blight (*P. infestans*) slightly more severe in organic houses; *Tomato ringspot virus* and *Tomato bushy stunt virus* similar	79
Tomato	Experimental conventional and organic field plots; intensive fertilizer and insecticide treatments in conventional plots; organic treatments, plant extracts, copper fungicide in organic plots	*Tomato spotted wilt virus* more severe in organic plots Leaf spots (*S. lycopersici* and *X. vesicatoria*) more severe in organic plots; early blight and fruit rot (*Alternaria solani*) less in organic plots	8

(*Continued*)

Table 2 ***(Continued)***

Crop	Management practices in organic crops	Disease intensity in organic as compared with conventional systems	References
Tomato	Long-term organic, biodynamic, and conventional (DOK) experiment	In bioassays: late blight (*P. infestans*) similar in DOK soil with regular fertility, but reduced in the no-fertility treatment	118
Perennial crops			
Almond	Surveys in adjacent orchards; mixed cover crops, no fertilizers or pesticides in organic orchards	Shot hole (*Stigmina carpophila*) more severe, almond scab on leaves and fruits similar; no differences in fungal communities	Teviotdale & Hendricks (1994) in Reference 70
Apple	Survey in conventional and organic apple orchards; organic amendments, cover crops, sulfur sprays in organic orchards	More severe apple scab (*Venturia inaequalis*) in organic orchards	Vossen et al. (1994) in Reference 70
Apple	Fungicide experiments in conventional and organic orchards; cover crops, copper and sulfur sprays, winter pruning in organic orchards	More severe apple scab (*V. inaequalis*) in organic orchards	49, 50
Coffee	Survey of conventional and organic farms; organic under shade, foliar nutrients, manure, inorganic Cu and Zn sprays	Brown eyespot (*Cercospora coffeicola*) less severe on organic under shade than conventional without shade	115
Strawberry	Survey of conventional and organic fields; straw mulch, no fumigation or fungicides, low fertility in organic fields	Less fruit rot by *Botrytis cinerea*; variable gray mold severity depending on cultural practices	Gliessman et al. (1996) and Daugaard (1999) in Reference 70
Variouscrops in rotation or in bioassays	Long-term DOK experiment	In bioassays: downy mildew (*Hyaloperonospora parasitica*) on *Arabidopsis* less in biodynamic soil than other treatments	118

tendency to add more maize to the rotation and increase nitrogen fertilization to improve baking quality of organic wheat may increase susceptibility to *F. graminearum* (24, 25, 28). However, the use of the herbicide glyphosate (on Roundup-ready® maize) increases the risk of *Fusarium* infection in CFSs compared with the production of traditional maize without herbicide in OFSs (59). Contrary to *Fusarium* toxins, the concentration of ochratoxin A (produced by *Penicillium* or *Aspergillus*) can sometimes be higher on organic grains than on conventional grains (20, 53). This may be attributed to storage conditions (33, ch. 4.9).

Foliar diseases in dicotyledonous field and vegetable crops. Foliar diseases caused by pathogens that can be transported over long distances and are primarily dependent on high humidity and leaf wetness for infection can be a serious problem for all organic farmers in humid climates (**Table 2**). This holds in particular for polycyclic diseases such as late blight on potatoes and tomatoes (*Phytophthora infestans*) and downy mildews (32; 33, ch. 5.1; 70; 79). However, in bioassays with soils from the Swiss long-term DOK experimental plots mentioned earlier, potato late blight severity was similar in the organic, biodynamic, and conventional treatments with regular fertility but reduced in a no-fertility treatment (118). Although late blight might be reduced at low fertility levels, nutrient availability may be more limiting than late blight to potato yields in many OFSs (12; 32; 33, ch. 5.1; 87). Some biofertilizers also contribute to late blight reduction (e.g., in tomatoes) (110). Relatively low nitrogen levels in soil and plant tissues may also be responsible for the reduced severity of powdery mildew on cucurbits and tomatoes in OFSs (79, 111).

Splash-dispersed pathogens such as *Septoria* and *Colletotrichum*, which cause leaf spot diseases, can also be severe in OFSs because seed and in-field treatments with fungicides are not possible or are ineffective (33, ch. 5.5). No differences have been reported for splash-dispersed bacterial diseases between OFSs and CFSs. For example, black rot on brassicas (**Table 2**) was similar in both farm types (111), presumably because the same seed sources were used.

