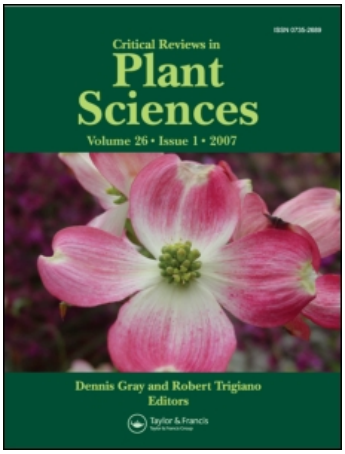

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Plant Pathogens in Irrigation Water: Challenges and Opportunities

C. X. Hong[a]; G. W. Moorman[b]
[a] Department of Plant Pathology, Physiology, and Weed Science, Virginia Polytechnic Institute and State University, Hampton Roads Agricultural Research and Extension Center, Virginia Beach, VA [b] Department of Plant Pathology, The Pennsylvania State University, University Park, PA

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Plant Pathogens in Irrigation Water: Challenges and Opportunities

C. X. Hong
Department of Plant Pathology, Physiology, and Weed Science, Virginia Polytechnic Institute and State University, Hampton Roads Agricultural Research and Extension Center, Virginia Beach, VA 23455-3315

G. W. Moorman
Department of Plant Pathology, The Pennsylvania State University, University Park, PA 16802-4506

Plant pathogens in irrigation water were recognized early in the last century as a significant crop health issue. This issue has increased greatly in scope and degree of impact since that time and it will continue to be a problem as agriculture increasingly depends on the use of recycled water. Plant pathogens detected from water resources include 17 species of *Phytophthora*, 26 of *Pythium*, 27 genera of fungi, 8 species of bacteria, 10 viruses, and 13 species of plant parasitic nematodes. There is substantial evidence demonstrating that contaminated irrigation water is a primary, if not the sole, source of inoculum for *Phytophthora* diseases of numerous nursery, fruit, and vegetable crops. These findings pose great challenges and opportunities to the plant pathology community. A variety of water treatment methods are available but few have been assessed for agricultural purposes under commercial conditions. Investigations into their technical feasibility and economics are urgently needed. Aquatic ecology of plant pathogens is an emerging field of research that holds great promise for developing ecologically based water decontamination and other strategies of pathogen mitigation. Pathogen detection and monitoring as well as biological and economic thresholds are much-needed IPM tools and should be priorities of future research. Teaming with hydrologists, agricultural engineers, ecologists, geneticists, economists, statisticians, and farmers is essential to effectively attack such a complex issue of growing global importance. Research should proceed in conjunction with nutrient and pesticide management studies in a coordinated and comprehensive approach as they are interrelated components of water resource conservation and protection.

Keywords aquatic ecology, biological threshold, pathogen detection and monitoring, IPM, water resource conservation and protection

I. INTRODUCTION

One factor common to all crop production is the need for water. As a common denominator in growing plants, water and all that it contains is a potential risk factor, particularly if it must be repeatedly applied to crops to compensate for limited rainfall or made available at a specific time in the crop's development. If the water carries undesirable chemicals or microbes, an entire crop can be lost. The subject of this review, the risk posed by the plant pathogens in irrigation water, was recognized early in the last century as a significant crop health issue (Bewley and Buddin, 1921; Oyler and Bewley, 1937). Whether the initial source of water harbors pathogens or pathogens enter the water along the path of distribution, one consequence is the repeated inoculation of plants with the pathogens.

The problem of plant pathogens in irrigation water is aggravated by the increasing use of recycled water. Recycling irrigation in some locales is crucial to comply with stringent water policies and regulations. As the concern over water scarcity spreads, agricultural use of water resources is being more closely monitored and regulated by governments. In some localities, it is mandated or considered highly desirable that runoff and leachate from irrigated agricultural areas be captured to prevent nitrogen, phosphorus, and pesticides from contaminating groundwater and surface supplies (Kabashima, 1993; von Broembsen *et al*., 2001; Norman *et al*., 2003). The trend in the United States is for farms to be viewed as point sources of pollution. If designated as such by regulatory agencies, farmers will be required to comply with some of the same regulations as manufacturers. Although farmers are forced to look at production methods in new ways because of this possibility, it is important to note that most farm families live close to and utilize for personal purposes the same water resources used as for growing crops or raising livestock (Scarpa, 2000). Farmers too are very interested in preventing the degradation of the water and conserving this vital resource. In the course of devising and implementing best water conservation management practices, the issue of plant pathogens in water has come to the forefront.

There are reports of the presence of almost every major pathogen group in water. In this review, we will discuss the possible sources of plant pathogens in irrigation water, how irrigation may distribute these pathogens, the methods used to detect and

Address correspondence to C. X. Hong, Department of Plant Pathology, Physiology, and Weed Science, Virginia Polytechnic Institute and State University, Hampton Roads Agricultural Research and Extension Center, Virginia Beach, VA 23455-3315. E-mail: chhong2@vt.edu

monitor the presence of plant pathogens, and the current technology available for the mitigation of pathogens in water. Our objectives are to highlight selected papers that are the basis of our current understanding of the problem of plant pathogens in water and to point out what additional knowledge is needed to attack this issue of global importance.

II. WATER SOURCES, IRRIGATION METHODS, AND PLANT PATHOGENS

Well water seldom contains plant pathogens (McCarter-Zorner *et al*., 1984; Pottorff and Panter, 1997; Themann *et al*., 2002; Yun, 2003). If, however, the well is not cased or if the head is not sealed near the surface, runoff carrying sediment can enter the well and contaminate the water with plant pathogens. When water is collected in cisterns recharged by rainfall from the roof, it may not necessarily be free of pathogens, but the number of contaminant species would be limited (Rattink, 1991). Runoff of surface water or wind-blown soil can contaminate water storage tanks, regardless of how the water is initially collected. Surface water supplies including ponds, lakes, rivers, and streams as well as manmade reservoirs and canals are all possible sources of plant pathogens that originate from the underlying and surrounding soil or plant debris (Tables 1–6). Through these various avenues, the initial water used for irrigation may be the source of plant pathogens.

If the water source is free of pathogens, then pathogens may enter the water at several points along the distribution path. Any irrigation method in which the water comes in contact with soil or plant debris has an increased likelihood of acquiring plant pathogens. Furrow flooding and runoff from other methods of irrigation can then carry soilborne pathogens throughout the watered area. In outdoor production facilities where plants are grown in containers and excess water and leachate are captured and recycled, underlying soil may be a significant source of pathogens if containers rest directly on the soil. Even if the area under and between containers is covered with impervious fabric for capturing the excess water, most facilities do not have lined, soil-free channels directing water back to a holding pond, nor is the pond itself lined. The water comes in direct contact with underlying, possibly contaminated, soil. Pathogens in facilities growing containerized plant material can also originate from infected crop plants placed in the system. In greenhouses for example, pathogens may originate from infected plants started elsewhere and then placed in the system. Also potting soil that was not pasteurized may be the initial inoculum source. Pathogen-contaminated soil from immediately outside or on the floors of the greenhouse may fall into holding tanks, be brought in contact with the plants or potting soil via contaminated tools, or be blown about by strong ventilation systems. Shoreflies (*Scatella stagnalis*) also can move pathogens within greenhouses (Goldberg and Stanghellini, 1990; Stanghellini *et al*., 1999), although the importance of such vectoring has not been fully assessed. Modern greenhouses have benches raised off the ground for holding potted plants away from untreated soil. Some operators employ impervious "ebb and flow" or "flood and drain" benches that are temporarily flooded with water and then drained to tanks where the water is stored until pumped back onto the benches at the next irrigation cycle. A variation of this technique, termed "flooded floor" irrigation, positions containers of plants on an impervious floor with a surrounding low curbing that allows the entire production floor to be flooded to the depth of a few centimeters during irrigation and then drained away to a storage tank for reuse. Equipment driven across these floors and workers traversing the area can be the means of introducing contaminated soil to the water used to flood this area and ultimately to the holding tank and all the connecting plumbing. In hydroponic, nutrient film, and other methods of producing plants with bare roots, the main sources of pathogens are the initial water source, plants infected as seedlings and then placed in the system, pathogen-contaminated soil allowed to get into the system, and the activity of insect vectors.

To summarize, the initial contamination with plant pathogens of the water supply used for irrigation can originate from several sources. The pathogen may be a natural inhabitant of the water source or reside in the soil or in infected resident plants near the water and only be a transient inhabitant of the irrigation water. Alternatively, a pathogen may not be endemic to an area but may be brought to the production area from some distance on infected plants transplanted into the watershed or placed in the production area. Because the reduction or elimination of waterborne pathogens is time consuming, expensive, and not a simple task, it is important to determine the point source of pathogens suspected of being carried in water so that those points of entry can be specifically targeted for treatment.

