Ariena H. C. van Bruggen
Department of Plant Pathology, University of California, Davis

SARE Project EW94-003

Plant Disease Severity in High-Input Compared to Reduced-Input and Organic Farming Systems

There are several major concerns about current practices in high-input conventional agriculture. The most important concern in many agricultural areas is loss of topsoil (38). On average, about 20 metric tons of topsoil are lost per hectare per year in the United States (15,38). This can amount to more than half of the topsoil layer in 100 years of continuous corn production (15). Soil erosion also results in reductions in organic matter, water penetration and availability, and rooting depth (38,39). Another important concern for some areas in the United States and many areas in Europe is the effect of nitrate and pesticides on the environment, specifically in ground and surface water. In addition, pesticide efficacy has often been diminished, for example as a result of insensitivity of the targeted organisms to organic pesticides or enhanced biodegradation of these pesticides. Finally, the general public is very concerned about human health and safety and pesticide residues on food, whether this is justified or not. All these concerns have raised questions about the sustainability of conventional agriculture (8,32,36).

Although the development of alternative agricultural systems is generally considered important, it is not clear which practices will improve sustainability and maintain adequate productivity. Many alternative agricultural systems exist, but only organic farming (also called biological farming or ecofarming) has become a well-defined and certified alternative to conventional farming in North America and Europe. Organic farming is characterized by the absence of synthetic fertilizers and pesticides and the use of organic amendments such as animal manures, green manures, and composts to maintain soil fertility (32). Usually crop rotations are longer and spatial diversity is greater under organic management than under conventional management. In addition, reduced tillage or no-till is practiced on some organic farms. Finally, when disease-resistant varieties are available, they are preferred by organic growers. A variant of organic farming is biodynamic farming, which is more prevalent in Europe than in the United States. Biodynamic farmers adhere to the philosophy of Rudolph Steiner. In addition to the common organic farming practices, biodynamic farming practices include the use of dilute preparations (analogous to homeopathic preparations) derived from manure or specific wild plants applied to crop foliage or soil. Planting schedules take lunar cycles and constellations into consideration (43).

In Europe, integrated farming systems have been developed as a less stringent alternative to organic farming (52). In these farming systems, crop rotations are longer than in conventional farms, use of pesticides and fertilizers is minimized, disease-resistant varieties and disease forecasting systems are used when available, and use of organic amendments and biocontrol agents is recommended. Reduced tillage or no-till is also practiced on integrated farms in some areas (10,11,38). In the United States, reduced-input farming systems are similar to the integrated farming systems in Europe. In this paper, the terms integrated and reduced-input are considered synonyms and will be used interchangeably. Alternative farming systems will be used as a collective term for reduced-input or integrated farming systems as well as for organic and biodynamic farming systems.

Although it is by no means certain in which direction conventional farming systems will change, it is likely that profound changes will occur in cropping patterns, the use of organic amendments, tillage practices, and the use of synthetic fertilizers and pesticides. Potential effects of these practices on disease development can in part be gleaned from research on the effects of individual practices in conventional farms or experiment stations. However, these effects will need to be verified in comparative studies of different agricultural systems on experiment stations or on conventional and alternative farms. Since there are few reports on plant diseases in conventional vs. alternative farming systems, I will first give an overview of potential differences in disease development based on research into effects of individual cultural practices on plant disease before discussing the differences that were actually observed in comparative farming systems studies.

Cultural Practices and Plant Disease

In recent decades, crop rotations have become shorter, and field and farm sizes have increased to such an extent that large-scale monocropping is becoming the rule rather than the exception. Moreover, uniform hybrid cultivars of some crops are now grown at a regional scale. Intensive cropping systems, in particular monocropping, favor epidemic development of many plant diseases caused by fungi, bacteria, nematodes, and viruses (1,16,34,48,51). Moreover, plant growth can be retarded by deleterious rhizosphere bacteria, which become more prominent with increased frequency of certain crops (for example, potato and cereal crops) in the same field (34,44). On the other hand, long-term monocropping has led to a decline in several soilborne diseases, for example those caused by *Gaeumannomyces graminis* var. *tritici*, *Rhizoctonia solani*, and even by the nematode *Heterodera avenae* (reviewed in 3). When disease decline develops after monocropping, suppression is usually due to a specific interaction between a plant pathogen and its antagonist rather than to competition for nutrients (3).

In alternative farming systems, crop diversity is generally greater in both time and space than in the current conventional systems. Intra- or interspecific crop mixtures and the use of barrier or cover crops can curb epidemic spread of some plant diseases (51). Similarly, long crop rotations can keep many soilborne diseases under control, including fungus- and nematode-transmitted virus diseases (51). On the other hand, organic farming systems often have smaller fields surrounded by riparian habitat, which may harbor viruses and their vectors. Smaller fields can be more easily invaded by nonpersistent viruses than large fields, while the reverse is true for persistent viruses (51).

Dr. van Bruggen's address is: Department of Plant Pathology, University of California, Davis 95616; E-mail: AHVANBRUGGEN@UCDAVIS.EDU

To reduce soil erosion, minimum- or no-till soil cultivation is recommended instead of plowing or disking. These changes in tillage may lead to increased disease severity by pathogens that survive better when infested crop debris remains on or near the soil surface. For example, tan spot and Septoria blotch on wheat caused by *Pyrenophora tritici-repentis* and *Phaeosphaeria nodorum*, respectively, can be more severe in reduced-till or no-till wheat production, depending on the previous crop in the rotation (50,56). Moreover, soilborne root diseases can be exacerbated if a cash crop is planted too soon after strip-application of herbicides in a green manure crop or strip-tillage of stubble from the previous crop (4). However, this potential problem can be alleviated by using proper crop rotations and allowing sufficient time for decomposition of organic debris before planting (4).

In many areas of the world (except for areas with intensive animal husbandry), organic amendments have not been used extensively since the advent of synthetic fertilizers. Use of winter cover crops to prevent leaching of nitrate into the groundwater would imply an increase in organic amendments. Similarly, composting and redistribution of manure (rather than disposing of excessive manure on limited areas of land) will promote more equitable utilization of this organic resource. Finally, to reduce the pressure on landfills, organic urban waste is increasingly recycled, partially in the form of compost. All these factors contribute to an expected increase in the on-farm use of organic amendments in the near future.