Foliar diseases on perennial crops. Few comparative studies were conducted on foliar diseases in orchard crops (**Table 2**). Most of those diseases were more problematic in organic than in conventional orchards. For example, apple scab (*Venturia inaequalis*) can be a severe problem in organic orchards in humid climates or during wet spring seasons despite various sanitation methods and spraying with copper or sulfur compounds (33, ch. 2.3, 4.7, 5.6; 70). Also, organic banana production is usually restricted to regions nonconducive to the development of Black Sigatoka (*Mycosphaerella fijiensis*) (33, ch. 5.8). However, brown eyespot of coffee (*Cercospora coffeicola*) and coffee leaf rust (*Hemileia vastatrix*) are often less severe on organic trees than on conventional trees. Organic coffee is mostly grown under shade, which reduces the day-night temperature variations and thus dew formation and leaf wetness (33, ch. 3.1), whereas conventional coffee is usually grown without shade (33, ch. 5.9; 115).

PLANT DISEASE MANAGEMENT IN ORGANIC AGRICULTURE

General Considerations

The conceptual approaches to disease management differ fundamentally between OFSs and CFSs. Organic disease management involves a wide range of management practices that maintain ecosystem health and foster ecosystem services (33, ch. 4.1; 58; 70; 128). An important goal is to provide internal stability to the agroecosystem by enhancing biological diversity both above- and belowground (9, 123, 133). Thus, organic growers commonly rely on cultural plant protection methods, such as sanitation, organic soil amendments, lengthy crop rotations, reduced tillage, proper timing of crops, crop and cultivar selection, intercropping, and cover cropping (33, ch. 4.1; 71; 128; 135). Increased habitat diversity is used to enhance natural pest and disease control, among others by intercropping and planting of trees, shrubs, wild grasses, and flowering plants (33, ch. 4.4; 38). Genetically modified organisms (GMOs) are not used, partly because of concerns about unknown impacts of gene manipulation, but also to avoid genetic uniformity that can promote pest and disease outbreaks (33, ch. 2.1, 4.4).

A recent review covers most methods for plant disease management in OFSs in detail (129). We therefore summarize only the strategies and methods aimed at limiting pathogen invasion and spread, analogous to the barriers against biological invasions in natural ecosystems (70). We distinguish three basic tactics for disease management: (*a*) minimizing initial inoculum, (*b*) minimizing the suitability of the host and its environment for infection and reproduction, and (*c*) curative methods that limit further spread.

Minimizing Initial Inoculum

Initial inoculum can be reduced by removing infected plant materials, various ways of soil disinfestation, and prevention of entry of pathogens in a crop, for example by disinfection of seeds and vegetative planting materials.

Sanitation. Similar to CFSs, overwintering inoculum is commonly removed in OFSs. In vineyards and orchards, diseased branches are pruned away (33, ch. 2.3, 4.6) and plant residues are removed from greenhouses (33, ch. 2.4). Branches and residues are composted instead of burned to reduce CO_2 emissions and return carbon to the soil. Like in CFSs, covering or removing cull piles and removal of volunteer plants and alternate hosts for pathogens such as *P. infestans* are very important in reducing the initial inoculum (32; 33, ch. 5.2).

Soil disinfestation. Several methods of soil disinfestation can be used in OA, namely flooding, soil steaming, solarization, anaerobic (or biological) soil disinfestation (ASD), and biofumigation, and are discussed in recent reviews (36, 129). Soil flooding is rarely used because of lack of water in most areas. Soil steaming is sometimes used when plant-parasitic nematodes and/or root pathogens have accumulated due to a limited rotation of high-value crops in greenhouses (33, ch. 2.4; 36; 43). Steaming kills all heat-sensitive plant pathogens, nematodes, and weeds to a certain soil depth, but large parts of the soil microbial community and fauna are also eliminated. Therefore, this method actually goes against the production principles of many organic growers.

For soil solarization, moist soil is covered with transparent, UV-resistant plastic and exposed to sunlight for a few weeks (35, 36). Most plant-pathogenic fungi, bacteria, and nematodes, except for some heat-tolerant fungi and viruses, are quite sensitive to increased temperatures (45–55°C) (33, ch. 4.8; 56; 57; 146). The solarization effect can be enhanced by incorporation of isothiocyanate-producing residues from brassica crops into soil before covering with plastic (56, 57). Along with the direct heat effects on pathogens, soil solarization can also enhance plant growth by increasing the availability of mineral nutrients and improving soil tilth (35).

For ASD, fresh organic material is incorporated into soil, and the soil is moistened and covered by airtight plastic for 3–6 weeks (62, 88). Proliferating bacteria deplete the available oxygen until anaerobic bacteria continue to decompose the carbon source. Toxic products, including alcohols, aldehydes, organic acids, and other volatile compounds accumulate and soil pH is reduced (46, 51, 88), affecting the survival of soilborne pathogens. Anaerobic bacteria such as *Bacillus* and *Clostridium* spp. may also contribute to pathogen inactivation. ASD results in the control of many soilborne plant-pathogenic fungi, bacteria, and nematodes, including *Rhizoctonia*, *Fusarium*, *Verticillium*, *Sclerotinia*, *Phytophthora*, *Ralstonia*, *Meloidogyne*, and *Globodera* spp., as well as most weeds (14, 40, 51, 62, 86). The changes in microbial communities characteristic for ASD (86) often result in general disease suppression that can remain active for several years (40). In contrast to soil steaming and chemical soil disinfestation, which result in a biological vacuum, the risk of a significant increase in conduciveness to reintroduced soilborne pathogens after ASD is limited (40).