III. PLANT PATHOGENS IN WATER

There are many examples in the literature associating crop losses with plant pathogens in water. Although almost every major pathogen group is represented among these cases, there is limited field data directly demonstrating the epidemiological and economic significance of these waterborne pathogens (Hong *et al*., 2002a). When a particular species of pathogen is isolated from infected plants and also from the associated water source, sediment, or particulates in the water source, a causal linkage is assumed. For example, there are reports from surveys of microbes in water noting the presence of species known to be pathogenic (Klotz *et al*., 1959; McIntosh, 1966; Taylor, 1977; Ali-Shtayeh and MacDonald, 1991; MacDonald *et al*., 1994; Oudemans, 1999; Bush, 2002; Yamak *et al*., 2002; Bush *et al*., 2003). The implication is that the isolates from the various positions in the production area are one and the same. Until recently, techniques have not been available to prove that those different isolates of the same genus and species are actually identical. DNA analyses now can more clearly establish such relationships. Evidence that a particular isolate from an infected plant is the same as one in water is more direct when experiments are performed. In some cases, an isolate known to have been responsible for an epidemic was put in the water used to irrigate test plants

and re-isolated from newly infected plants. Also, plants have been inoculated, put into a production area, and the pathogen later was detected in water that had been previously free of that pathogen. The evidence, including circumstantial evidence, that irrigation water can be a very significant avenue of introducing pathogens or moving pathogens within a crop is overwhelming.

A. *Phytophthora* and *Pythium* Species in Irrigation Water

Some of the earliest reports of plant pathogens in water have implicated the "water molds," *Phytophthora* (Table 1) and *Pythium* (Table 2). These oomycetes resemble fungi both morphologically and physiologically, but they are actually phylogenetic cousins of diatoms and brown algae, within the kingdom Stramenopiles (Tyler, 2001). These zoosporic organisms are generally viewed as well adapted to the aquatic environment. Although not all members of these genera readily form zoospores nor appear to reside in water for long periods, there are numerous cases in which they have been implicated in crop losses through irrigation dissemination (Whiteside and Oswalt, 1973; van Kuik, 1992; MacDonald *et al*., 1997; Bush, 2002; Hong *et al*., 2002a, 2002b).

In earlier works, Bewley and Buddin (1921) found *P. cryptogea* and *P. parasitica* (syn. *P. nicotianae*) in greenhouse irrigation water, whereas Oyler and Bewley (1937) found *P. cinnamomi* in water and infecting heath plants being grown in a nursery. Since that time, many species of *Phytophthora* carried in water have been implicated in the outbreak of disease in fruit crops (Whiteside and Oswalt, 1973; Oudemans, 1999; Yamak *et al*., 2002), tobacco (Thung, 1938; Wills, 1964; Dukes *et al*., 1977), vegetables (Shokes and McCarter, 1979; Jenkins and Averre, 1983; Neher and Duniway, 1992), ornamentals (Thinggaard and Middelboe, 1989; MacDonald *et al*., 1994; Strong *et al.*, 1997; von Broembsen and Wilson, 1998; Bush, 2002; Themann *et al*., 2002), and forest trees (Kliejunas and Ko, 1976). In greenhouse experiments, *P. cryptogea* readily spreads in recirculating systems in which potted *Gerbera* (Thinggaard and Andersen, 1995) or tomatoes are grown (Evans, 1979). *Phytophthora nicotianae* spreads in crops of *Saintpaulia* (van der Gaag *et al*., 2001) and tomato (van Voorst *et al.*, 1987) when contaminated water is recycled. *Phytophthora ramorum*, the sudden oak death pathogen, has been found in many streams and watersheds in California (Maloney *et al*., 2002; Tjosvold *et al*., 2002; Murphy *et al*., 2005) and Oregon (Hansen *et al*., 2005). Kaminiski *et al*. (2005) further demonstrated that this pathogen survived and was disseminated through recirculating systems, causing typical blight on rhododendron plants at a nursery in Germany.

Similarly, many species of *Pythium* have been found in water used to irrigate vegetables (Gill, 1970; Shokes and McCarter, 1979; Bates and Stanghellini, 1984; Postma *et al*., 2000; Utkhede *et al*., 2000), ornamentals (Pittis and Colhoun, 1984; Thinggaard and Middelboe, 1989; MacDonald *et al*., 1994; Moorman *et al*., 2002; Bush *et al*., 2003; Kageyama *et al*., 2003), tobacco (Fortnum *et al*., 2000), and sprouts (Yun, 2003). The difficulty of identifying *Pythium* isolates to the species level often deters workers from reporting more than the presence of members of the genus. When the species is determined, it is assumed that any isolates of species well known to cause disease are very likely involved in the epidemic (MacDonald *et al.*, 1994). However, depending upon the host plants present in the system, the prevailing environment, and other factors, not all species or isolates within a species of *Pythium* are pathogenic under production conditions (Pittis and Colhoun, 1984; Thinggaard and Middelboe, 1989; Moulin *et al.*, 1994; Pottorff and Panter, 1997; Moorman *et al.*, 2002). Therefore, it cannot be assumed that an isolate of a given species from an infected plant is identical to an isolate obtained from water used to irrigate that plant. A more direct association between a pathogen in roots and an isolate of the same species in water occurs in relatively closed production systems such as hydroponics (Gill, 1970; Bates and Stanghellini, 1984; Stanghellini and Kronland, 1986; Moulin *et al.*, 1994; Stanghellini and Rasmussen, 1994; Owen-Going *et al.*, 2003). In some cases the evidence linking isolates may be stronger because they share some characteristic such as resistance to one or more fungicides. Also, several controlled experiments demonstrated that *Pythium* species can spread through irrigation water and cause diseases when they are introduced into the system (Evans, 1979; Hoitink *et al.*, 1991; Sanogo and Moorman, 1993).

B. Fungi in Irrigation Water

Numerous fungi have been found in water (Table 3), but the significance of these findings is difficult to assess. Species in the genera *Alternaria*, *Botrytis*, *Ascochyta*, *Rhizoctonia*, and *Verticillium* are present in water because of their sheer abundance in nature but may not survive in water (Bewley and Buddin, 1921; Shokes and McCarter, 1976). The presence of species known to be plant pathogens has been reported, but without data indicating the epidemiological and economic importance to production agriculture of those particular isolates (Cooke, 1956; Thomson and Allen, 1974). Although *Fusarium oxysporum* may not be long-lived in water and may settle out quickly and not infect plants in some cases (Rattink, 1990), it did spread and infect plants in other situations (Evans, 1979; Kegler *et al.*, 1982; Jenkins and Averre, 1983). *Colletotrichum* spreads via water in hydroponically grown tomatoes (Jenkins and Averre, 1983). *Olpidium*, a vector of the virus that causes lettuce big vein disease, can be spread in nutrient film irrigation production (Tomlinson and Faithfull, 1979a) and hydroponic systems (Paludan, 1985). The significance of many other species of fungi in water needs to be assessed.

C. Bacteria in Irrigation Water

Genera and species of bacteria found in irrigation water are summarized in Table 4. *Erwinia* species have frequently been found in water supplies (Harrison *et al.*, 1987; Cappaert *et al.*, 1988; Eayre *et al.*, 1995). Some species are thought to be natural components of the aquatic ecosystem (McCarter-Zorner