The effect of amendments on disease severity depends on the type of material used, its C:N ratio, and the time elapsed since incorporation (3,21). Many plant pathogens are facultative saprophytes and can compete quite well with the soil microflora for colonization of fresh organic matter. If a cash crop is planted too soon after incorporation of a cover crop, the cash crop may succumb to seedling damping-off caused by *Pythium* or *Rhizoctonia* (3). On the other hand, regular additions of organic amendments may lead to induced disease suppression (20,21). Suppressive soils generally have a more active soil microflora than do conducive soils, but the exact mechanisms of disease suppression are not fully understood (20). Increased organic substrate will enhance 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 (9,13). Primary decomposers can act as antagonists of plant pathogens by competition for nutrients, antibiosis, and parasitism, while the micro- and mesofauna can contribute to control of plant pathogens by predation. For example, *Rhizoctonia solani* can be partially controlled by predatory activity of mycophagous nematodes or collembola (2,28). Furthermore, earthworm populations can be enhanced by organic amendments. A reduction in *Rhizoctonia* bare patch disease on wheat was associated with the presence of earthworms (49). The mechanisms underlying this suppression of *Rhizoctonia* bare patch are not known. Both increased microbial activity and improvement in soil structure after repeated application of organic amendments may have contributed to the reduction in this disease. Similarly, increased microbial activity and improved soil structure may have contributed to a reduction in Phytophthora root rots following application of organic amendments (30).

Excessive use of nitrogen fertilizers has frequently led to unacceptably high nitrate concentrations in ground- and drinking water. In many areas, growers are strongly encouraged to reduce fertilizer applications to curb nitrate contamination. It has long been known that nitrogen can have a profound effect on disease severity. Several biotrophic fungal pathogens, such as those causing rust and powdery mildew diseases, are enhanced by high levels of nitrogen, in particular in the form of nitrate (22). Similarly, many bacterial diseases are promoted by high nitrogen levels (22). Plants high in nitrogen also support large aphid or leafhopper populations and are often more susceptible to virus infection (51). Besides a direct effect on disease development, ammonium-containing fertilizers can have an indirect effect by lowering the pH in the rhizosphere and bulk soil. In turn, the lower pH can increase susceptibility to certain diseases, for example Fusarium wilt (25).

Until recently, pesticide use increased almost exponentially, with the largest increase occurring in herbicide use (23,36). This trend may continue for herbicide use, in view of the expansion of no-tillage practices. On the other hand, there is already a downward trend in the use of other pesticides. Several European countries have enacted legislation to reduce the use of pesticides, in many cases down to 50% of the pesticide use in the 1980s (23). In the United States, the use of soil fumigants, in particular methyl bromide, is expected to be curbed or even banned. The use of soil-applied insecticides and nematicides is also expected to be reduced. These expected changes in pesticide use will have a profound effect on plant disease development. A reduction in soil fumigants does not necessarily need to result in an increase in root diseases if basic cropping practices (such as the use of resistant varieties, crop rotation, and the addition of organic amendments) are also changed (see below). Besides effects on target organisms, pesticides often also have unintended side effects on other organisms, resulting in either enhanced or reduced plant disease. Herbicides, for example, can have both positive and negative effects on plant pathogen–host interactions (29). However, the best documented effect is a predisposition of plants to root pathogens by sublethal doses of various herbicides (29). Since herbicides are not used in organically grown crops, this could be one of the reasons for a reduction in root diseases in organic compared to conventional farms.

Although effects of individual agricultural practices on disease development, as studied in conventionally managed experiment stations or farms, can give an indication of potential changes in epidemic development in alternative farming systems, the combined effects of all of these practices would need to be studied in large-scale farming system experiments or on commercial farms.

Comparative Studies of Farming Systems

Farming systems are compared by two fundamentally different approaches: field experiments simulating different farming practices and surveys of commercial farms (46). In the first approach, plot sizes can be as large as whole fields with little or no replication (5,6,31) or smaller with the appropriate number of replications (17,27,45). The disadvantage of small-scale experiments is that realistic assessment of community level interactions such as insect pests and their parasitoids or epidemic development of foliar diseases is difficult (46). Time- and space-dependent factors such as long-term crop history, habitat and soil management regimes, cumulative effects of pesticide applications, and border effects of surrounding vegetation cannot be duplicated in experiment station plots (46). Experimental comparative studies are usually short term (generally less than 10 years) so that the ecological community structure is still in a transition phase when observations are being made. In particular, the soil microbial community is still changing during the first 4 to 5 years after major changes in farming practices (45).

On-farm comparative studies have the advantage of encompassing many different cultural practices, all considered integral parts of conventional or alternative farming in a realistic setting. Another advantage of on-farm comparisons is that a dynamic equilibrium with respect to soil biological properties has been established on farms that have followed consistent management practices for at least 5 years (45). On the other hand, due to the large number of variables that differ simultaneously between the different farming systems, cause and effect relationships cannot be determined in on-farm studies.

As a result of the general interest in developing alternative, more sustainable farm the ecological sense) agricultural systems, many experimental and on-farm comparative studies were conducted in the last two decades. In addition to these recent studies, there is also a renewed interest in the long-term agricultural research plots that were established in the nineteenth century in Europe and the United States. Particularly noteworthy are the Rothamsted Classical Experiments in England (notably the Broadbalk wheat experiment), the Morrow plots in Illinois, the Sanborn field in Missouri, the Magruder plots in Oklahoma, and the Old Rotation plots in Alabama. The treatments in these experiments consist of various combinations of fertilization, manure, and rotations applied in large, nonreplicated fields (24,31). These treatments are directly relevant to various questions concerning sustainability of agricultural production. Thus, both the long-term field plots and the more recently established farming systems experiments provide unique opportunities to compare trends in soil characteristics, plant productivity, pests, and diseases in relation to the biological communities established as a result of the different treatments.

Although numerous differences between conventional and alternative farming systems have been published, very little research has been done on plant diseases in those systems (5,11,18,37). With few exceptions, plant pathologists have been conspicuously absent from [illegible] comparative studies (31,34). In the Rothamsted long-term experiments, [illegible] plots with monocultures, for example those in potato, had to be abandoned, presumably due to diseases (24). Some of the observations on diseases of wheat in the Broadbalk long-term experiment with different fertilization and rotation treatments were summarized in 1969 (16). Recently, Olsson compared root diseases on barley, in particular those caused by *Pythium arrhenomanes* and deleterious rhizosphere bacteria, in three long-term cropping frequency experiments (34).