Aerobic soil disinfestation, also called biofumigation, involves the addition of organic amendments to soil, generating biologically derived volatile compounds that are toxic to soil microorganisms. Green manure crops that contain glucosinolates, mainly *Brassica* spp., are most commonly used (19). After tissue decomposition, hydrolysis results in the release of various toxic compounds, such as organic cyanides, nitriles, and thiocyanates, which have fungistatic or biocidal properties (33, ch. 4.8). Application of animal-derived residues that are high in nitrogen, such as manure or compost, can result in the production of ammonia gas, which is toxic to a wide range of pathogens and nematode pests (65).

Prevention of entry of pathogens in organic crops. Seeds and planting materials used in organic crop production must originate from certified organic sources, if available (63). Organically produced seeds must be extracted from fruits by natural means, e.g., fermentation. Because chemical seed treatment after extraction is not allowed, alternative seed treatment methods have been investigated (54, 104). There are three main seed treatment methods for organically produced seeds: (*a*) physical methods, (*b*) treatment with plant or microbial extracts, and (*c*) seed coating with biological control agents (33, ch. 4.6; 99). As physical methods, hot water or steam treatment, followed by drying, can be used (33, ch. 4.6). In addition, various seed sorting machines have been developed, so that immature or diseased seeds can be eliminated (63). Several biocontrol agents and plant extracts are commercially available to treat organic seeds against fungal and bacterial contaminants (15).

Vegetatively propagated plants, such as potatoes and strawberries, must also start with certified planting materials. Interestingly, some organic growers have fewer problems with black scurf on potatoes (*R. solani*) if they use seed tubers produced on their own farm than if they use organic certified seed tubers produced elsewhere, suggesting a *Rhizoctonia* decline phenomenon at certain OFSs (97). This is comparable to the decline in Rhizoctonia bare patch in long-term no-till wheat fields (94, 103).

Temporal and Spatial Isolation

Susceptible host plants can be isolated in time or space with the purpose of forming a barrier for the accumulation of pathogen propagules.

Temporal isolation. Disease damage can be reduced by adapting the crop planting time, choosing early maturing cultivars, or rotating with crops that are not susceptible to the pathogen involved. Planting times can be adjusted to avoid heavy aphid flights or periods when other diseases will surge by planting crops at the proper time of year (33, ch. 3.4) or by ensuring enough crop growth (e.g., through presprouting) before onset of an epidemic, for example, of potato late blight (33, ch. 5.1).

Crop rotation, the most commonly used temporal isolation tactic, prevents inoculum buildup and allows the natural decline of various pathogens between host crops (33, ch. 4.2). Organic rotations often include a multiyear grass ley or grass-legume ley or an alfalfa crop, contributing to the formation and maintenance of a healthy soil (33, ch. 4.2; 135). However, crop rotation has a limited effect on disease development if the pathogen is carried over long distances by wind, has a wide host range, or has highly persistent resting structures.

Cover crops in the rotation, used for nitrogen fixation or a reduction in nitrate leaching, have to be chosen carefully to reduce the chance of disease outbreaks and nematode damage in the following cash crop. Even when a cover crop is not susceptible to a particular pathogen in terms of symptom development, the pathogen may still multiply in the root cortex, resulting in an increase in initial inoculum for a following susceptible host crop (69). Moreover, cover crops have to be rotated themselves, especially legumes (33, ch. 5.4). Some cover crops are planted as trap or allelopathic crops for nematodes. For example, *Crotalaria* spp., *Mucuna* spp., *Tagetes* spp., and some brassicas can be used for this purpose (33, ch. 3.3, 4.2; 81).