TABLE 1
Research on *Phytophthora* species in water

Species	Locations	Plants affected	References
cactorum	Pond, river, canal, runoff	Ornamental, fruit	McIntosh, 1966; Hong et al., 2001; Themann et al., 2002; Yamak *et al.*, 2002
cambivora	Pond, river, canal	Ornamental, fruit	McIntosh, 1966; Hong *et al.*, 2001; Themann *et al.*, 2002
capsici	Pond, runoff	Ornamental	Hong *et al.*, 2001; Bush *et al.*, 2003
cinnamomi	Stream, river, pond, runoff, canal, sediment	Forest, ornamental, fruit	Kliejunas and Ko, 1976; van Kuik, 1992; MacDonald *et al.*, 1994; Lauderdale and Jones, 1997; von Broembsen and Wilson, 1998; Oudemans, 1999; Themann *et al.*, 2002; Bush *et al.*, 2003
citricola	Pond, river, canal, lake, runoff	Ornamental, fruit	McIntosh, 1966; Smith and Ousley, 1985; MacDonald *et al.*, 1994; von Broembsen and Wilson, 1998; Oudemans, 1999; Hong *et al.*, 2001; Themann *et al.*, 2002; Yamak *et al.*, 2002; Bush *et al.*, 2003
citrophthora	Canal, reservoir, pond, river, runoff	Ornamental, fruit	Klotz *et al.*, 1959; Mitchell and Zentmyer, 1971; Whiteside and Oswalt, 1973; Thomson and Allen, 1974; Ali-Shtayeh and MacDonald, 1991; MacDonald *et al.*, 1994; Wilson *et al.*, 1998; von Broembsen and Charlton, 2000; Hong *et al.*, 2001
cryptogea	Well, stream, pond, canal, river, runoff, ebb and flow, nutrient film	Ornamental, fruit	Bewley and Buddin, 1921; Thomson and Allen, 1974; Taylor, 1977; Evans, 1979; Smith and Ousley, 1985; Ali-Shtayeh and MacDonald, 1991; MacDonald *et al.*, 1994; Thinggaard and Andersen, 1995; Lauderdale and Jones, 1997; Pettitt *et al.*, 1998; von Broembsen and Wilson, 1998; Hong *et al.*, 2001; van der Gaag *et al.*, 2001; Themann *et al.*, 2002; Bush *et al.*, 2003
drechsleri	River, canal, pond, runoff	Ornamental	Thomson and Allen, 1974; Hong *et al.*, 2001; Themann *et al.*, 2002; Bush *et al.*, 2003
gonapodyides	Lake	Ornamental	Pittis and Colhoun, 1984; Smith and Ousley, 1985; Themann *et al.*, 2002
megasperma	Pond, canal, river, runoff, stream	Ornamental, fruit	McIntosh, 1966; Taylor, 1977; MacDonald *et al.*, 1994; Oudemans, 1999; Hong *et al.*, 2001
nicotianae	Well, stream, pond, canal, reservoir, runoff, ebb and flow, nutrient film	Fruit, tobacco, ornamental	Bewley and Buddin, 1921; Klotz *et al.*, 1959; Wills, 1964; Thomson and Allen, 1974; Dukes *et al.*, 1977; Taylor, 1977; van Voorst *et al.*, 1987; Thinggaard and Middelboe, 1989; Feld *et al.*, 1990; Ali-Shtayeh and MacDonald, 1991; Grech and Rijkenberg, 1992; Neher and Duniway, 1992; Strong *et al.*, 1993; MacDonald *et al.*, 1994; Lauderdale and Jones, 1997; von Broembsen and Wilson, 1998; Hong *et al.*, 2001; van der Gaag *et al.*, 2001; Bush *et al.*, 2003
palmivora	Canal	Fruit	Ali-Shtayeh and MacDonald, 1991
ramorum	Stream, watershed, recirculating system	Forest, ornamental	Hansen *et al.*, 2005; Kaminiski *et al.*, 2005; Maloney *et al.*, 2002; Murphy *et al.*, 2005; Tjosvold *et al.*, 2002

TABLE 1
Research on *Phytophthora* species in water *(Continued)*

Species	Locations	Plants affected	References
syringae	Canal, reservoir, river, runoff, pond	Fruit, ornamental	Klotz *et al.*, 1959; MacDonald *et al.*, 1994; Hong *et al.*, 2001; Themann *et al.*, 2002
tropicalis	Pond, runoff	Ornamental	Hong *et al.*, 2001
undulata	Recirculating system	Ornamental	Themann *et al.*, 2002
Phytophthora spp.	pond, canal, river, lake, runoff, ebb and flow system	Fruit, vegetable, ornamental,	Klotz *et al.*, 1959; Thomson and Allen, 1974; Taylor, 1977; Shokes and McCarter, 1979; Smith and Ousley, 1985; Ali-Shtayeh and MacDonald, 1991; Grech and Rijkenberg, 1992; Wilson *et al.*, 1998; Hong *et al.*, 2001; van der Gaag *et al.*, 2001; Themann *et al.*, 2002; Yamak *et al.*, 2002

et al., 1984; Cother and Gilbert, 1990) and experimentation has demonstrated that *Erwinia* isolates from water can be pathogenic to important crops (Kelman *et al.*, 1957; Lacy *et al.*, 1981; Harrison *et al.*, 1987; Norman *et al.*, 2003).

Xanthomonas (Steadman *et al.*, 1975) and *Corynebacterium* (Schuster, 1959) have also been found in irrigation water. *Corynebacterium* can remain biologically active in recirculating nutrient solutions for almost a month (Kegler *et al.*, 1982) and *Xanthomonas campestris* pv. *begonia* spreads via water and causes disease in begonias grown in ebb-and-flow irrigation systems (Hoitink *et al.*, 1991). In one case, *Ralstonia solancearum* (= *Pseudomonas solancearum*), but not *Erwinia*, was shown to spread among hydroponically grown tomatoes (Jenkins and Averre, 1983).

D. Viruses in Irrigation Water

At least 10 viruses have been documented in irrigation water (Table 5). Half of these were detected in river and lake water (Tošic and Tošic, 1984; Koenig, 1986) and others were found in irrigation systems (Paludan, 1985; Pategas *et al.*, 1989; Pares *et al.*, 1992; Berkelmann *et al.*, 1995). The highly contagious Pelargonium flower break virus can be spread in recirculating nutrient solutions in greenhouses (Albouy *et al.*, 1993; Berkelmann *et al.*, 1995) as can tomato mosaic virus whose virions can be found in water three days after the leaves of test plants in the system are inoculated (Pares *et al.*, 1992).

E. Nematodes in Irrigation Water

Most plant parasitic nematodes spend part of their lives in soil or in plant debris in soil. Therefore, it is not surprising that plant parasitic nematodes are found associated with irrigation water (Table 6). When nematode-infested irrigation water is used for crops grown in fumigated soil, populations of those nematodes build up in the soil, whereas populations do not greatly increase in the same soil irrigated with well water free of nematodes (Faulkner and Bolander, 1970). Cyst-forming species, such as *Heterodera*, can be carried in water (Petherbridge and Jones, 1944). Depending upon the water distribution equipment used, relatively fragile nematode larvae may not survive the application or retain infectivity. Heald and Johnson (1969) found that several species of nematodes in a water source did not become problems in container-grown ornamentals when the water was pumped through a sprinkler system. They speculated that the pressure at the nozzles or in the pump may have injured the larvae.

IV. WHY SUSPECT THAT THE PATHOGEN IS IRRIGATION WATER-BORNE?

The examples mentioned previously document that one or more members of almost every major pathogen group have been implicated in waterborne movement in crop production systems. It is important to step back and point out clues that may lead one to suspect that a pathogen is waterborne. Probably the first clue would be that the identified pathogen has been reported in the literature to be spread by irrigation and the crop in question is being irrigated. However, rather than providing the inoculum, irrigation water may merely be providing conditions for enhanced root development in a location where the pathogen resides or may be providing the moist conditions required by the resident pathogen to be active (Feld *et al.*, 1990). Keeping those alternative explanations in mind, the spatial distribution of diseased plants should be examined. If only a portion of the crop is irrigated, then the irrigated and nonirrigated areas should exhibit definite differences in the number and distribution pattern of diseased plants. If the introduction of a pathogen is via waterborne inoculum, often the number of affected plants is large and many exhibit symptoms at about the same time in relation to the onset of irrigation. Early in the epidemic, the distribution of affected plants may be highly aggregated, associated with where the water flows or accumulates, and not randomly scattered in the crop. As the disease progresses, a large number of plants are affected and the distribution may be more pronounced where leachate and runoff water move. In a field situation where a large volume of water is applied to a small area, such as furrow