Among comparative studies initiated in the last two decades, plant diseases were

Table 1. Relative disease severity[a] in organic, integrated, and conventional farms

Experiment	Crop	Disease	Pathogen	Org.	Int.	Conv.	Ref.
DFS[b]	Wheat	Stripe rust	*Puccinia striiformis*	1	2	2	(5)
	Wheat	Leaf rust	*Puccinia recondita*	1-2	1-2	1	
	Wheat	Powdery mildew	*Erysiphe graminis*	0-1	2	2	
	Wheat	Leaf blotch	*Mycosphaerella graminicola*	2	2-3	2-3	
	Wheat	Glume blotch	*Leptosphaeria nodorum*	1	1	1	
	Wheat	Snow mold	*Gerlachia nivalis*	1	2	2	
	Wheat	Sharp eyespot	*Rhizoctonia cerealis*	1	2	2	
	Wheat	Eyespot	*Pseudocercosporella herpotrichoides*	1	1-2	1-2	
	Wheat	Brown foot rot	*Fusarium* spp.	2	2-3	2-3	
Lautenbach[c]	Wheat	Powdery mildew	*Erysiphe graminis*	...[d]	2-1[e]	1-2	(11)
	Wheat	Leaf rust	*Puccinia recondita*	...	1-2	1-2	
	Wheat	Glume blotch	*Leptosphaeria nodorum*	...	1-2	1	(10)
	Wheat	Eyespot and foot rot	*Pseudocercosporella herpotrichoides*	...	1-2	2	(11)
	Wheat	Brown foot rot	*Fusarium* spp.	...	1-2	1-3	(10)
	Sugar beet	Damping-off	Unspecified	...	2	3	(11)
Rheinland[f]	Wheat	Powdery mildew	*Erysiphe graminis*	1-2	...[g]	3	(36)
	Wheat	Leaf spot, glume blotch	*Leptosphaeria nodorum*	1	...	2-3	
	Wheat	Foot rots	*Fusarium* spp.	2-3	...	3	
			Rhizoctonia cerealis	2-3	...	3	
			Pseudocercosporella herpotrichoides	2-3	...	3	
	Rye	Leaf blotch	*Rhynchosporium secalis*	2-3	...	2	
	Rye	Leaf rust	*Puccinia dispersa*	2-3	...	1	
	Rye	Foot rots	*Fusarium* spp.	1-2	...	2	
			Rhizoctonia cerealis	1-2	...	2	
			Pseudocercosporella herpotrichoides	1-2	...	2	
	Potato	Late blight	*Phytophthora infestans*	3	...	1	
Suitia[h]	Wheat	Powdery mildew	*Erysiphe graminis*	1	...	3	(18)
	Wheat	Leaf spot and					
	Wheat	Glume blotch	*Leptosphaeria nodorum*	2	...	2	
	Wheat	Stripe rust	*Puccinia striiformis*	2	...	2-3	
	Wheat	Leaf rust	*Puccinia recondita*	1	...	1	
	Wheat	Foot rots	*Fusarium* spp.	2	...	2-3	
	Wheat	Take-all	*Gaeumannomyces graminis*	3	...	1	
	Barley	Net blotch	*Pyrenophora teres*	1	...	1	
	Barley	Scald	*Rhynchosporium secalis*	1	...	1	
	Barley	Leaf rust	*Puccinia recondita*	1	...	1	
	Barley	Damping-off	*Bipolaris sorokiniana*	2	...	1	
	Barley	Foot/root rots	*Fusarium* spp.	1-2	...	2-3	
	Barley	Root rot	*Gaeumannomyces graminis*	1-2	...	1-3	

[a] 0 = none, 1 = low, 2 = moderate, 3 = severe, summarized from several years of observations.
[b] Development of Farming Systems at Nagele, the Netherlands; not replicated, 2 or 3 years of observations; fungicides applied in both conventional and integrated farming systems.
[c] Plant Protection Service, Baden-Wuerttemberg, Germany; not replicated, 4 or 5 years of observations; fungicides rarely applied in the integrated farming system.
[d] Organic treatment not included.
[e] In the first 4 years, higher in integrated than in conventional fields, subsequently lower in integrated fields.
[f] Conversion study from a conventional to a biodynamic farm, compared with a conventional farm near Moers, Germany; not replicated, 5 years of observations; no fungicides applied in biodynamic farm.
[g] Integrated treatment not included.
[h] Field experiment with four cropping systems at Suitia, Finland; three replications, 2 or 3 years of observations; no foliar fungicides applied in either system; seed treatments in conventional system; organic fields were drained less well than conventional fields (17).

compared at the seven locations. Four of these are experimental studies in Europe, namely the Development of Farming Systems project with an organic, integrated, and conventional farm at Nagele, the Netherlands; the Lautenbach and Rheinland conversion studies (integrated and biodynamic farming, respectively, compared to conventional farming) in Germany; and the Suitia experiment with four organic and conventional cropping systems in Finland (Table 1). Another experimental study (the Sustainable Agriculture Farming Systems or SAFS project) was initiated in 1989 at Davis, California (Fig. 1). This experiment entails comparisons of organic, reduced-input, and conventional farming practices in 4-year rotations of tomato–safflower–corn–wheat/bean. The organic and reduced-input rotations also include annual winter cover crops of oat/vetch. An additional conventional treatment is a 2-year rotation of wheat and tomato (45). Recently, soilborne plant pathogens were compared in the different treatments.

Two comparative studies were conducted on existing farms. The first was a well-known study on *Phytophthora cinnamomi* on avocado in Australia (although it is not generally recognized that the suppressive soils in this study were located on organic farms) (30). The second location is in the Central Valley of California, where we compared tomato root diseases in a 2-year survey of organic and conventional tomato fields (55).

Foliar and Stem Diseases

In most of the locations where foliar diseases were observed, stripe rust, powdery mildew, and snow mold (when observed) of wheat were less severe in organic or integrated fields than in conventional fields (Table 1), despite fungicide applications in the conventional fields (5,11,18,37). Increased disease severity in conventional fields was often associated with higher nitrogen fertilization and use of haulm shorteners, resulting in a denser canopy. Other foliar diseases, such as leaf rust of wheat, barley, or rye, leaf blotch and glume blotch of wheat and rye, and net blotch and scald of barley, were often similar in the different farming systems (5,10,18,37). This group of diseases was sometimes slightly more severe in organic or integrated fields, which may be related to inoculum survival in crop residues if these are not turned under in organic or integrated systems (10). The only foliar disease that was significantly more severe in organic fields was late blight of potato. This difference was attributed to the absence of effective fungicide sprays in a biodynamic farm (37).

In the long-term fertilizer and crop rotation experiment at Broadbalk, powdery mildew was enhanced by high-nitrogen fertilizer applications (16). Differences between farmyard manure and synthetic fertilizers were not reported.

Soil Environments

Since the development of root diseases is profoundly affected by the physical, chemical, and biological soil environment, I will first discuss differences reported in soil environment between conventional and alternative farming systems before proceeding with a discussion of root diseases in those systems.

Both experimental and on-farm comparisons indicate that different management practices can result in qualitatively different soil environments (6,38,40). Organic and reduced-input farming systems were found to have a thicker topsoil layer, lower soil bulk density, and greater water-holding and cation-exchange capacity than conventional systems. Soil nitrate content tends to be lower (6,8) and nitrogen mineralization rate higher in organic and reduced-input systems than in conventional systems. Calculations of nitrogen flows in organic or conventional farming systems showed increased internal cycling and reduced nutrient losses in organic systems (3). The organic matter content and associated microbial biomass and activity are generally higher in organic production systems (6,14,38), partly due to return of organic matter to the system in the form of cover crops and manure, partly as a result of erosion control.