Spatial isolation. Spatial separation of the pathogen from a susceptible host plant can be achieved by tillage, by planting barrier crops around fields, or by planting nonsusceptible crops between susceptible ones. Separation can be created at various scales, and the distance between susceptible patches or plants that is required to slow down disease spread depends on the distance that the inoculum can travel (120). Commonly, a mosaic of crops is planted in OFSs to accommodate multiple-year crop rotations. Separation of fields by natural vegetation (to enhance parasitoids and predators for insect vector control) is also common, so that epidemic development is potentially more limited (33, ch. 4.1, 4.4; 70). However, natural vegetation and weeds surrounding cropping areas may harbor pathogens and pests or produce a disease-conducive microclimate. Many organic farmers are aware of this risk and remove weeds selectively within crops and between crops, and manage hedges so as to avoid the spread of pests and diseases into their crops. The prevention of viruliferous vectors from probing a potential host can also be considered a means of spatial isolation. This can be accomplished by the use of straw or plastic mulches or oils that repel aphids (101, 106, 117). The most effective artificial mulches are those reflecting daylight, including UV, disorienting aphids and whiteflies (96). In contrast, the texture of straw confuses the aphids' tactile senses (101). Reflective yellow mulch can attract whiteflies onto the hot film, resulting in mortality (35).

Host Plant Resistance

Many organic farmers prefer open pollinated cultivars to hybrids for a variety of reasons (63). When diseases can severely limit crop yield, organic farmers try to use the most resistant varieties available to them, e.g., potato cultivars that have more general resistance to late blight (*P. infestans*) and mature early to avoid epidemic development (33, ch. 5.1; 60). Organic growers prefer to use cultivars with partial resistance based on multiple genes, which can still be effective if the pathogen pressure is lowered by additional management tactics. Although dominant single-gene resistances can frequently be overcome by an evolving pathogen, recessive qualitative resistances can be quite stable (33, ch. 4.5; 131). Prominent examples are the barley *mlo* powdery mildew resistance that has not yet been overcome since its introduction in 1976 (34), the resistance in cabbage to *F. oxysporum* f. sp. *conglutinans* that has been effective since the 1920s (95), and the resistance to corky root of lettuce caused by *R. suberifaciens* that has been effective since the 1980s (131). However, for several of the most damaging plant diseases, such as tomato late blight and white rot (*Sclerotium cepivorum*) of *Allium* species, no horticulturally acceptable resistant cultivars are available. The development of disease-resistant cultivars of perennial crops that thrive well under organic conditions is direly needed (52). Fortunately, considerable progress has been made in resistance breeding of apple trees and grape vines (33, ch. 5.6, 5.7).

The phenotype and physiology of plants, in particular, the nutrient content of a crop, can be managed to some extent to reduce its suitability for pathogens and insect vectors (24). Management practices can enhance or reduce host plant resistance by regulating the quality of the food source for pathogens or pests and the production of toxic or repellent chemicals (70). In addition, rhizosphere bacteria and fungi can induce systemic resistance against plant pathogens as well as some insect pests (125). Induced system resistance can be stimulated by certain organic amendments, including composts (33, ch. 3.1; 125), and can provide moderate levels of resistance against a wide range of pathogens. In contrast, systemic acquired resistance can be induced by pathogens as well as externally applied chemical compounds such as salicylic acid and potassium phosphite (125), but these products have not been approved for organic production (33, ch. 4.7).

Regulation of Establishment and Spread of Pathogens in Organic Crops

Once a pathogen has entered a crop field, various conditions can either enhance or suppress infection, multiplication, and spread, and thus its establishment in the field. These conditions include environmental conduciveness, host quality and resistance, resistance diversity, and the presence of nonhost plants and suppressive agents in the community that regulate epidemic development, or a combination of these factors (70).

Improving and maintaining soil quality. The most important cultural practices in OFSs revolve around improving and maintaining soil quality. Longer crop rotations, cover crops, grass leys in the rotation, and applications of composted manure or plant materials are instrumental in improving soil physical, biological, and chemical characteristics (132).

Physical soil quality can be greatly improved by the incorporation of recalcitrant organic matter and by supporting earthworm activity. This enhances water infiltration and drainage and reduces fluctuations in water potential, thus supporting development of deep and extensive root systems. This decreases susceptibility to a variety of root-rotting and wilt-inducing pathogens, such as *R. solani*, *Macrophomina phaseolina*, and *F. oxysporum* (135), and water molds, such as *Pythium*, *Phytophthora*, and *Aphanomyces*, that produce zoospores that swim toward and infect host roots under wet conditions (68).

Chemical soil quality and availability of nutrients are profoundly affected by the return of organic matter to soil (26, 37, 133). High nitrogen concentrations in soil and plant tissues, in particular, nitrate, may predispose a crop to several soilborne fungal and bacterial pathogens as well as to biotrophic foliar pathogens (67, 85, 135, 140). Fluctuations in nutrient supply can be minimized by focusing on buildup of organic matter over many years and minimizing applications of additional organic fertilizers during crop growth. Where stable organic matter has built up in the soil, nitrate concentrations are generally lower than in conventionally managed soils, except immediately after disking under of a grass-legume ley or when cover crops release large amounts of nitrogen in a short period of time (150). Soil pH and the ammonium:nitrate ratio are often higher in organically managed soils than in conventionally managed soils (41, 98, 128, 130). At high soil pH, ammonium can be transformed into ammonia, which is toxic to most microorganisms. The combination of lower nitrate levels and higher ammonium levels can contribute to the lower incidence and severity of soilborne diseases in organic soils than in conventional soils.

