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 soil 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 the use of synthetic pesticides and the use of organic pesticides or enhanced biodegradation. These concerns have raised general public is very concerned about the use of synthetic pesticides and the use of organic pesticides or enhanced biodegradation. 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 yield and field 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 *Gaumannomyces 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 barriers or cover crops can curtail 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).
To reduce soil erosion, minimum- or no-till soil cultivation is recommended instead of plowing or diskig. 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 blight 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 green-amendment. A reduction in excessive manure on fields (2,28). Plants high in nitrogen also support increased microbial activity and improved soil structure (46). Time- and space-dependent factors such as long-term crop rotation, habitat and soil management regimes, cumulative effects of pesticide applications, and border effects of surrounding vegetation cannot be duplicated in experiment station plots (46). Experiments and comparative studies are usually short term (generally less than 10 years) so that biological 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).

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 parasites and the epidemic development of foliar diseases is difficult (46). Time- and space-dependent factors such as long-term crop rotation, habitat and soil management regimes, cumulative effects of pesticide applications, and border effects of surrounding vegetation cannot be duplicated in experiment station plots (46). Experiments and comparative studies are usually short term (generally less than 10 years) so that biological 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).

Upon comparative studies have an advantage of encompassing many different cultural practices, all considered in parts of conventional or alternative farming in a realistic setting. Another advantage of on-farm comparisons is that dynamic equilibrium with respect to biological properties has been established on farms that have followed conventional management practices for at least 50 years (45). However, due to the large number of variables that differ simultaneously between the different farming systems, cause and effect relationships can be determined in on-farm studies. As a result of the general interest in developing alternative, more sustainable 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.
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 experiments; 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 recent comparative studies (21,24). In the Rothamsted long-term experiments, 4 by 12 plots with monocultures, 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 (1). Recently, Olsson compared root diseases on barley, in particular those caused by *Pythium arrhenomanes* and deleterious rootzone bacteria, in three long-term cropping frequency experiments (24).

Among comparative studies initiated in the last two decades, plant diseases were not included.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Crop</th>
<th>Disease</th>
<th>Pathogen</th>
<th>Org.</th>
<th>Int.</th>
<th>Conv.</th>
<th>Ref.</th>
</tr>
</thead>
</table>
| DFS⁹       | 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 | 2 | |}
|            | Wheat| Leaf blotch | *Myosphaerella graminicola* | 2 | 2-3 | 2 | |}
|            | Wheat| Glume blotch | *Leptosphaeria nodorum* | 1 | 1 | 1 | |}
|            | Wheat| Snow mold | *Gaeumannomyces graminicola* | 1 | 2 | 2 | |}
|            | Wheat| Sharp eyespot | *Rhizoctonia cerealis* | 1 | 2 | 2 | |}
|            | Wheat| Eyespot | *Pseudoperonospora herpotrichoides* | 1 | 2-3 | 2 | |}
|            | Wheat| Brown foot rot | *Fusarium spp.* | 2 | 2-3 | 3 | |}
| Lautenbach⁶ | Wheat| Powdery mildew | *Erysiphe graminis* | 3 | 2-1 | 1-2 | 11 |}
|            | Wheat| Leaf rust | *Puccinia recondita* | 1-2 | 1-2 | 1 | |}
|            | Wheat| Glume blotch | *Leptosphaeria nodorum* | 1-2 | 1-2 | 1 | |}
|            | Wheat| Eyespot and foot rot | *Pseudoperonospora herpotrichoides* | 1-2 | 1-2 | 1-2 | |}
|            | Wheat| Brown foot rot | *Fusarium spp.* | 1-2 | 1-3 | 3 | |}
|            | Sugar beet | Damping-off | Unspecified | 2 | 3 | | |}
| Rheinland⁷ | Wheat| Powdery mildew | *Erysiphe graminis* | 1-2 | 3 | 3 | |}
|            | Wheat| Leaf spot, glume blotch | *Leptosphaeria nodorum* | 1 | 2-3 | 3 | |}
|            | Wheat| Foot rot | *Fusarium spp.* | 2-3 | 3 | | |}
|            | Rye | Leaf blotch | *Rhizoctonia cerealis* | 2-3 | 3 | 3 | |}
|            | Rye | Leaf rust | *Pseudoperonospora herpotrichoides* | 2-3 | 3 | 3 | |}
|            | Rye | Foot rot | *Pseudoperonospora herpotrichoides* | 1-2 | 2 | 2 | |}
|            | Rye | Foot rot | *Rhizoctonia cerealis* | 1-2 | 2 | 2 | |}
|            | Rye | Foot rot | *Phytophthora infestans* | 3 | 3 | 3 | |}
| Sutia⁸     | Potato | Late blight | *Erysiphe graminis* | 1 | 3 | 3 | 18 |}
|            | Wheat| Powdery mildew | *Erysiphe graminis* | 1 | 3 | 3 | 18 |}
|            | Wheat| Leaf spot and | *Leptosphaeria nodorum* | 2 | 2 | 2 | |}
|            | Wheat| Glume blotch | *Puccinia striiformis* | 2 | 2-3 | 3 | |}
|            | Wheat| Leaf rust | *Puccinia recondita* | 1 | 1 | 1 | |}
|            | Wheat| Foot rot | *Fusarium spp.* | 2 | 2-3 | 3 | |}
|            | Wheat| Take-all | *Gaumannomyces graminis* | 3 | 1 | 1 | |}
|            | Barley| Net blotch | *Pyrenophora teres* | 1 | 1 | 1 | |}
|            | Barley| Sclerotinia | *Rhynchosporum secalis* | 1 | 1 | 1 | |}
|            | Barley| Leaf rust | *Fusarium recondita* | 1 | 1 | 1 | |}
|            | Barley| Damping-off | *Biopolaris sorokiniana* | 2 | 1 | 1 | |}
|            | Barley| Foot rot | *Fusarium spp.* | 1-2 | 2-3 | 3 | |}
|            | Barley| Root rot | *Gaumannomyces graminis* | 1-2 | 2-3 | 3 | |}