TABLE 2
Research on *Pythium* species in water

Species	Locations	Plants affected	References
acanthicum	Pond	Vegetable	Shokes and McCarter, 1979
aphanidermatum	Pond, hydroponics	Vegetable	Bewley and Buddin, 1921; Takahashi, 1952; Shokes and McCarter, 1979; Jenkins and Averre, 1983; Bates and Stanghellini, 1984; Owen-Going *et al.*, 2003
catenulatum	Pond	Vegetable, ornamental	Shokes and McCarter, 1979; Sanchez and Gallego, 2000
coloratum	Canal, runoff	Ornamental	Ali-Shtayeh and MacDonald, 1991; MacDonald *et al.*, 1994
debaryanum	River, lake, hydroponics	Vegetable	Harvey, 1952; Jenkins and Averre, 1983
deliense	Hydroponic system	Sprout	Yun, 2003
diclinum	Pond	Ornamental	Sanchez and Gallego, 2000
dissotocum	Pond, holding tank, hydroponics	Vegetable, ornamental	Shokes and McCarter, 1979; Bates and Stanghellini, 1984; Pittis and Colhoun, 1984; Stanghellini and Kronland, 1986; Thinggaard and Middelboe, 1989; Pottorff and Panter, 1997; Owen-Going *et al.*, 2003
flevoense	Holding tank	Ornamental	Thinggaard and Middelboe, 1989
graminicola	Holding tank	Ornamental	Thinggaard and Middelboe, 1989
inflatum	Pond	Vegetable	Shokes and McCarter, 1979
irregulare	Pond, holding tank	Vegetable, ornamental	Shokes and McCarter, 1979; Thinggaard and Middelboe, 1989; Moorman *et al.*, 2002
mamillatum	Canal, runoff	Ornamental	Pittis and Colhoun, 1984
middletonii	Canal, runoff	Ornamental	Pittis and Colhoun, 1984; Ali-Shtayeh and MacDonald, 1991; MacDonald *et al.*, 1994
monospermum	Pond	Vegetable	Takahashi, 1952
myriotylum	Pond, hydroponics	Vegetable	Gill, 1970; Jenkins and Averre, 1983
paroecandrum	Pond	Vegetable, ornamental	Shokes and McCarter, 1979; Sanchez and Gallego, 2000
rostratum	Pond, holding tank, canal, runoff	Vegetable, ornamental	Shokes and McCarter, 1979; Pittis and Colhoun, 1984; Thinggaard and Middelboe, 1989; Ali-Shtayeh and MacDonald, 1991; MacDonald *et al.*, 1994; Pottorff and Panter, 1997
salpingophorum	Holding tank	Ornamental	Thinggaard and Middelboe, 1989
spinosum	Pond	Vegetable	Shokes and McCarter, 1979
splendens	Pond	Vegetable	Shokes and McCarter, 1979
sylvaticum	Pond	Vegetable	Shokes and McCarter, 1979
toruloides	Pond, river, lake	Vegetable	Harvey, 1952; Shokes and McCarter, 1979
tracheiphilum	Holding tank	Ornamental	Thinggaard and Middelboe, 1989
ultimum	Hydroponics, nutrient film	Vegetable	Evans, 1979; Jenkins and Averre, 1983
ultimum var. *sporangiiferum*	Holding tank, river, lake, runoff	Ornamental	Harvey, 1952; Thinggaard and Middelboe, 1989; MacDonald *et al.*, 1994
vexans	Pond, holding tank	Vegetable	Shokes and McCarter, 1979; Thinggaard and Middelboe, 1989
Pythium spp.	Pond, river, lake, holding tank, hydroponics, nutrient film	Vegetable, ornamental	Harvey, 1952; Gill, 1970; Shokes and McCarter, 1979; Pittis and Colhoun, 1984; Thinggaard and Middelboe, 1989; Lauderdale and Jones, 1997; Sanchez and Gallego, 2000; Koohakan *et al.*, 2004

TABLE 3
Research on fungi in water

Genera	Locations	Plants affected	References
Alternaria	Effluent, pond	Fruit, vegetable	Cooke, 1956; Thomson and Allen, 1974; Shokes and McCarter, 1979
Ascochyta	Pond	Fruit, vegetable	Thomson and Allen, 1974; Shokes and McCarter, 1979
Aspergillus	Effluent, pond	Fruit, vegetable	Cooke, 1956; Thomson and Allen, 1974; Shokes and McCarter, 1979
Botrytis	Effluent, well, stream, pond	NS*	Bewley and Buddin, 1921; Cooke, 1956
Cephalosporium	Effluent, pond	Vegetable	Cooke, 1956; Shokes and McCarter, 1979
Chaetomium	Effluent	NS	Cooke, 1956
Cladosporium	Effluent, pond	Fruit, vegetable	Cooke, 1956; Thomson and Allen, 1974; Shokes and McCarter, 1979
Colletotrichum	Hydroponics	Vegetable	Jenkins and Averre, 1983
Coniothyrium	Effluent	NS	Cooke, 1956
Curvularia	Effluent	NS	Cooke, 1956
Diplodia	Pond	Fruit, vegetable	Thomson and Allen, 1974; Shokes and McCarter, 1979
Fusarium	Effluent, well, stream, pond, ebb and flow, nutrient film	Fruit, vegetable, ornamental	Bewley and Buddin, 1921; Cooke, 1956; Thomson and Allen, 1974; Evans, 1979; Shokes and McCarter, 1979; Jenkins and Averre, 1983; Rattink, 1990; Grech and Rijkenberg, 1992; Lievens *et al.*, 2003
Geotrichum	Pond	Fruit	Thomson and Allen, 1974
Gliocladium	Effluent	NS	Cooke, 1956
Microsporium	Well, stream, pond	NS	Bewley and Buddin, 1921
Mucor	Effluent, pond	Fruit	Cooke, 1956; Thomson and Allen, 1974
Penicillium	Effluent, pond	Fruit	Cooke, 1956; Thomson and Allen, 1974
Phoma	Well, stream, pond	Fruit, vegetable	Bewley and Buddin, 1921; Thomson and Allen, 1974; Shokes and McCarter, 1979
Plasmodiophora	Pond sediment	Vegetable	Datnoff *et al.*, 1984
Rhizoctonia	Effluent, well, stream, pond	Vegetable	Bewley and Buddin, 1921; Cooke, 1956; Shokes and McCarter, 1979
Rhizopus	Pond	Vegetable	Shokes and McCarter, 1979
Sclerotium	Pond	Vegetable	Shokes and McCarter, 1979
Scopulariopsis	Effluent	NS	Cooke, 1956
Stemphyllium	Effluent	NS	Cooke, 1956
Trichoderma	Effluent, pond	Fruit	Cooke, 1956; Thomson and Allen, 1974
Verticillium	Well, stream, pond, runoff, nutrient film	Potato, vegetable	Bewley and Buddin, 1921; Easton *et al.*, 1969; Evans, 1979; Lievens *et al.*, 2003
Whetzelinia	Canal	NS	Steadman *et al.*, 1975
Others	Pond	Vegetable	Harvey, 1952; Shokes and McCarter, 1979

*NS=not specified.

irrigation, there is a steep gradient in the distribution of affected plants from many diseased plants in the immediate proximity to very few diseased plants a short distance away. If the water is applied over the entire area, such as by ebb-and-flow irrigation of benches or flooded floors or overhead sprinkler irrigation, there may be few or no foci because most of the plants are affected. If such distributions are noted and the symptoms being observed are associated with the same organism throughout the affected crop, then a strategy can be selected for testing the water for that pathogen. The simplest strategy may be to irrigate plants known to be healthy with the same water as is being used for the affected crop. Either the water can be collected and applied to these plants at another location or container-grown plants can be placed within the affected crops but protected from inoculation by means other than irrigation water application. In addition, the irrigation water can be tested for the pathogen.

TABLE 4
Research on bacteria in water

Genus and species	Locations	Plants affected	References
Corynebacterium flaccumfaciens	NS*	Bean	Schuster, 1959
Erwinia carotovora pv. *atroseptica*	River, streams, lakes, ponds	Potato	McCarter-Zorner *et al.*, 1984; Jorge and Harrison, 1986
E. carotovora pv. *carotovora*	Pond, lake, river, stream	Ornamental, potato	Lacy *et al.*, 1981; McCarter-Zorner *et al.*, 1984; Jorge and Harrison, 1986; Norman *et al.*, 2003
E. carotovora pv. *zea*	Pond	Corn	Thompson, 1965
E. chrysanthemi	Pond, lake	Ornamental	Norman *et al.*, 2003
Erwinia spp.	Pond, lake	Corn, ornamental	Kelman *et al.*, 1957; Norman *et al.*, 2003
Pseudomonas syringae pv. *aptata*	Pond	Cantaloupe	Riffaud and Morris, 2002
Ralstonia solanacearum	Hydroponics	Vegetable, geranium, potato	Jenkins and Averre, 1983; van Elsas *et al.*, 2001; Swanson *et al.*, 2005
Xanthomonas campestris pv. begonia	Ebb and flow system	Ornamental	Hoitink *et al.*, 1991
X. phaseoli	Pond	Bean	Steadman *et al.*, 1975

*NS=not specified.

V. DETECTION AND MONITORING OF PATHOGENS IN WATER

When presence of a pathogen in irrigation water is suspected, several questions should be answered before a management strategy is selected. An unbiased evaluation of the threat is important because the expenses incurred to eliminate or reduce pathogens in water are significant. Foremost in this evaluation are whether the pathogen can be detected in the water (detection threshold) and is it in high enough quantity or present frequently enough to pose a real threat to the crop (biological threshold).