The higher pH in OFSs may contribute to a shortage of available phosphorous, unless manure or compost is applied on a regular basis. Because of the low phosphorous levels in many OFSs, arbuscular mycorrhizal fungi (AMFs) colonize plant roots more extensively in organic soils than in conventional soils (77, 93, 135, 139), potentially protecting the plants against pathogenic root-infecting fungi. However, AMFs are seriously affected by plowing (93). Shortages of some other elements may enhance the susceptibility to certain diseases; for example, potassium shortages increase the risk of *Verticillium* wilt in cotton, and calcium shortages enhance susceptibility to *Pythium* root rot (24). Calcium is usually not in short supply in organic soils thanks to the organic amendments and relatively high pH. Phosphorous, potassium, calcium, magnesium, and sulfur can be replenished with organic amendments or allowed minerals (33, ch. 3.1).

Biological soil quality is primarily determined by the return of organic matter to soil. However, the effect of organic amendments on disease severity depends on the type of material used, its state of decomposition, its carbon:nitrogen ratio and lignin content, and the time elapsed since incorporation (23, 42). The addition of organic substrate enhances the activity of primary decomposers, mainly bacteria and fungi, and the associated food web, in particular, bacteria-feeding protozoa and nematodes and fungivorous collembola, mites, and nematodes (77, 136, 149). Primary decomposers can act as antagonists of plant pathogens by competition for nutrients, antibiosis, and parasitism, whereas the micro- and mesofauna can contribute to control of plant pathogens by predation. In addition, complex evolutionary dynamics over time (55) can lead to the buildup of specific antagonists.

Organically managed soils generally have a greater microbial and faunal diversity than conventionally managed soils (136). Higher diversity of nonpathogenic strains of particular pathogenic fungi or bacteria has also been documented (83). Such nonpathogenic strains are thought to be responsible for the suppression of pathogens of the same genus or species, for example the suppression of *Fusarium* wilt by nonpathogenic *Fusarium* species or *F. oxysporum* strains competing for nutrients in the same niche (135). Similar phenomena have been observed for nonpathogenic *Pythium* spp. (83), *Rhizoctonia* spp. (122), *Streptomyces* spp. (74), and *R. suberifaciens* (127).

Management of the aerial environment. Many foliar diseases are enhanced by moist or humid conditions. To control these diseases, organic growers can provide more air and light and reduce relative humidity by thinning, pruning, leaf plucking, removing weeds, using a wider planting distance, planting parallel to the wind direction, optimal fertilization, and/or ventilating the greenhouse (33, ch. 2.4, 4.1). Leaf removal in vineyards is now a common practice to control diseases such as *Botrytis* and powdery mildew on the grape bunches (33, ch. 5.7). For weed suppression, a dense, quickly closing canopy is needed. To avoid a disease-conducive microclimate, low-growing living mulches are an option (16). Mulching the soil in greenhouse production of tomatoes and cucumbers can reduce the severity of late blight and downy mildew (112).

Maintaining plant diversity. Crop diversity can increase the number and diversity of beneficial organisms, control weeds, make more efficient use of natural resources, and reduce the risk of crop failure. More diversity can be obtained by wider crop rotations, the use of diversified varieties, variety mixtures, intercropping, undersowing a mixed cover crop or living mulch in the main annual or perennial crop, and planting noncrop plants in hedgerows or field margins (33, ch. 4.4; 90). Especially in organic orchards, managed ground cover, which is cut periodically and used as mulch, is widely adopted (90). Pathogen spread and epidemic development is primarily determined by the number and distribution of susceptible plants in the mixture; the longer the distance between susceptible plants, the slower the spread (47, 71). In addition to the distance, the presence of a barrier and induced resistance can limit disease development (33, ch. 4.4; 47; 145). The positive effects of diversity increase with scale, especially for foliar diseases (12, 89, 113, 120).

Despite the potential benefits, crop species mixtures are often not used because of technical problems with cultivation and harvesting. However, cultivar mixtures of cereal crops and rice are used more widely, in both OFSs and CFSs, to control foliar diseases (33, ch. 5.3). Strip cropping and mosaics of crop fields may control late blight of potatoes to some degree (12; 33, ch. 5.1; 113), but this effect is not sufficient to provide protection unless combined with several other methods (33, ch. 5.1; 116). One of the greatest economic successes of resistance diversity is likely the coffee multiline strategy in Colombia against coffee leaf rust (*H. vastatrix*). Multilines have been used since 1984 and have saved many millions of dollars in fungicide applications. In the past six years, the area grown to multilines has doubled to more than 700,000 ha, resulting in almost complete protection from coffee rust (33, ch. 4.4).