The rhizosphere microflora of organic or integrated farms was compared to that of conventional farms in only a few studies. Populations of spores of vesicular-arbuscular mycorrhizae (VAM) and VAM colonization of roots of wheat, maize, soybean, and rye were consistently lower on conventional farms than on organic or integrated farms in studies in Australia, the

Fig. 1. Aerial photograph of the Sustainable Agriculture Farming Systems (SAFS) field plots at the University of California at Davis in the summer of 1989. There are four blocks with 14 plots of 0.12 ha each. The treatments are organic, low-input, and conventional (high-input) with 4-year rotations (tomato, safflower, corn, and wheat or beans), and conventional with 2-year rotations (tomato and wheat). All entries into the rotations are represented each year. In addition to cash crops in the rotation, winter cover crops (a vetch/oats mix) are grown annually in the organic and low-input plots. Dark green is corn, lighter green is tomato, white is wheat, and yellow is safflower.

United States, and Europe (7,41,42). The differences were associated with differences in soluble phosphorous levels in soil as a result of the extensive use of fertilizers containing soluble phosphorous in conventional farms (41,42). Differences in vegetative diversity due to narrower crop rotations and use of herbicides in conventional farms could also have contributed to differences in VAM colonization (7,42).

Sivapalan et al. (47) monitored changes in soil populations of fungi, bacteria, and actinomycetes during conversion to organic farming in relation to populations of these organisms in a conventionally farmed area in Australia. Populations of total fungi and bacteria were significantly higher in the organically farmed areas. Fluorescent pseudomonads and actinomycetes were more numerous in the organically farmed areas at three of the five sampling dates. Species diversity of fungi was also higher in the organic than in the conventional soil. Similarly, the diversity of fungal genera isolated from roots of five continuously monocropped crops was lower than that of the same crops grown in rotation in a Japanese study (33). Fungal diversity was increased when farmyard manure or crop residues were added to monocropped or rotation fields.

We compared the abundance and diversity of actinomycetes, bacteria, and fungi isolated from rhizospheres of tomato plants grown in soil samples from three organic and three conventional farms with similar soil types in the Central Valley of California (54). Total numbers of actinomycetes, numbers of fluorescent pseudomonads, and proportions of cellulolytic and hemicellulolytic actinomycetes and of chitinolytic fungi were higher in organically than conventionally managed rhizosphere soils (Table 2). Communities of functional groups of actinomycetes and bacteria (in terms of ability to hydrolyze several substrates) were more similar among samples with the same soil management than between different soil management types, indicating functional homogeneity within a farming system. The differences observed between communities from organic and conventional soils were mainly in the percentages of cellulolytic and hemicellulolytic actinomycetes, possibly due to recent additions of cellulosic and hemicellulosic materials in the form of green manure or compost on organic farms, which would encourage rapid multiplication of actinomycetes (26). Besides total populations and composition of actinomycete and bacterial communities, the diversity of actinomycetes was also higher in soils from organic than from conventional farms (54).

Increased diversity of soil fauna in organic or reduced-input farming systems has also been demonstrated in some studies (9–11), and greater abundance and biomass of the soil fauna in many other studies (9,12,13). In particular, the numbers and biomass of earthworms, protozoa, collembola, predatory nematodes and mites, and carabid beetles were increased in several organic or integrated farming systems relative to conventional systems. The differences between individual groups varied, depending on the systems under study. The most important factors affecting the soil fauna seemed to be the quantity and quality of organic matter input (9,13), because only slight differences were found when animal manure was applied in both organic and conventional systems (13). Another factor that greatly affected the soil fauna was soil tillage, with a richer soil fauna in no-till or reduced-tillage, low-input fields than in plowed, high-input fields (9,12). Finally, greater differences were found in more arid regions than in humid regions due to improved soil structure and water-holding capacity in organic farms than in conventional farms, in particular in arid regions (13).

All these changes in soil physical and biological properties in organic or integrated relative to conventional farms will affect incidence and severity of root diseases and injuries caused by fungi, bacteria, or nematodes.

Foot and Root Diseases

Over a period of more than 100 years in the Broadbalk experiment, eyespot (*Pseudocercosporella herpotrichoides*) and take-all (*Gaeumannomyces graminis* var. *tritici*) were more severe after monocrops of wheat than after fallow or other rotation crops. Take-all severity declined after the fourth year of wheat but was still more severe than after fallow (16). Eyespot, brown foot rot (*Fusarium* spp.), and sharp eyespot (*Rhizoctonia cerealis*) were more severe in the well-fertilized plots (with farmyard manure or synthetic fertilizer). In contrast to the expectations, little difference was observed between plots that received farmyard manure and those that received synthetic fertilizers (16). In other long-term crop rotation experiments in Sweden, barley root rot caused by *Pythium arrhenomanes* and "retarded root growth" caused by deleterious rhizobacteria were significantly more severe in fields that were monocropped for at least 20 years than in rotation fields (34).

In the more recently initiated comparative studies in Europe (Table 1), sharp eyespot and eyespot on wheat and various foot rots on wheat, rye, and barley were enhanced in conventional farming systems (5,10,11,18,37). Damping-off of sugar beet was also more severe in a conventional farm (11). On the other hand, take-all and root rot of wheat caused by *Gaeumannomyces graminis* and damping-off of barley caused by *Bipolaris sorokiniana* were more severe in the organic plots of the Suitia experiment (18). However, these plots were located in areas that were less well drained than their conventional counterparts (17). The mechanisms underlying differences in disease severity between conventional and organic or integrated farming systems were not investigated in any of these studies. Daamen (5)

Table 2. Populations and diversity of fungi, actinomycetes, and bacteria isolated on various media from organically and conventionally managed rhizosphere soils from commercial farms in the Central Valley of California, and microbial activity and suppression of corky root of tomato (*Pyrenochaeta lycopersici*) in the same soils (summarized from reference 54)

Variable	Farming system: Organic (n=3)	Farming system: Conventional (n=3)	Significance[a]
Total CFU (×10⁴/g of dry soil)			
Fungi[b]	2.4	2.0	
Actinomycetes[c]	9.6	4.4	**
Bacteria[d]	42.3	41.1	
Fluorescent pseudomonads[e]	5.5	1.4	*
Diversity index[f] for functional groups			
Fungi	1.1	1.3	
Actinomycetes	1.5	1.0	**
Bacteria	1.3	1.3	
Microbial activity[g]	1.0	0.2	**
Suppression of corky root of tomato[h]	67.7	41.4	**