TABLE 5
Research on viruses in water

Viruses	Locations	Plants affected	References
Pelargonium flower break	Ebb and flow system	*Pelargonium*	Berkelmann *et al.*, 1995
Tomato bushy stunt	Lake, river	*Chenopodium*	Koenig and Lesemann, 1985
Carnation mottle	Lake, river	*Chenopodium*	Koenig and Lesemann, 1985
Tobacco mosaic	Lake, river	*Chenopodium*	Tošic and Tošic, 1984; Koenig and Lesemann, 1985
Tomato mosaic	Hydroponic system	*Lycopersicon*, *Capsicum*	Paludan, 1985; Pategas *et al.*, 1989; Pares *et al.*, 1992
Cucumber green mosaic	Rock wool/ continuous recycling nutrients	*Cucumis*	Paludan, 1985
Tobacco necrosis	Rock wool/ continuous recycling nutrients	*Phaseolus*	Paludan, 1985
Lettuce big vein	Rock wool/ continuous recycling nutrients	*Lactuca*	Tomlinson and Faithfull, 1979b; Paludan, 1985
Tobamovirus	Lake, river	*Chenopodium*	Koenig and Lesemann, 1985
Potexvirus	Lake, river	*Chenopodium*	Koenig and Lesemann, 1985

TABLE 6
Research on nematodes in water

Genus	Locations	Plants affected	References
Aphelenchoides	Waterway, runoff	NS*	Steadman *et al.*, 1975
Criconemoides	Pond, runoff	Ornamental	Heald and Johnson, 1969
Ditylenchus	Canal	Field crop	Faulkner and Bolander, 1967; 1970; Steadman *et al.*, 1975
Helicotylenchus	Pond, runoff	Ornamental	Heald and Johnson, 1969
Hemicycliophora	Canal	NS	Faulkner and Bolander, 1967
Heterodera	Canal	Beet	Petherbridge and Jones, 1944; Faulkner and Bolander, 1967; Steadman *et al.*, 1975
Hoploliamus	Pond, runoff	Ornamental	Heald and Johnson, 1969
Meloidogyne	Pond, runoff, canal	Ornamental, field crop	Faulkner and Bolander, 1967; Heald and Johnson, 1969; Faulkner and Bolander, 1970
Paratylenchus	Canal	Field crop	Faulkner and Bolander, 1967; 1970
Pratylenchus	Pond, runoff, canal	Ornamental, field crop	Faulkner and Bolander, 1967; Heald and Johnson, 1969; Faulkner and Bolander, 1970; Steadman *et al.*, 1975
Trichodorus	Pond, runoff, canal	Ornamental	Faulkner and Bolander, 1967; Heald and Johnson, 1969
Tylenchorhynchus	Pond, runoff, canal	Ornamental, field crop	Faulkner and Bolander, 1967; Heald and Johnson, 1969; Faulkner and Bolander, 1970
Tylenchulus	River, pond	Fruit	Grech and Rijkenberg, 1992

*NS=not specified.

The detection threshold of the method to be used must be known in order to decide how many samples must be collected and what volume should be collected. Then it must be decided what samples are to be taken (clear water, turbid water, sediment, suspended particulates), where the samples should be collected (at the source, within the crop, at the sprinkler head or other point where water is first applied, as effluent exiting crop area, effluent in drainage ditches, at the intake or return point of the water to the reservoir, from the surface or at some depth), and when samples are to be taken (time of year, time of day, time of the irrigation cycle).

The detection threshold of any sampling method employed must be verified. Every step in the procedure, no matter how minor, may influence the number of propagules detected. The temperatures maintained during shipment and storage of samples, using dilute agar instead of water to suspend pathogen propagules trapped on filter paper, avoiding the use of very high vacuums to filter samples, avoiding excessively high centrifugation speeds, exposing baits for too long or too short a time period, using intact vs. sliced baits, and temperatures and light conditions used for incubating culture plates may significantly influence detection resolution and accuracy. Decisions on the number of samples that need to be taken and the volumes to be collected are largely dependent upon detection and biological thresholds and are determined through trial and error by working with test samples containing known numbers of pathogen propagules according to the detection protocol. Care must be taken to ensure that the test samples are composed of the propagules or life stages of the pathogen that are most likely to be encountered in the actual collections.

Numerous techniques have been employed in pathogen detection and quantification and new ones are being developed. Fungi, bacteria, and nematodes can be trapped on filters or sieves (Bewley and Buddin, 1921; Faulkner and Bolander, 1967; Steadman *et al.*, 1975; Shokes and McCarter, 1979; Wakeham *et al.*, 1997; Hong *et al.*, 2002c; Pettitt *et al.*, 2002), resuspended, and observed directly. For pathogens that can be cultured, the filter can be plated directly on media or the residues washed from the filter and plated directly or diluted then plated on general or semi-selective media (Tsao, 1970; Hall, 1979; Jeffers and Martin, 1986; Oudemans, 1999). Water samples also can be centrifuged to concentrate organisms and the pellet suspended and plated (Steadman *et al.*, 1975). If the target organism is suspected to be present in extremely low numbers, the sample can be amended with an appropriate nutrient and incubated to enhance its numbers (Harrison *et al.*, 1987; Norman *et al.*, 2003) and then processed. Centrifugation combined with direct observation via electron microscopy, indicator plant inoculation, ELISA, or other techniques have been used to detect viruses in water (Tošic and Tošic, 1984; Pares *et al.*, 1992; Berkelmann *et al.*, 1995; Kramberger *et al.*, 2004).

Another frequently used method for detection is baiting with plant parts or whole trap plants and plating the colonized tissue onto media (Tucker, 1931; Klotz *et al.*, 1959; Easton *et al.*, 1969; Gill, 1970; Dukes *et al.*, 1977; Kegler *et al.*, 1982; Datnoff *et al.*, 1984; Pares *et al.*, 1992; Themann and Werres, 1998; Sanchez *et al.*, 2000; Bush *et al.*, 2003; Hong *et al.*, 2003a). The trap plant or bait detection efficacy and pathogen species selectivity must be examined. A significant problem with both baits and trap plants is the sometimes rapid and extensive colonization by

nontarget organisms. For example, *Pythium* species tend to colonize baits more rapidly than *Phytophthora* species, particularly if the bait is wounded during preparation (Themann and Werres, 1998).

Immunochemical techniques enable very sensitive detection and, sometimes, identification of the pathogen to the species level (Ali-Shtayeh *et al.*, 1991; Pettitt *et al.*, 2002). Such tests may detect low numbers of pathogen propagules and do so more rapidly than culture tests. Theoretically, the method with the greatest resolution for DNA-containing organisms is polymerase chain reaction (PCR) amplification of DNA. DNA can be extracted from the residue on the filter paper, colonies on plates, pellets from centrifugation, or colonized baits. It is also possible to obtain results by preparing the PCR mixture and then scraping a sterile disposable pipet tip across a colony on agar and swirling and titurating the tip in the reaction mixture or by using other colony-PCR techniques (van Zeijl *et al.*, 1998; Kong *et al.*, 2005) without extracting DNA. Amplification can be done with universal (Kong *et al.*, 2003a) or species-specific primers (Bonants *et al.*, 1997; Bonants *et al.*, 2000; Kong *et al.*, 2003b). The PCR products can then be processed and analyzed for a distinctive electrophoretic pattern (Kong *et al.*, 2003a), probed with species-specific DNA fragments (Lévesque *et al.*, 1994; Lévesque *et al.*, 1998; Bailey *et al.*, 2002), or sequenced and then identified by comparing the sequence to those of known organisms in a database such as GenBank. PCR-DGGE (denaturing gradient gel electrophoresis) is widely used to assess the structure of microbial communities in environmental samples without culturing. While such a technique can provide a general idea of what may be occurring in aquatic communities, it may also underestimate the size of those communities. For those few organisms that have been tested, DGGE detection thresholds can be as high as 10^4 to 10^8 cfu/ml (Muyzer, 1999; Ercolini, 2004). DNA array technology is a means of monitoring multiple species of pathogens in samples (Lievens *et al.*, 2003). Each of these methodologies has strengths and weaknesses, not the least of which is that they detect the DNA from dead propagules as well as living ones. Although PCR and other DNA-based methods should detect the presence of even one copy of target DNA, many factors come into play to determine the success or failure of the method.

A vexing problem in all detection techniques, whether direct observation, culturing, or molecular, is interpreting the negative result. Was the organism truly absent or did the sampling scheme fail to find the organism that was present in low numbers? Did other organisms overgrow the target organism and prevent detection? Did chemicals present in the sample inhibit reactions used in molecular techniques? Verification of the resolution and accuracy of the methods, using test samples prepared with known numbers of target organisms, should help in this interpretation. The inclusion of an internal check in molecular methods is very helpful. For example in a multiplex system, primers that amplify a segment of DNA that is common in plants, protists, and true fungi are included in the PCR reaction in addition to primers targeting the pathogen. If conditions are conducive to PCR, the reaction should always yield the control product whether the pathogen DNA is present or not (Winton and Hansen, 2001). If such an internal check cannot be designed, the absence of a PCR product makes the interpretation of a negative test difficult.