Enhanced and augmented biological control. Two basic strategies of biological control are (*a*) enhanced biological control via endemic natural enemies, including competitors, antagonists, predators, or parasites, by means of habitat management, and (*b*) inundative biological control via the release of specific competitors, antagonists, predators, or parasites (70). OA aims to enhance natural control by increasing the diversity in the terrestrial and soil food webs (5). The mechanisms underlying successful biological control vary from niche competition and antagonism to parasitism and predation. Those mechanisms are more likely to control belowground diseases and pests than aerial diseases, which are much more influenced by microclimatological conditions (72, 135). However, when microbial products are applied on seeds or soil, they may also induce systemic resistance to foliar diseases (125).

Although many potential biocontrol agents have been identified, only a few formulated products have been approved for disease control in OA, as petroleum-based synergists or carriers cannot be used in organic formulations. Biocontrol products are sometimes used as seed treatment (33, ch. 4.6) or as soil drench in the greenhouse; for example, various species of *Gliocladium*, *Trichoderma*, *Streptomyces*, *Pseudomonas*, and *Bacillus* are used primarily for the control of soilborne plant pathogens (15, 138). Nematode populations could potentially be reduced by fungi such as *Myrothecium* and *Paecilomyces* or bacteria such as *Burkholderia* and *Pasteuria*, provided they are registered for use in OA (27). However, soil application of biocontrol agents is not always successful in OFSs because of the greater biological buffering capacity in organically managed soils (48, 136, 137). A biocontrol strain of *Pseudomonas fluorescens* survived longer in CFS than OFS soil (48), and controlled take-all disease (*G. graminis*) well in CFS soil but did not have an additive effect on natural disease suppression in OFS soil. Overall, most biocontrol agents are applied against insects in OFSs, especially in greenhouses (33, ch. 2.4), but *Bacillus thuringiensis* is also applied in the field.

Curative Control of Pathogens in Organic Crops

Curative control techniques involve inputs that are applied after a pathogen has established itself in the crop. There are limited options for curative control allowed under OA guidelines (33, ch. 4.1). Comprehensive reviews of the fungicidal compounds used in OFSs are provided by Finckh et al. (33, ch. 4.7) and van Bruggen et al. (129).

Fungicides. In most countries, copper-based fungicides are allowed for use against bacterial and fungal diseases (33, ch. 4.7). They have been used primarily to control foliar diseases caused by oomycetes, fungi, and bacteria that are difficult to control without fungicides, especially in the humid tropics (33, ch. 4.7, 5.7). The use of copper is quite controversial because of its environmental toxicity (141), and it is expected to be banned in Europe in the near future (33, ch. 5.1). Sulfur fungicides are less toxic and are widely used to control powdery mildew on various crops and scab (*V. inaequalis*) on apples and pears (33, ch. 4.7, 5.6). Bicarbonate salts can also be used for disease control in OA, especially against powdery mildews, some leaf spot diseases and mites (33, ch. 4.7; 61). Their effectiveness can be enhanced by an approved spreader-sticker such as soap or oil (15, 151). Some mineral, vegetable, and fish oils are permitted for use in OA against powdery mildews and may enhance host plant resistance (92). Oils can also inhibit insect vectors by interfering with the gas exchange or altering the behavior of the insects and the ability of aphids to acquire and transmit viruses (106). A detailed list of products allowed for organic production in the United States can be found on the websites of the Organic Materials Review Institute (OMRI) (**http://www.omri.org**) and the USDA National Organic Program (**https://www.ams.usda.gov/about-ams/programs-offices/national-organic-program**) (124). European and national regulations of European Union (EU) countries are constantly updated online (30). However, many organic farmers try to avoid spraying except in emergency situations (33, ch. 2.1, 3.1).

Plant and microbial extracts. Extracts from several plant species can be toxic to various plant pathogens and insect vectors, and some are allowed under organic guidelines. Several yucca, citrus, and kelp extracts are on the OMRI list as commercial products for OA. An extract from brown algae or kelp, laminarin, has been approved in the EU (31). Extracts from many herbs, spices, and medicinal plants have also been tested for their effects on various plant diseases (17, 22, 114). The organic pesticide Tillecur®, which is based on mustard extracts, successfully reduces stinking smut (*Tilletia caries*) on wheat (33, ch. 4.6). Some plant-derived products induce resistance, such as an extract from giant knotweed *Reynoutria sachalinensis* that can be used against cucumber powdery mildew and is registered as Milsana® (21). Several plant extracts have been formulated for use against insects, including virus vectors. Examples are natural pyrethrum extracted from dried *Chrysanthemum* flowers, and neem extracted from *Azadirachta indica* (70). These natural insecticides are frequently approved for use in OA but can have negative side effects on beneficial insects like bees and predators of virus vectors.