[a] *, $0.01 < P >= 0.05$, **, $P =< 0.01$ in *t* tests.
[b] Averages for isolations on Czapek's, chitin, and cellulose agar.
[c] Averages for isolations on water, chitin, and cellulose agar.
[d] On 10% trypticase soy agar.
[e] On King's B agar.
[f] Shannon Weaver diversity index for functional groups based on the ability to hydrolyze cellulose, chitin, pectin, starch, and xylan, as determined from the formation of a clear zone (>1 mm width) surrounding colonies on agar media amended with the respective substrates.
[g] Micrograms of hydrolyzed fluorescein diacetate (FDA) per g of dry soil per min.
[h] Percent reduction in corky root severity in nonirradiated soil compared to irradiated soil after addition of microsclerotia of *P. lycopersici*.

ascribed the greater incidence of Fusarium foot rot in conventional compared to integrated or organic fields to the use of a fungicide seeddressing at the conventional farm, which may have had a negative impact on antagonists. However, other factors such as differences in nutritional status of the crops or soil microbial activity cannot be excluded.

Recently, the effects of farming practices on soilborne pathogens have been studied in the SAFS experiment at Davis, California. In the first 4 years of the project, significant differences developed in soil microbiological and microfaunal characteristics (45). *Rhizoctonia solani* and *Verticillium dahliae* populations were monitored once a month in all fields that were cropped with tomato in the summer season. Five years after initiation of the experiment, populations of both pathogens were significantly greater in the conventional than in the organic and reduced-input plots at the end of the tomato growing season (27; M. Bolda, R. Guzman-Plazola, and J. J. Marois, *personal communication*).

A well-known example of disease suppression in organic farms is that of avocado root rot (*Phytophthora cinnamomi*) in Australia. High levels of organic matter were maintained in the surface layer of the orchard soil by green manuring with legumes and forage crops and the addition of manure and straw (30). The main mechanism for disease suppression was the increased microbial activity resulting in enhanced lysis of hyphae by bacteria and actinomycetes. The predatory activity of the microfauna, in particular by various amoebae, was also enhanced in soils high in organic matter. Conducive soils contained similar amoebae but at much lower densities (30).

In 1989 and 1990, we conducted a comparative study of 19 tomato farms ranging in management practices from conventional to transitional (less than 3 years organic) to longer term organic (up to 10 years). Disease severity was generally low. The only diseases commonly observed were corky root caused by *Pyrenochaeta lycopersici* (Fig. 2) and Phytophthora root rot caused by *Phytophthora parasitica* (55). Corky root was less severe in organic than in conventional farms, and was intermediate in transitional farms (55). Although *Phytophthora parasitica* was present in many soil samples, as determined by a leaf baiting technique, Phytophthora root rot occurred only in conventional farms and one transitional farm that had used organic practices for less than 3 years. Discriminant analyses for both years combined with 11 soil and plant parameters and disease severity as a classification variable resulted in significant separations between disease severity classes that corresponded well with farm type (Fig. 3). The variables that were consistently related to corky root severity were soil nitrate and tissue N, both positively correlated with disease severity, and N mineralization potential or microbial activity (fluorescein diacetate or FDA hydrolytic activity), negatively correlated with disease severity. Populations of *Phytophthora parasitica* in soil were positively associated with clay content, water-stable aggregates, soil nitrate concentration, electrical conductivity, and soil water content, while they were negatively associated with soil organic carbon content. Clay content and water-stable aggregates were also positively associated with Phytophthora root rot severity. These soil variables were slightly greater in some conventional farms than in the organic farms and were unrelated to farming practices. In summary, variables associated with corky root severity reflected plant and soil nitrogen status and biological characteristics of the soil, whereas variables associated with *Phytophthora parasitica* mostly reflected soil physical and chemical rather than biological characteristics (55).

A negative association between microbial activity and corky root severity indicated that biological disease suppression could be operating in organically managed soils. This hypothesis was confirmed in controlled experiments using irradiated and nonirradiated potted soil from organic and conventional farms infested with microsclerotia of *Pyrenochaeta lycopersici*. The increase in disease severity in irradiated soil compared to natural soil was significantly higher for organically managed than for conventionally managed soils and was positively correlated with microbial activity (53). These results indicated that biological entities were probably involved in disease suppression in nonirradiated, organically managed soils (53). In additional studies, suppression of corky root proved to be associated with greater numbers of total actinomycetes and cellulolytic actinomycetes in organically managed soils (Table 3). There were also associative trends between the number of fluorescent pseudomonads or chitinolytic fungi and suppression of this disease (Table 3). The correlations of total actinomycete population and cellulolytic actinomycetes with corky root suppression suggest that actinomycetes may have played a role in disease suppression. Actinomycetes were shown to be associated with suppression of various other plant diseases (20). Hydrolysis of chitin may also play a role in corky root suppression, since cell walls of the majority of plant pathogenic fungi contain chitin. There are several reports of the association of chitin-hydrolyzing fungi with suppression of plant diseases (19,20). Besides the abundance of particular functional groups of microorganisms, actinomycete diversity was also positively correlated to corky root suppression (54). In the Japanese study mentioned above, the incidence of brown stem rot of adzuki bean caused by *Acremonium gregatum* was negatively correlated with fungal diversity in the rhizosphere, which was greater in soils amended with farmyard manure or crop residues and reduced applications of synthetic fertilizers (33).

In addition to biological disease suppression on the organic farms we studied, lower nitrogen concentrations in tomato plants from these farms may have rendered the plants more resistant to corky root. Greenhouse studies with organically and conventionally managed soils infested with microsclerotia of the pathogen indicated that both mechanisms—increased natural biological control and reduced host susceptibility due to lower nitrogen concentrations in tomato tissue—were involved in corky root suppression in organically managed soil (53).

Root-Feeding Nematodes

Plant parasitic nematodes, in particular *Heterodera avenae* and *Ditylenchus dipsaci*, were significantly more numerous in conventional than in integrated fields at Lautenbach in Germany (9). One possible explanation is the significantly larger populations of predatory mites and nematodes in the integrated fields, since crop rotations were the same in the two farming systems. The abundance of plant parasitic nematodes was also consistently higher in conventional than in organic or reduced-input plots of the SAFS project, even 3 to 4 years after initiation of this experiment (27,45). However, none of the plant parasitic nematodes reached damaging levels in the initial phase of this project (27), probably due to the different host status of the crops in rotation in relation to the nematodes present at the site.