Once the detection threshold is established and the sample volume and numbers determined, then the other sampling questions can be answered. Many studies have reported the temporal fluctuation in both microbial population size and community composition in water over the course of the year or growing season (Cooke, 1956; Faulkner and Bolander, 1970; Thomson and Allen, 1974; Steadman *et al.*, 1975; Dukes *et al.*, 1977; Shokes and McCarter, 1979; Paludan, 1985; Jorge and Harrison, 1986; Harrison *et al.*, 1987; Thinggaard and Middelboe, 1989; MacDonald *et al.*, 1994; Berkelmann *et al.*, 1995; Pottorff and Panter, 1997; Themann *et al.*, 2002; Bush *et al.*, 2003; Koohakan *et al.*, 2004). It is important to study these fluctuations so that it can be determined when samples should be collected. Populations of some pathogens have been shown to vary in horizontal and vertical spatial distribution in water (Harvey, 1952; Easton *et al.*, 1969; Dukes *et al.*, 1977; Shokes and McCarter, 1979; Rattink, 1990; MacDonald *et al.*, 1994; Wilson *et al.*, 1998; Oudemans, 1999; Themann *et al.*, 2002; Bush *et al.*, 2003), whereas others may be fairly uniformly distributed (Faulkner and Bolander, 1967; Neher and Duniway, 1992). Knowledge of the spatial distribution will determine where sampling is best conducted as well as help determine the size and number of samples collected. As will be discussed later, knowledge of a pathogen's temporal and spatial distribution in the system may be used to advantage in developing control tactics.

While many of the techniques noted here can be used to quantify the target organism in samples, there is little information on biological thresholds, that is, the amount of inoculum present in irrigation water associated with subsequent disease development. This is an essential question to address in disease management (Riffaud and Morris, 2002). The number of infective propagules necessary to incite disease depends on pathogen exposure frequency (Hong and Epelman, 2000; 2001), irrigation method (Stanghellini *et al.*, 2000), and soil or growing media (Spencer and Benson, 1982; Boehm and Hoitink, 1992; Diab *et al.*, 2003). In cases where pathogen-containing water is used throughout the season, the detection of any amount of inoculum of a major pathogen may call for the implementation of control measures because repeated inoculation occurs. However, if a pathogen is only intermittently present, control may not be called for unless propagule numbers approach some critical level.

If more than one species of plant pathogen is found in the irrigation water, as is often the case (Cooke, 1956; Thomson and Allen, 1974; Bush, 2002; Bush *et al.*, 2003), the task of determining biological thresholds is further complicated. It may be assumed that certain species are highly pathogenic and their presence at any level is of serious concern but many other species are secondary parasites or only able to cause crop losses under

specific conditions. For example, *Pythium aphanidermatum* is a serious and lethal pathogen of many herbaceous plants, whereas *Py. irregulare*, in the same production facility, stunts but seldom kills plants (Pittis and Colhoun, 1984; Moorman *et al.*, 2002). *Pythium dissotocum* carried in irrigation water can suppress yields without causing other symptoms (Stanghellini and Kronland, 1986). Depending upon the mix of pathogens in the water, the growing conditions, and the susceptibility of the single or multiple crop species being irrigated, biological threshold information may be needed on each host-parasite combination or only one or two of the major ones. Until research explores the additive, synergistic, and antagonistic effects that probably occur among pathogens and that probably also occur between pathogens and the other microbes in the aquatic community, this is largely speculation.

The speed, accuracy, and resolution of detection and monitoring methods have improved greatly with the advent and development of immunochemical and molecular techniques. Molecular methods that can definitely show, for example, that an isolate obtained from infected plant roots is identical to one isolated from irrigation water need to be applied. AFLP (amplified fragment length polymorphisms), ISSR (inter-simple sequence repeat) and other analyses promise such capabilities (Vos *et al.*, 1995; Chowdappa *et al.*, 2003; Lamour *et al.*, 2003; Menzies *et al.*, 2003; Garzón, 2004; Huang *et al.*, 2004). Procedural problems yet to be solved to facilitate the research include the need for the following: 1) high throughput procedures so that large numbers of environmental samples can be processed quickly, 2) lowering the cost of the research through a reduction in the man hours required for processing samples, and 3) reducing the cost of materials needed in the various procedures. Looking beyond the research, growers will need simple, user-friendly, accurate and reliable methods for detecting and monitoring pathogens in their water at the farm or production facility.

TABLE 7
Methods of reducing or eliminating plant pathogens from water

Method	Reference
Slow sand filtration	Ellis, 1985; Logsdon, 1990; Barrett *et al.*, 1991; Wohanka, 1992; Collins and Graham, 1994; Calvo-Bado *et al.*, 2003
Ultraviolet light	Runia, 1988
Chlorination	Daughtry, 1988; Austin, 1989; Skimina, 1992; White, 1999; Hong *et al.*, 2003b
Ozonation	Yamamoto *et al.*, 1990
Heat	Runia, 1988; van Os *et al.*, 1988; Ehret *et al.*, 2001
Pressure	Heald and Johnson, 1969
Surfactants	Spotts, 1982; Stanghellini *et al.*, 1996; Stanghellini and Miller, 1997; Stanghellini *et al.*, 2000
Sedimentation	Rattink, 1990; Skimina, 1992; Wilson *et al.*, 1998; Sojka and Entry, 2000
Antimicrobial compounds	Haglund *et al.*, 1972; Cohen and Coffey, 1986; Lyr, 1995; Knight *et al.*, 1997; Thomson, 1997
Suppressive potting mixes	Boehm and Hoitink, 1992; Hoitink and Boehm, 1999; Diab *et al.*, 2003
Biological control agents	Liu and Baker, 1980; Laing and Deacon, 1990; Deacon and Berry, 1993; Jeong *et al.*, 1997; Jeong *et al.*, 1997; Paulitz and Belanger, 2001; Guetsky*et al.*, 2002; Ramon, 2003

VI. MANAGEMENT OF PLANT PATHOGENS IN IRRIGATION WATER

Once it has been verified that a pathogen is indeed being carried in the irrigation water, an assessment must be made as to whether and when the pathogen poses such a significant threat to the crop to require treatment. Natural pathogen population fluctuations may allow the cessation of treatment at certain times of the year, thereby reducing management costs while not jeopardizing the health of the crop. Likewise, if a highly susceptible crop is not present at certain times of the year, the crops that are present may not require control of a particular pathogen. In some cases, the pathogen's presence can be tolerated as long as growing conditions inhibit its activity or enhance host plant resistance (Moorman, 1986; Gladstone and Moorman, 1989; Thinggaard and Andersen, 1995; von Broembsen and Deacon, 1997). When control is necessary, strategies and tactics can be selected from an arsenal of methods currently available to reduce or eliminate a wide variety of plant pathogens from water (Table 7). Each approach has advantages and disadvantages and each requires a certain level of grower education and commitment to be successfully applied. None of the methods is simple or a one-time treatment (von Broembsen *et al.*, 2001).

Control strategies for pathogens in water have been developed and tested through experimentation, often in prototype systems rather than under actual use conditions. The lack of published reports on the performance of various systems under actual use conditions is a serious gap in our knowledge. *Fusarium*, *Pythium*, tobacco mosaic virus, *Olpidium*, *Agrobacterium*, and *Verticillium* are frequently employed as test organisms to verify system efficacy, presumably under best-case scenarios (Yamamoto *et al.*, 1990; Paludan, 1992; Poncet *et al.*, 2001). Viable propagule counts reduced by 95 percent or 99.9 percent by a strategy may be judged as sufficient, depending upon the test organism used, but this can be questioned since repeated inoculation occurs when a pathogen is in irrigation water. What follows is based on available published information and what, in theory, seems to make sense.

Since most water treatment methods are expensive, at least to establish initially, all possible steps should be taken to use an initial water source that is free of the pathogen and to prevent

the pathogen from entering the water. If a clean water source is not available or the pathogen cannot be prevented from entering the irrigation system, then a number of physical and chemical control methods are possible. A blanket recommendation for the treatment of pathogens in water cannot be made because every production facility is unique and each individual case is influenced by the following factors:

1. quality of the water to be treated, its pH, turbidity, and mineral content,
2. quantity of water that must be treated in a given period of time,
3. allowable changes in water quality that occur during treatment,
4. population level to which the pathogen must be reduced to protect the crop,
5. susceptibility of crops being grown,
6. cultural practices being used, and
7. economic resources, education level, and time commitment required of the persons who must apply the strategy in an effective manner.

Mitigation of plant pathogens in irrigation water requires a case-by-case evaluation and a customized approach to control (Pettitt, 2003).

A. Avoidance

Steps should be taken to prevent the introduction of plant pathogens from known possible sources into water. For example, if plants are seeded elsewhere and then transplanted into an irrigated area, it is important to transplant only healthy material, free of pathogens that may spread via water. Also, great care should be taken to prevent contaminated soil or crop debris from being carried into the water. Relatively simple sanitation procedures can help to avoid introducing pathogens into otherwise clean water.