Besides these plant extracts, cell wall fragments of *Penicillium chrysogenum* are strong resistance inducers against a wide spectrum of pathogens (33, ch. 4.7; 110; 119; 121). Some bacterial extracts can also be effective in controlling diseases (99). Compost extracts are sometimes used by organic growers with mixed success (2, 72, 102). The action mechanisms of these extracts are often not clear; there may be microbial or chemical components that have a direct effect on the pathogen or an indirect effect through induced resistance in the plants.

Despite the fact that some of the plant and microbial extracts may be effective compared with an untreated control, the extracts are frequently less effective than synthetic fungicides. Therefore, an integrated approach to plant disease management is needed in OFSs (126, 135).

DISCUSSION AND RECOMMENDATIONS

From the many comparisons of plant disease incidence and severity in OFSs and CFSs in field surveys, field experiments, and bioassays with field soil, it can be concluded that root diseases are less severe in OFSs, whereas shoot diseases are either more or less severe in OFSs than in CFSs, depending on the particular pathosystem and climatological circumstances. In numerical terms, root disease severities in OFSs fall in the 0–2 range on a 0–3 scale, where 3 is severely diseased, whereas root disease scores generally range from 1–3 in CFSs (33, ch. 3.2; 135). Using a similar scoring scale, foliar disease severities vary widely and fall in the 0–3 range in both farming systems, depending on the pathosystem and the environment. Diseases or pests that are promoted by high nitrogen contents in plant tissues, such as several root diseases, some rusts, powdery mildews, or aphids, can be more problematic in CFSs than in OFSs, despite the absence of pesticide use in OFSs. However, virus diseases can be more problematic in OFSs owing to the smaller scale and thus the proximity of field margins containing alternative hosts and virus vectors. Moreover, diseases caused by multiple-cycle foliar pathogens, such as late blight of potatoes, can constitute a severe problem for organic farmers in humid areas because effective control measures have not been developed.

Information about relative plant disease severity is most useful if it can be related to crop loss. However, quantitative crop-loss assessment is seldom carried out on a large scale (29) and certainly not for a comparison of OFSs and CFSs. Our overall impression (and also that of organic farmers) is that diseases in OA are generally not so severe that they limit yield (except for downy mildews, late blight, and some other foliar diseases in conducive climates); other factors such as weeds and plant nutrition are usually more limiting (12; 33, ch. 3.1; 98). Quantitative research determining factors contributing to crop loss in OFSs and CFSs would be very useful to answer some questions about the relative sustainability of these systems and indicate research areas that deserve more attention. However, the usual crop-loss assessment method in CFSs comparing yield in nontreated plots with that in fungicide-treated plots is not possible in OFSs. Instead, yields could be compared on isogenic lines with and without resistance to the common race of a pathogen, but to our knowledge, this has not been done. Yield loss could also be estimated by inoculating plants with different doses of a pathogen. This has been done with soilborne pathogens for disease-suppression bioassays (134) but rarely in field experiments, except with nematodes (33, ch. 3.3).