Conclusions and Outlook

In the comparative studies reviewed in this paper, root diseases and pests were generally less severe or similar in organic or reduced-input farms, while some foliar diseases were less severe and others more severe in organic or reduced-input than in conventional farms (5,11,18,37). The main reason why differences in foliar diseases are more variable than differences in root diseases may be that foliar disease development is much more determined by climatic and weather factors than by antagonistic or parasitic interactions on the leaf surface, while the reverse is true for root disease development. It is therefore more difficult to control foliar diseases than root diseases by biological or cultural means. However, foliar diseases that are enhanced by nitrogen fertilization would be reduced when fertilizer use is diminished or abandoned (as in organic agriculture). For other foliar diseases such as late blight, fungicide use could be reduced if forecasting systems were adopted, as is the case in integrated farming systems in Europe (5,11), but it would be difficult to eliminate fungicide use altogether without substantial yield losses. Thus, I expect that certain foliar diseases will constitute a problem in organic farming in humid climates. This is one reason why Pimentel (35) expected that yields of fruits and vegetables would be lower under organic production than under conventional production, whereas this would not be so for grain crops. This may be true for humid climates, but we demonstrated that yields of fresh market tomatoes were equal in both farming systems in arid climates such as California (8).

The consistent reduction in root disease severity in organic and reduced-input compared to conventional farms can be ascribed to longer rotations, regular applications of organic amendments, and abstinence from or reductions in pesticide use. Reduced tillage, which can result in increases in root diseases caused by *Rhizoctonia* species in conventional agriculture (4), did not pose a problem in integrated farming systems as long as other cultural practices such as appropriate rotations and use of organic amendments were implemented (11). The exact mechanisms of root disease control in organic and integrated farming systems are not known. However, it is generally assumed that organic amendments reduce root diseases by increasing the general level of microbial activity, resulting in increased competition and/or antagonism in the rhizosphere. The reduction in VAM infection of roots in conventionally compared to organically managed soils (7) may also contribute to the increase in root diseases observed in conventionally managed soils. Relatively little attention has been paid to the role of the soil fauna in disease suppression. Since there are such striking differences in soil fauna between organic and conventional farming systems (9,13), plant pathologists need to collaborate with nematologists and soil ecologists to study the role of the soil fauna in disease suppression.

Another aspect that has been neglected in comparative studies of organic and conventional farming systems is the incidence of virus diseases. Since many virus diseases spread at a regional scale, studying these diseases in experimental plots is not very meaningful. The effects of farming practices on virus diseases would therefore need to be addressed in systems-level research on commercial farms. Potential problems with confounding [illegible] could be overcome by selecting [illegible] farms with a similar climate and [illegible]ing habitat (46).

Systems-level research will be important to understanding the ramifications of the whole complex of cultural practices, not only for virus diseases but also for other foliar and root diseases. Farming systems research with farmer participation is essential to devise appropriate management strategies for alternative agricultural systems. Changes in agricultural practices will not be implemented if each of us is recommending an individual solution to an isolated problem. Truly interdisciplinary research will be needed rather than disciplinary or even multidisciplinary research (46).

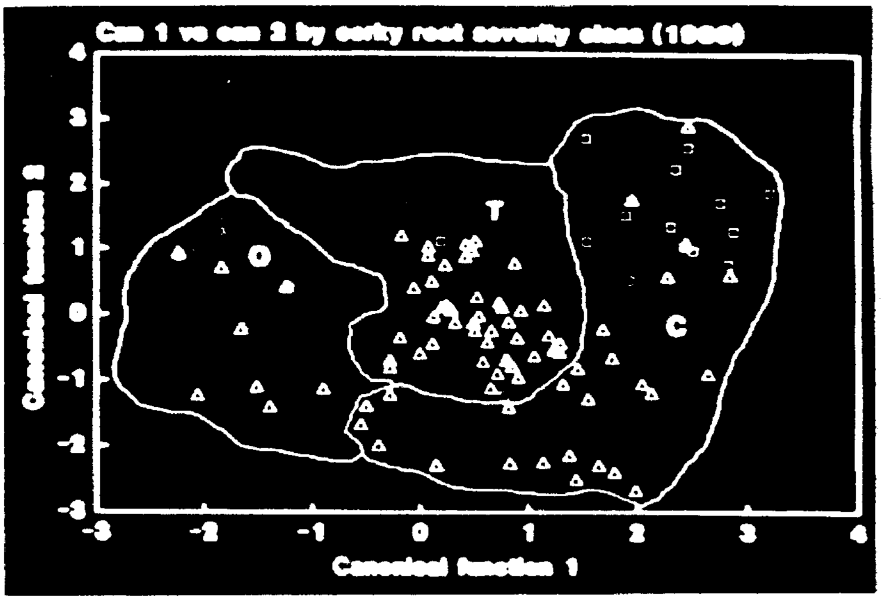

Fig. 3. Plot of the second and first canonical functions discriminating among three corky root (*Pyrenochaeta lycopersici*) severity classes (0%, red circles; <5%, yellow triangles; >5%, green squares), based on 10 soil variables and tissue nitrogen measured on individual soil and plant samples. Nitrogen mineralization potential, microbial activity, nitrogen content in tomato tissues, and soil nitrate concentration contributed most to the distinction between corky root severity classes. The lines indicate the grouping by farm type (O = organic, T = transitional, and C = conventional). (Courtesy F. Workneh)

Fig. 2. Typical symptoms of corky root of tomato caused by *Pyrenochaeta lycopersici*. Note the banded root lesions with a corky appearance. (Photograph by R. N. Campbell)

Table 3. Correlations of microbial activity, populations of actinomycetes, cellulolytic actinomycetes, fluorescent pseudomonads, and chitinolytic fungi (isolated from organically and conventionally managed rhizosphere soils), and actinomycete diversity[a] with suppression of corky root of tomato[b] (*Pyrenochaeta lycopersici*) (summarized from reference 54)

Microbial activity and populations	*r*	Significance[c]
Microbial activity	0.96	0.01
Total actinomycetes	0.89	0.02
Cellulolytic actinomycetes	0.84	0.04
Actinomycete diversity	0.89	0.02
Fluorescent pseudomonads	0.70	0.14
Chitinolytic fungi	0.71	0.12

[a] For explanations of the measured variables see Table 2.
[b] Relative reduction in corky root severity (percent root length infected) in natural field soil compared to corky root severity in gamma-irradiated soil.
[c] Significance level.

Unfortunately, there are several constraints to interdisciplinary, systems-level research. Private companies are generally not inclined to fund this kind of research. Commodity groups are only interested in their own commodity, not in rotation or companion crops. Funding from federal agencies is generally restricted to short-term, mechanistic rather than holistic research, except for the USDA Sustainable Agriculture Research and Education (SARE) program, which controls only a minor portion of the USDA funds. Moreover, there is relatively limited expertise and interest among researchers in integrated holistic research. Interdisciplinary research is challenging and does not result in many quick publications. So this kind of research is risky for untenured faculty and graduate students who need to finish a thesis in 3 or 4 years. However, personally I believe it is worth the effort. The results obtained from systems-level interdisciplinary research, be it in large experimental plots or on commercial farms, are directly relevant to the development of ecologically sustainable agricultural systems. Comparison of disease suppression and the associated ecological factors in different farming systems could be used as a tool to answer basic agroecological questions. In turn, answers to these basic questions would be more helpful in designing alternative farming systems than results of single-factor controlled experiments would be.