Along the lines of avoidance is the management of water sources in a manner that inhibits the growth and development of pathogen populations. Themann *et al.* (2002) raise the idea that susceptible species should not be planted near reservoirs because their leaves could fall into the water and become good food sources for pathogen survival and propagation. A common practice of many ornamental producers is to enhance their grounds with examples of the crops they grow or use these plants for erosion control. Planting susceptible species close to or in water supplies, canals, or drainage ditches may significantly contribute to the amount of inoculum in the system. It could also be argued that algal growth be kept to a minimum in water (Bewley and Buddin, 1921) and that plant debris from mowing, brush management, pruning, fruit culling, and various plant-grooming measures be kept out of all parts of a water system in order to reduce the organic matter available for saprophytic activity of pathogens (Hockenhull and Funck-Jensen, 1983).

As noted previously, the horizontal and vertical distribution of plant pathogens in the water and the production area may vary greatly. It may be possible to avoid the uptake of propagules by placing intake pipes at depths or in locations where the pathogen is least likely to be located (Harvey, 1952; Easton *et al.*, 1969; Dukes *et al.*, 1977; Shokes and McCarter, 1979; Rattink, 1990; MacDonald *et al.*, 1994; Wilson *et al.*, 1998; Oudemans, 1999; Themann *et al.*, 2002; Bush *et al.*, 2003). In some cases, the pathogen may be fairly uniformly distributed, however (Faulkner and Bolander, 1967; Neher and Duniway, 1992).

In systems that recycle the water, it may be possible to reduce the amount of inoculum circulated in the system by minimizing or eliminating the volume of excess water. Trickle or drip irrigation systems, controlled to add just enough volume to provide sufficient water to maintain growth without adding excessive amounts that must be captured, could minimize the washing of propagules from the crop to holding ponds and also minimize erosion of contaminated soil into drainage ditches and ponds. Such pulsed irrigation regimes are being used in greenhouses and nurseries in order to conserve water and have been documented to reduce water runoff by as much as 77 percent (Kabashima, 1993). In containerized production, this requires the careful adjustment of fertilizer applications and the monitoring of soluble salts in the containers because there is little or no leaching to remove accumulating nutrient salts.

B. Physical Barrier

In greenhouses, growers sometimes place potted plants on a fiber mat that is then wetted to allow the water to be taken up by the potting soil via capillary action through holes in the bottoms of the containers. One study suggests that less Phytophthora rot develops if the zoospores must pass through such a mat (van der Gaag *et al.*, 2001). Larger spores of other organisms may also be excluded by use of a physical barrier between the water and the potting soil.

C. Sedimentation

Fusarium spores (Price and Fox, 1984; Rattink, 1990) and *Phytophthora* propagules (Wilson *et al.*, 1998) tend to settle out of water. Use of this settling process for water decontamination may be accomplished by addition of primary and secondary ponds between the water source or the effluent returning to holding ponds for recycling and the point where the water is taken up for distribution to the crop (Dukes *et al.*, 1977; Shokes and McCarter, 1979; Rattink, 1990; Skimina, 1992; Wilson *et al.*, 1998). In addition, non-toxic, high molecular weight anionic polyacrylamides could facilitate the sedimentation and immobilization of microbes in irrigation water (Sojka and Entry, 2000). These materials have been used to remove clay particles from flowing water.

D. Filtration

Filters of many porosities and designs are available to treat water. Their main limitations are clogging caused by particulate

matter, labor and replacement costs required to keep them free of clogging, the size required to treat the requisite amount of water in the desired time frame, and the expense of initial installation.

Slow sand filtration has been used for over a century for drinking water treatment and continues to be used for that purpose (Ellis, 1985; Barrett *et al.*, 1991). The physical pore space removes many propagules and a biologically active layer or *schmutzdecke* reduces the number of viable propagules. The amount of time the water is held in the space above the sand filter plays a role in improving the quality of the water (Ellis, 1985). The sand column need only be about 1 meter in depth but only can filter water at a rate of 2.4 m^3 of water per m^2 of filter surface area per day by gravity after the water is pumped to the head space of the unit. Therefore, to increase the filtering capacity, the surface area of the filter must be increased. The space needed for a filter of the required diameter may be very large. In a cold climate, a small filter may need to be in an area insulated well enough to prevent it from freezing. However, slow sand filters are easily built from readily available materials and can be maintained by someone with minimal construction and plumbing skills.

There are a number of membrane-type filtration systems that can be used to remove microbes from the water. Various synthetic materials formed into flat sheets, pleated sheets, or cylinders can be used alone or in various combinations to remove large particulates from the water and then progressively smaller entities. Although some units can pass up to 100,000 liters of water through a 5-μm filter without pretreatment, prefiltering would extend the time that good flow rates can be maintained (Palzer, 1980). Systems are available that automatically backwash the filters to alleviate clogging and improve their efficiency. Reverse osmosis, used to clean mineral-contaminated water, removes microbes. The options for filtration are numerous. There are companies whose specialty it is to consult with growers and design filtering systems to specifically meet their water treatment needs. There are few water filtration requirements that cannot be met by products currently on the market, as long as sufficient funds are available for their purchase and installation and the grower can be educated to operate the system properly.

E. Heat

Heat is one of the most reliable methods for treating water to eliminate all types of plant pathogens. Heat exchangers can be used to first preheat and then further heat water to a desired temperature (Runia, 1995; Poncet *et al.*, 2001). The quality of the water to be treated must be good, in that it must be mostly free of particulate matter. High mineral content will, in the long term, result in the formation of deposits in the exchangers and associated plumbing and result in a lowering of efficiency of the system over time. To reduce costs, the treated water is pumped back through one exchanger to recover some of the energy for preheating the initial water and to begin to cool the treated water. It is then pumped to a holding tank to further cool and store it. These holding tanks must be in an area where the water can be protected from contamination prior to use. The major limitation of using heat is the cost of the energy and equipment required, the amount of time needed for treatment, and the volume of the storage tank needed to treat and hold water. It may be feasible to use heat-treated water for just the critical stages of crop production such as during the propagation of young, highly susceptible plants (Bewley and Buddin, 1921).

F. Ultraviolet Light

Radiation with a wavelength between 200 and 280 nm is strongly germicidal and has been used to eliminate microbes from drinking water (Downey *et al.*, 1998). At the appropriate intensity and exposure time, ultraviolet light can eliminate species of all major plant pathogen groups from water of the proper quality. The water to be treated must be free of particulates, clear, and relatively uncolored. Some of these factors can be adjusted through filtration (Grech *et al.*, 1989; Runia, 1994) and it is possible to predict the disinfection efficacy of an ultraviolet light system (Downey *et al.*, 1998). The main limiting factors in using ultraviolet light are the quality of the water to be treated and the expense of purchasing and installing equipment of sufficient capacity to meet the needs of the grower. The cost of operating the systems may be somewhat reduced as the technology of pulsed ultraviolet light is introduced (Demirci, 2002).

G. Pressure

A great deal of work in food science has been done to determine whether pressure (Hoover, 1992) and turbulence can eliminate bacteria and fungi during food processing. This treatment requires a closed chamber. For example, pressurization of a chamber with carbon dioxide can kill some bacteria on seeds without reducing the germination of the seeds (Mazzoni *et al.*, 2001). Although pressure chambers are unlikely to find a use in large-scale water treatment, pressure at the water pump or at the sprinkler nozzle may damage, and render noninfective, nematode larvae in water (Heald and Johnson, 1969). More work must be done to test this possibility with other plant pathogens in water.

H. Surfactants

Plant pathogens whose inoculum is primarily zoospores are susceptible to control through the application of surfactants to the water. Surfactants rapidly lyse *Olpidium* (Tomlinson and Faithfull, 1979a), *Phytophthora* (Stanghellini and Tomlinson, 1987; Stanghellini *et al.*, 2000), and *Pythium* zoospores (Stanghellini *et al.*, 1996; Stanghellini and Miller, 1997). If any of the inoculum is in the form of mycelium or encysted zoospores that germinate directly, surfactants do not disrupt those life stages (Stanghellini and Tomlinson, 1987). If the concentration of the surfactant can be maintained in the system,

plants can be protected from zoosporic inoculum but not inoculum of other types (Moorman and Lease, 1999).

I. Chlorination

Chlorine has been used successfully to disinfect public water supplies, to control post harvest diseases of fruits and vegetables, and to treat water in nursery and greenhouse irrigation systems (Steadman *et al.*, 1979; Lacy *et al.*, 1981; Daughtry, 1988; Poncet *et al.*, 2001). It has been shown that while effective in reducing numbers of plant pathogens in water, chlorinated water does not necessarily do so in the soil, and that pathogens differ in sensitivity to chlorine (Datnoff *et al.*, 1987; Grech and Rijkenberg, 1992). Chlorine can be added in a number of ways including granular materials (as for swimming pools), injection of gaseous chlorine, and the electrolysis of sodium chloride (Demirci, 2002). Chlorine dioxide has been tested for disinfesting fruit and vegetable wash water rather than irrigation water but was found ineffective or not economically feasible in some cases (Spotts and Peaters, 1980).