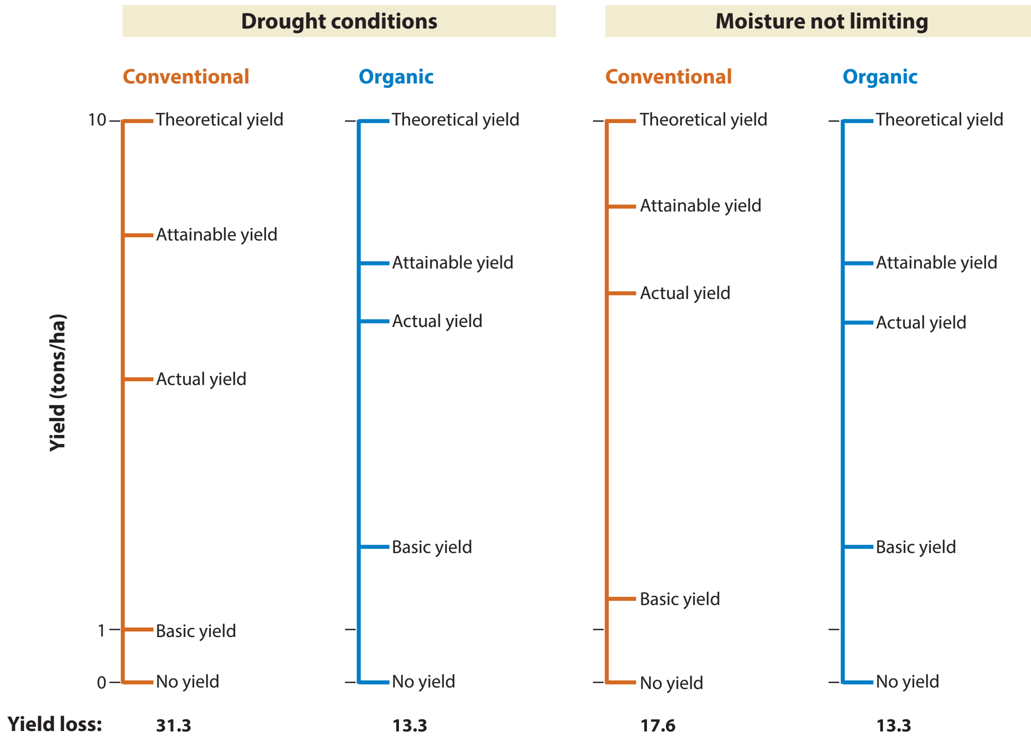

Figure 1

Hypothetical yield levels in conventional (CFSs) and organic farming systems (OFSs) under moderate drought conditions and conditions without moisture limitation, assuming that the moisture holding capacity and yield are higher in drought years in OFSs (75). This example is based on global data for a cereal crop. The actual yields are commonly 5–10% higher in OFSs than CFSs under drought conditions but lower when moisture is not limiting. The basic yields are generally higher in OFSs than in CFSs because of higher soil fertility in OFSs. Yield losses due to pests and diseases are generally lower in OFSs than in CFSs. Theoretical yield is the maximum theoretical yield from a simulation model driven by light and CO_2 absorption, and other yield-forming factors (water, nutrients) are not considered; attainable yield is the yield achieved when all yield-forming factors are optimal and yield-reducing (pests and diseases) factors are minimized by pest-control technologies; actual yield is the yield obtained under common production practices; basic yield is the yield obtained without specific capital-intensive or knowledge-intensive inputs (inappropriately termed primitive yield in older literature); yield loss is (attainable yield − actual yield)/attainable yield (148).

Potential losses have been related to different theoretical yield levels (29). The theoretical maximal yield, as calculated from simulation models, would be the same for OFSs and CFSs, but the other hypothetical yield levels for OFSs and CFSs would be different, depending on the availability of soil moisture (**Figure 1**). The yields in OFSs are primarily determined by yield-forming factors, such as plant nutrient availability, which are strongly affected by weeds. The yield-reducing components such as insect pests and diseases are often relatively small in OFSs compared with CFSs, even when the actual yield may be lower in OFSs than in CFSs. In CFSs, the yield potential can be higher, but the risk of losses due to yield-reducing factors can also be greater, resulting in more extreme fluctuations in yield. In OFSs, yield fluctuations are, with a few exceptions, relatively small because of the greater diversity and buffering capacity of the soil. Some foliar diseases can be devastating in OFSs, but organic farmers avoid growing certain crops that are too risky in a particular season or area. The greater importance of yield-forming factors like nitrogen than of yield-reducing factors like late blight has been shown for organic potato production in a temperate climate by multiple regression (12, 87). Although crop-loss assessment is less straightforward in OFSs than in CFSs, a systems analysis including pest and disease severity, nutrient and water availability, and plant resistance in relation to attained yields can provide insight into the relative importance of yield-forming and -reducing factors in OFSs. An interdisciplinary approach is needed for such crop-loss assessments (29).

Based on reports by development agencies, the attained yields close to the basic yields are frequently higher in small-scale OFSs than in similar CFSs in tropical climates (4). This is related to the greater soil quality and biodiversity in those OFSs as well as to the level of ecological knowledge of the organic farmers who often participate in organic cooperatives with group certification (107). The OFSs in tropical regions are often highly diverse ecosystems with minimal erosion and nutrient losses, and with a natural buffering capacity against diseases and pests (11; 33, ch. 4.4, 5.8, 5.9). Organic crops like coffee, cocoa, tea, and bananas are often produced in an agroforestry setting, with tall nitrogen-fixing trees, fruit trees, or banana plants providing shade for the medium-height coffee, cocoa, and tea plants as well as for the annual food crops planted underneath. This great diversity can provide a variety of ecosystem services and also food and nutritional security and poverty alleviation (58, 66). Organic certification can increase rural incomes. Thus, OA can contribute significantly to global and local food security by providing nutritious food for rural populations in developing countries (4, 107), provided that solutions are found for the occasional plant disease outbreaks. Interdisciplinary research is needed to solve these problems with a coherent set of cultural practices. Optimal farming systems need to be designed that will satisfy the requirements of sustained economic viability, regional self-reliance, crop and ecosystem health, and minimal environmental impact. This can be achieved by working with farmers rather than for farmers.

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