³ 0 = none, 1 = low, 2 = moderate, 3 = severe, summarized from several years of observations.
⁴ 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.
⁵ Organic treatment not included.
⁶ In the first 4 years, higher in integrated than in conventional fields; subsequently lower in integrated fields.
⁷ 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.
⁸ Integrated treatment not included.
⁹ Field experiment with four cropping systems at Sutia, 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).
The organic and reduced-input rotations ob­
erved mildew, and snow mold (when organic farms) (30). The second location nanwini on avocado in Australia (although ducted on existing farms. The first was a oat/vetch. An additional conventional
tomato fields (55).

Foliar and Stem Diseases
In most of the locations where foliar diseases were observed, stripe rust, pow­
dery mildew, and snow mold (when observed) of wheat were less severe in or­
ganic 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 high-nitrogen shorthaired, resulting in a denser crop. 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 dis­
cases 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 tung­
ticide sprays in a biodynamic farm (37).

In the long-term fertilizers and crop ro­
tation experiment at Broadbalk, powdery mildews was enhanced by high-nitrogen fertilizers applications (16). Differences

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 com­
parsions indicate that different manage­ment practices can result in qualitatively different soil environments (5,38,40). Or­
ganic 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 min­
eralization rate higher in conventional or reduced-input systems than in conven­tional systems. Calculations of nitrogen losses 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 NAM 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,
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 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 cellulose and hemicellulose materials in the form of green manure or compost on organic farms, which would encourage rapid multiplication of actinomycetes (26). Besides total populations of actinomycetes 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.

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 and 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 (Rhzoctonia cerealis) were more severe in the well-fertilized plots than the farmyard manure or synthetic fertilizer plots in the Broadbalk experiment, eyespot on wheat and barley were also more severe in a conventional farm (5,10,11,18,37). Damping-off of wheat caused by Gaeumannomyces graminis 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 barley were enhanced in conventional farming systems (5,10,11,18,37). Damping-off of potatoes 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 Suits 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 were twofold: conventional and organic or integrated farming systems were not investigated in any of these studies. Daamen-
The microfauna, in particular by various increased microbial activity resulting in orchard soil by green manuring with legamoebae, was also enhanced in soils high manure and straw (30). The main mechanisms were maintained in the surface layer of the 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 cellulytic 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 cellulytic 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 azuki bean caused by *Acremonium gregarium* 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 dip-saci*, 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 (31), but it would be difficult to eliminate long-term 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 and 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 (44), 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 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 entomologists 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 contamination that could be overcome by selecting farms with a similar climate and crop rotation and habit (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. 2.** Typical symptoms of corky root of tomato caused by *Pyrenochaeta lycopersici*. Note the banded root lesion with a corky appearance. (Photograph by R. N. Campbell)

**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 concentrations of 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 of farm type (O = organic, T = transitional, and C = conventional). (Courtesy, F. Workneh)

**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 with suppression of corky root of tomato (46) (*Pyrenochaeta lycopersici*) summarized from reference 54.

<table>
<thead>
<tr>
<th>Microbial activity and populations</th>
<th>r</th>
<th>Significance</th>
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<tbody>
<tr>
<td>Microbial activity</td>
<td>0.96</td>
<td>0.01</td>
</tr>
<tr>
<td>Total actinomycetes</td>
<td>0.89</td>
<td>0.02</td>
</tr>
<tr>
<td>Cellulolytic actinomycetes</td>
<td>0.84</td>
<td>0.04</td>
</tr>
<tr>
<td>Actinomycete diversity</td>
<td>0.89</td>
<td>0.02</td>
</tr>
<tr>
<td>Fluorescent pseudomonads</td>
<td>0.70</td>
<td>0.14</td>
</tr>
<tr>
<td>Chitinolytic fungi</td>
<td>0.71</td>
<td>0.12</td>
</tr>
</tbody>
</table>

* For explanations of the measured variables see Table 2.
* Relative reduction in corky root severity (percent root length infected) in natural field compared to corky root severity in gamma-irradiated soil.
* 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.

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Literature Cited

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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 rot of letuce caused by a new group of bacteria, and the Ciba Geyg 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.