Acknowledgments

I thank Diana Friedman, Bob Campbell, and Fekede Workneh for supplying slides for Figures 1, 2, and 3, respectively. I thank Nik Grunwald, Howard Ferris, and two anonymous reviewers for reviewing the text. I also thank Laurie Drinkwater, Deborah Letourneau, Carol Shennan, Fekede Workneh, and many collaborating organic and conventional growers for the opportunity to conduct truly interdisciplinary farming systems research.

Literature Cited

1. Alvarez, J., Datnoff, L. E., and Nagata, R. T. 1992. Crop rotation minimizes losses from corky root in Florida lettuce. HortScience 27:66-68.
2. Barnes, G. L., Russell, C. C., Foster, W. D., and McNew, R. W. 1981. *Aphelenchus avenae*, a potential biological control agent for root rot fungi. Plant Dis. 65:423-424.
3. Cook, R. J. and Baker, K. F. 1983. The Nature and Practice of Biological Control of Plant Pathogens. American Phytopathological Society, St. Paul, MN.
4. Cook, R. J., and Haglund, W. A. 1991. Wheat yield depression associated with conservation tillage caused by root pathogens in the soil not phytotoxins from the straw. Soil Biol. Biochem. 23:1125-1132.
5. Daamen, R. A., Wijnands, F. G., and van der Vliet, G. 1989. Epidemics of diseases and pests of winter wheat at different levels of agrochemical input. A study on the possibilities for designing an integrated cropping system. J. Phytopathol. 125:305-319.
6. Doran, J. W., Fraser, D. G., Culik, M. N., and Liebhardt, W. C. 1987. Influence of alternative and conventional agricultural management on soil microbial processes and nitrogen availability. Am. J. Alternative Agric. 2:99-106.
7. Douds, D. D., Janke, R. R., and Peters, S. E. 1993. VAM fungus spore populations and colonization of roots of maize and soybean under conventional and low-input sustainable agriculture. Agric. Ecosys. Environ. 43:325-335.
8. Drinkwater, L. E., Letourneau, D. K., Workneh, F., van Bruggen, A. H. C., and Shennan, C. 1995. Fundamental differences between conventional and organic tomato agroecosystems in California. Ecol. Applic. In press.
9. El Titi, A., and Ipach, U. 1989. Soil fauna in sustainable agriculture: Results of an integrated farming system at Lautenbach, F. R. G. Agric. Ecosys. Environ. 27:561-572.
10. El Titi, A., and Landes, H. 1990. Integrated Farming System of Lautenbach: A practical contribution toward sustainable agriculture in Europe. Pages 265-286 in: Sustainable Agricultural Systems. C. A. Edwards, R. Lal, P. Madden, R. H. Miller, and G. House, eds. Soil and Water Conservation Society, Ankeny, Iowa.
11. El Titi, A., and Richter, J. 1987. Integrierter Pflanzenschutz im Ackerbau: Das Lautenbach Projekt. III. Schaedlinge und Krankheiten 1979-1983. Z. Pflanzenkrankh. Pflanzenschutz 94:1-13.
12. Fan, Y., Liebman, M., Groden, E., and Alfred, A. R. 1993. Abundance of carabid beetles and other ground dwelling arthropods in conventional versus low-input bean cropping systems. Agric. Ecosys. Environ. 43:127-139.
13. Foissner, W. 1992. Comparative studies on the soil life in ecofarmed and conventionally farmed fields and grasslands of Austria. Agric. Ecosys. Environ. 40:207-218.
14. Fraser, D. G., Doran, J. W., Shas, W. W., and Lesoing, G. W. 1988. Soil microbial populations and activities under conventional and organic management. J. Environ. Qual. 17:585-590.
15. Gantzer, C. J., Anderson, S. H., Thompson, A. L., and Brown J. R. 1991. Evaluation of soil loss after 100 years of soil and crop management. Agron. J. 83:74-77.
16. Glynne, M. D. 1969. Fungus diseases of wheat on Broadbalk, 1843-1967. Rothamsted Exp. Stn. Rep. 1968, Part 2:116-136.
17. Hannukkala, A. O., Korva, J., and Tapio, E. 1990. Conventional and organic cropping systems at Suitia I: Experimental design and summaries. J. Agric. Sci. Finland 62:295-307.
18. Hannukkala, A. O., and Tapio, E. 1990. Conventional and organic cropping systems at Suitia V: Cereal diseases. J. Agric. Sci. Finland 62:339-347.
19. Henis, Y., Ghaffar, A., and Baker, R. 1979. Factors affecting suppressiveness to *Rhizoctonia solani* in soil. Phytopathology 69:1164-1169.
20. Hornby, D. 1983. Suppressive soils. Annu. Rev. Phytopathol. 21:65-85.
21. Huber, D. M., and Watson, R. D. 1970. Effects of organic amendments on soilborne plant pathogens. Phytopathology 60:22-26.
22. Huber, D. M., and Watson, R. D. 1974. Nitrogen form and plant disease. Annu. Rev. Phytopathol. 12:139-165.
23. Jansma, J. E., van Keulen, H., and Zadoks, J. C. 1993. Crop protection in the year 2000: A comparison of current policies towards agrochemical usage in four West European countries. Crop Prot. 12:483-489.
24. Jenkinson, D. S. 1991. The Rothamsted long-term experiments: Are they still of use? Agron. J. 83:2-10.
25. Jones, J. P., Engelhard, A. W., and Woltz, S. S. 1989. Management of Fusarium wilt of vegetables and ornamentals by macro- and microelement nutrition. Pages [illegible] in: Soilborne Plant Pathogens: Management of Diseases with Macro- and Microelements. A. W. Engelhard, ed. American Phytopathological Society, St. Paul, MN.
26. Kundu, P. K., and Nandi, B. 1985. Control of Rhizoctonia disease of cauliflower by competitive inhibition of the pathogen using organic amendments in soil. Plant Soil 83:357-362.
27. Lanini, T., Zalom, F., Marois, J., and Ferris, H. 1994. Researchers find short-term insect problems, long-term weed problems in low-input and organic systems. Calif. Agric. 48(5):27-33.
28. Lartey, R. T., Curl, E. A., and Peterson, C. M. 1994. Interactions of mycophagous collembola and biological control fungi in the suppression of *Rhizoctonia solani*. Soil Biol. Biochem. 26:81-88.
29. Levesque, C. A., and Rahe, J. E. 1992. Herbicide interactions with fungal root pathogens, with special reference to glyphosate. Annu. Rev. Phytopathol. 30:579-602.
30. Malajczuk, N. 1983. Microbial antagonism to *Phytophthora*. Pages 197-218 in: Phytophthora - Its Biology, Taxonomy, Ecology, and Pathology. D. C. Erwin, S. Bartnicki-Garcia, and P. H. Tsao, eds. American Phytopathological Society, St. Paul, MN.
31. Mitchell, C. C., Westerman, R. L., Brown, J.