Chlorination efficacy is influenced by the water pH, inorganic and organic chemical content, the microbial content in the water (Steadman *et al.*, 1979; Lacy *et al.*, 1981; Daughtry, 1984; Grech and Rijkenberg, 1992) and the life stage of the pathogen present (Hong *et al.*, 2003b). It is crucial for the user to test the treated water to be certain the desired amount of free available chlorine is present. Anywhere from 2 to 8 mg/L of free chlorine may be needed (Hong *et al.*, 2003b; Hong and Richardson, 2004) for a specific time period determined by the environmental conditions at the time of exposure. Concentrations needed to eliminate plant pathogens are known to be phytotoxic to some plants (Price and Fox, 1984; Bugbee, 1987; Datnoff *et al.*, 1987; Fett, 2002).

J. Ozonation

Ozone, used for drinking water treatment since 1906, quickly oxidizes substances when bubbled through water. The ozone is reduced to oxygen and has no residual activity against organisms in the water, and therefore leaves no residues that might be toxic to the irrigated plants. Plant pathogenic organisms have been shown to have widely differing sensitivities to ozonation (Yamamoto *et al.*, 1990). Inactivation of organisms is better under acidic conditions than under alkaline conditions (Runia, 1995). Major disadvantages of ozone treatment are that fertilizers in water being recycled will also be oxidized and a treatment tank and a holding tank are required.

K. Antimicrobial Compounds

Various classes of inorganic and organic antimicrobial compounds have been tested for use directly in the water, including copper and zinc (Smith, 1979; Tomlinson and Faithfull, 1979a; Toppe and Thinggaard, 1998), hydrogen peroxide, sodium phosphate, phosphorus acid, EDTA (Runia, 1995; Fett, 2002; Yun, 2003) and various organic fungicides and bactericides (Smith, 1979). Two approaches have been employed when antimicrobials are used to combat pathogens in irrigation water. The first is to apply the chemical to the plant or the surrounding soil. This is one of the most commonly selected tactics since fungicides became available in the 1940s and their efficacy has increased as better and more selective chemicals have been developed. The second approach, particularly in water recycling systems, is to put the antimicrobial compound directly in the irrigation water. The chemical is placed in direct contact with the pathogen propagule and is also being delivered to the plants to be protected. While placing the antimicrobial directly in the water may be a reasonable approach if the irrigation water is not captured and recycled, amending recycling irrigation water with a chemical poses two serious problems. First, if the amended water must be discarded before the active ingredient has broken down, the grower is faced with the task of properly disposing of thousands of liters of hazardous waste. Second, if the grower does not continue to add the chemical with each cycle of watering, the active ingredient is quickly diluted because the holding tank is toppedoff with fresh water to replace water used by the plants and lost through evaporation and system leakage. Under such conditions, surviving pathogen populations will be exposed to sub-lethal doses of active ingredients for an extended period of time, thus favoring the selection of fungicide-resistant individuals in the pathogen population. Fungicide-resistant populations of *Pythium* were first observed in ebb-and-flow irrigation systems in Pennsylvania in two such situations (Moorman, unpub.).

Although not antimicrobial, calcium has been added to irrigation water in an attempt to disrupt the activity of *Pythium* and *Phytophthora* zoospores (von Broembsen and Deacon, 1997; Moorman and Lease, 1999). Calcium concentration influences the motility pattern in these pathogens (Deacon and Donaldson, 1993; Reid *et al.*, 1995). While not providing adequate control alone, calcium supplementation may help in reducing some part of the epidemic caused by zoosporic inoculum.

L. Pathogen-Suppressive Soils and Biological Control Agents

Pathogen-suppressive soils were defined as soils in which the pathogen does not establish or persist, or establishes but causes little or no damage, or establishes and causes disease for a while but thereafter the disease is less important, although the pathogen may persist in soil (Baker and Cook, 1974). Use of suppressive soils or potting mixes or incorporation of suppressive materials around plants in the field is an alternative to treating the water to remove pathogens of concern or applying a chemical to protect plants (Hoitink *et al*., 1991; Hoitink and Boehm, 1999). Suppressive soils, composts and potting mixes could provide protection from a number of sources of oomycete and other pathogens (Cook and Baker, 1983; Diab *et al*., 2003).

Plants could also be protected from selected pathogens through the application of biocontrol agents to the soil (Martin and Loper, 1999; Paulitz and Belanger, 2001) or to recirculating nutrient solutions (Ehret *et al.*, 2001). Paulitz and Belanger

(2001) provided a thorough review on current products for biological control of soilborne and foliar pathogens. Whether the frequent and intensive use of biocontrol agents could eventually result in these agents becoming residents of a total production system and thus provide long-term control awaits evaluation.

In summary, each of these strategies has advantages, disadvantages, costs, and benefits. They can be used singly or in various combinations (Grech *et al.*, 1989). Indeed, a municipal-type water treatment plant employing a sequence of methods may be appropriate in some situations (Skimina, 1992) if the grower can bear the cost. However, many factors influence the functioning of various systems and there is a tremendous need for information on the performance of these various control strategies under actual use conditions. Avoidance, sanitation, methods to exclude or remove pathogens from water, tactics to kill pathogens already in the water, and methods of protecting plants from the pathogens that evade these attempts could be thought of as obstacles of increasing height thrown in front of pathogens. The final and worst case is the one in which the pathogen very often evades all attempts at control and the inoculum consistently arrives at the infection court at some time during the growing season. Facing this situation, it may be necessary for a grower to raise only those species or cultivars that have tolerance or resistance to the pathogen in the irrigation water and grow susceptible species in another manner.

VII. CONCLUDING REMARKS

Information in numerous abstracts was not used in this review because final results can be very different from those in hand as abstracts are written. These reports indicate a wealth of data, observations, and experiences awaiting completion and final communication (Irwin and Vaughan, 1972; Mircetich *et al.*, 1985; von Broembsen and Wilson, 1998; McCracken and Jeffers, 2000; von Broembsen and Charlton, 2000; von Broembsen, 2002; Cohn and Hong, 2003; Banko *et al.*, 2004; Nielsen *et al.*, 2004). There is a great need for further work on the subject of plant pathogens in irrigation water.

A large diversity of organisms may be present in water. Accurate and rapid tests of high sensitivity are needed to detect plant pathogens in irrigation systems. Research should note the presence and pathogenicity of various isolates, but must also address the ecology of these organisms. It is crucial to learn whether each pathogen encountered is a resident of water or merely a transient traveler in the aquatic system. We need to determine why some species are able to thrive for long periods in water while others merely pass through. It is very likely that there are as yet undiscovered interactions among the various organisms in water. The significance of the presence of several "weak" parasites in one pond or one stream or one greenhouse holding tank is unknown as is their influence on the activity of more aggressive pathogens in the same location. Also awaiting elucidation are the identity and role of the numerous "contaminants," especially bacteria, encountered when isolating and maintaining plant pathogens from water. These may play significant roles in pathogen population fluctuations in nature.

Very little information on the efficacy of the various management methods noted here is available from the production setting. Scientists need to evaluate strategies and verify that a specific system actually results in significant crop protection under the prevailing production conditions. Those production conditions must be elucidated, noting the quality and quantity of water treated. Every production system or farm is a unique case to some extent or the grower is under different constraints from his neighbor. Management strategies must be designed to fit each case. If case histories can be accumulated and enough details provided, it should become easier to address each new case that arises.

To reach a better understanding of the ecology and management of plant pathogens in irrigation water, teams consisting of entomologists, hydrologists, agricultural engineers, agricultural economists, statisticians, population ecologists, population geneticists, plant pathologists and farmers are needed to ensure that sound and practical results are obtained. Our current lack of understanding requires that scientists assist growers in evaluating the problem and in making decisions as to what must be done. As our understanding increases and information is put in a format that can be used by farmers, farmers will demand tools for daily use to detect and monitor pathogens and track the effect that control measures are having on those pathogens. As was stated in 1988 (Zinnen), growers only assay for pathogens in water is still a bioassay, their crop. It is unlikely that research scientists will routinely assay water samples for growers. Assuming that a fee-based service for the rapid and accurate identification of plant pathogens in water is not in the offing, growers will require simple, user-friendly, do-it-yourself systems. Perhaps a microarray that merely needs to be incubated in the water for the detection of the common and major plant pathogens is not outside the realm of possibilities.

The problem of plant pathogens in irrigation water was recognized as a challenge to plant health early in the development of the science of phytopathology. Almost 100 years later, it is increasingly of global importance and continues to offer many challenges to our skills and creativity and opens many opportunities for developing a better understanding of plant pathogens.

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