Ariena H. C. van Bruggen

Dr. van Bruggen received her Ph.D. from Cornell University in 1985. She then worked in the environmental biology department of the Boyce Thompson Institute as a postdoctoral researcher. In 1986, she became an assistant and in 1993 an associate professor in vegetable pathology at the University of California at Davis. She recently received the Jakob Eriksson Award from the Swedish government for her work on corky root of lettuce caused by a new group of bacteria, and the Ciba Geigy Award from the American Phytopathological Society. Her current research interests are disease forecasting and sustainable agriculture in a collaborative project (Sustainable Agriculture Farming Systems) with soil scientists and nematologists at U.C. Davis.

R., and Peck, T. R. 1991. Overview of long-term agronomic research. Agron. J. 83:24-29.
32. National Research Council. 1989. Alternative Agriculture. National Academy Press, Washington, D.C.
33. Nitta, T. 1991. Diversity of root fungal floras: Its implications for soil-borne diseases and crop growth. Jpn. Agric. Res. Q. 25:6-11.
34. Olsson, S. 1995. On barley monoculture soil. Plant growth affecting microbiota in soil from three long-term field experiments on crop rotation. Ph.D. diss. Swedish University of Agricultural Sciences, Uppsala, Sweden.
35. Pimentel, D. 1993. Economics and energetics of organic and conventional farming. J. Agric. Environ. Ethics 6:53-60.
36. Pimentel, D., McLaughlin, L., Zepp, A., Lakitan, B., and Kraus, T. 1991. Environmental and economic effects of reducing pesticide use. BioScience 41:402-409.
37. Piorr, H. P., and Hindorf, H. 1986. The implication of plant disease and pests during the conversion from conventional to biological agriculture. Pages 421-435 in: The Importance of Biological Agriculture in a World of Diminishing Resources. H. Vogtmann, E. Boehncke, and I. Fricke, eds. Verlagsgruppe Witzenhausen, Germany.
38. Reganold, J. P. 1988. Comparison of soil properties as influenced by organic and conventional farming systems. Am. J. Alt. Agric. 3:144-154.
39. Reganold, J. P., Elliott, L. F., and Unger, Y. L. 1987. Long-term effects of organic and conventional farming on soil erosion. Nature 330:370-372.
40. Reganold, J. P., Palmer, A. S., Lockhart, J. C., and Macgregor, A. N. 1993. Soil quality and financial performance of biodynamic and conventional farms in New Zealand. Science 260:344-349.
41. Ryan, M. H., Chilvers, G. A., and Dumaresq, D. C. 1994. Colonization of wheat by VA-mycorrhizal fungi was found to be higher on a farm managed in an organic manner than on a conventional neighbour. Plant Soil 160:33-40.
42. Sattelmacher, B., Reinhard, S., and Pomikalko, A. 1991. Differences in mycorrhizal colonization of rye (*Secale cereale* L.) grown in conventional or organic (biological dynamic) farming systems. J. Agron. Crop Sci. 167:350-355.
43. Sattler, F., and von Wistinghausen, E. 1992. Bio-dynamic Farming Practice. Bio-dynamic Agricultural Association, Clent, Stourbridge, Great Britain.
44. Schippers, B., Bakker, A. W., and Bakker, P. A. H. M. 1987. Interactions of deleterious and beneficial rhizosphere microorganisms and the effect of cropping practices. Annu. Rev. Phytopathol. 25:339-358.
45. Scow, K. M., Somasco, O., Gunapala, N., Lau, S., Venette, R., Ferris, H., Miller, R., and Shennan, C. 1994. Changes in soil fertility and biology during the transition from conventional to low-input and organic farming systems. Calif. Agric. 48(5):20-26.
46. Shennan, C., Drinkwater, L. E., van Bruggen, A. H. C., Letourneau, D. K., and Workneh, F. 1991. Comparative study of organic and conventional tomato production systems: An approach to on-farm systems studies. Pages 109-132 in: Sustainable Agriculture Research and Education in the Field. B. Rice and J. P. Madden, eds. National Research Council, National Academy Press, Washington, D.C.
47. Sivapalan, A., Morgan, W. C., and Franz, P. R. 1993. Monitoring populations of soil microorganisms during a conversion from a conventional to an organic system of vegetable growing. Biol. Agric. Hortic. 10:9-27.
48. Smiley, R. W., Ingham, R. E., Uddin, W., and Cook, G. H. 1994. Crop sequences for managing cereal cyst nematode and fungal pathogens of winter wheat. Plant Dis. 78:1142-1149.
49. Stephens, P. M., Davoren, C. W., Ryder, M. H., Doube, B. M., and Correll, R. L. 1994 Field evidence for reduced severity of *Rhizoctonia* bare patch disease of wheat, due to the presence of the earthworms *Aporrectodea rosea* and *Aporrectodea trapezoides*. Soil Biol. Biochem. 26:1495-1500.
50. Sutton, J. C., and Vyn, T. J. 1990. Crop sequences and tillage practices in relation to diseases of winter wheat in Ontario. Can. J. Plant Pathol. 12:358-368.
51. Thresh, J. M. 1982. Cropping practices and virus spread. Annu. Rev. Phytopathol. 20:193-218.
52. Wijnands, F. G., and Vereijken, P. 1992. Region-wise development of prototypes of integrated arable farming and outdoor horticulture. Neth. J. Agric. Sci. 40:225-238.
53. Workneh, F., and van Bruggen, A. H. C. 1994. Suppression of corky root of tomatoes in soils from organic farms associated with soil microbial activity and nitrogen status of soil and tomato tissue. Phytopathology 84:688-694.
54. Workneh, F., and van Bruggen, A. H. C. 1994. Microbial density, composition, and diversity in organically and conventionally managed rhizosphere soil in relation to suppression of corky root of tomatoes. Appl. Soil Ecol. 1:219-230.
55. Workneh, F., van Bruggen, A. H. C., Drinkwater, L. E., and Shennan, C. 1993. Variables associated with corky root and Phytophthora root rot of tomatoes in organic and conventional farms. Phytopathology 83:581-589.
56. Zhang, W., and Pfender, W. F. 1992. Effect of residue management on wetness duration and ascocarp production by *Pyrenophora tritici-repentis* in wheat residue. Phytopathology 82:1434-1439.