Controlling Pests that are Spread in Irrigation Water

by Thomas D. Landis

The evidence that irrigation water can be a significant source of nursery pathogens has been accumulating for almost a century. In one of the first systematic testings of agricultural water sources, Bewley and Buddin (1921) isolated several pathogens including *Botrytis* spp. and *Phytophthora* spp. Although links between waterborne pests and nursery diseases have often been circumstantial, DNA analyses have now shown that specific isolates from diseased plants were identical to pests found in irrigation water (Hong and Moorman 2005).

Waterborne pests have been responsible for major losses in nurseries (Fisher and Smith 2007). *Phytophthora ramorum*, the cause of sudden oak death, spreads in water from plant-to-plant in nurseries and from nurseries to surrounding plant communties. Therefore, this waterborne pathogen is one of the most serious threats facing growers today (Chastagner and others 2010). Because *P. ramorum* not only causes shoot and leaf blights in a wide variety of nursery hosts but can also spread through runoff to plants in the surrounding forests, it is considered one of the most serious threats to forest, conservation, and native plant nurseries (Landis 2013).

It is critically important to have an overall plan. Two major approaches to phytosanitation can be employed. The systems approach is based on a hazard analysis of critical control points where waterborne pests could gain entry into your nursery. The comprehensive programs that have been developed for ornamental nurseries can easily be modified for forest, conservation, and native plant facilities (Parke and Grunwald 2012). Another option is based on target pests (Landis 2013): nurseries should learn as much as possible about potential waterborne pests and determine how, where, and when to check their irrigation water. So, the following discussion focuses on learning which pests can be spread in irrigation water, how to test irrigation water, and options for treating irrigation sources to eliminate any threats.

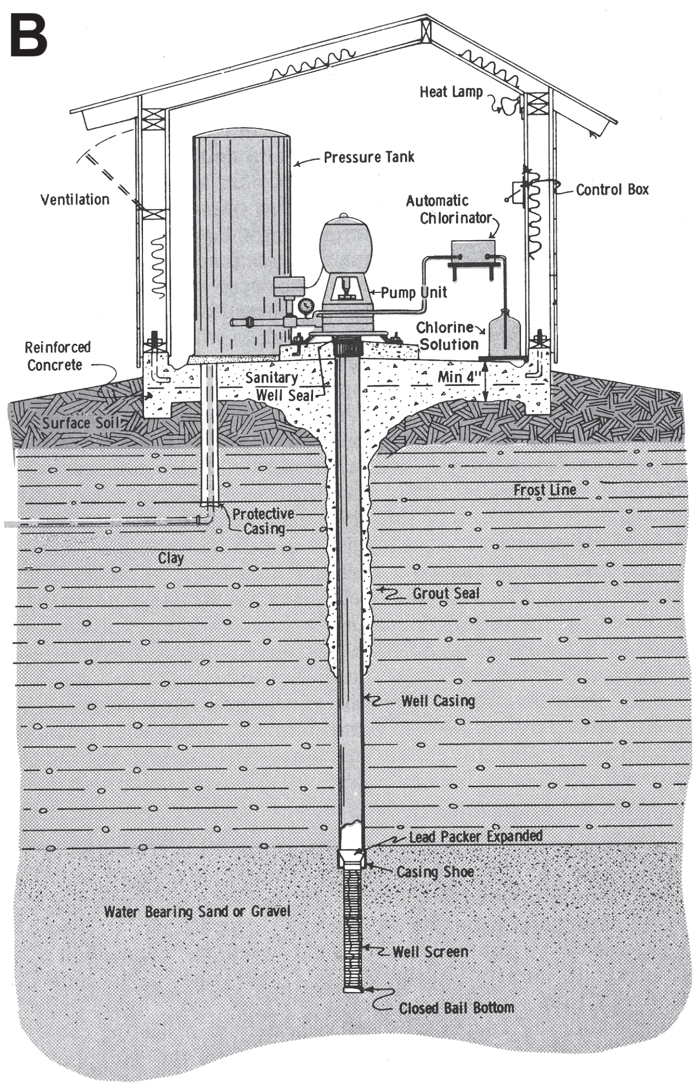


Figure 1 - Nurseries using irrigation water from surface water sources such as ponds, lakes, or rivers (A) may encounter problems with a variety of pests including weed seeds or spores of pathogenic fungi, moss, algae, or liverworts. Water from a well-designed well (B) has been shown to be free from waterborne pathogens (B modified from Whitsell and others 1982).

1. Pests in irrigation water

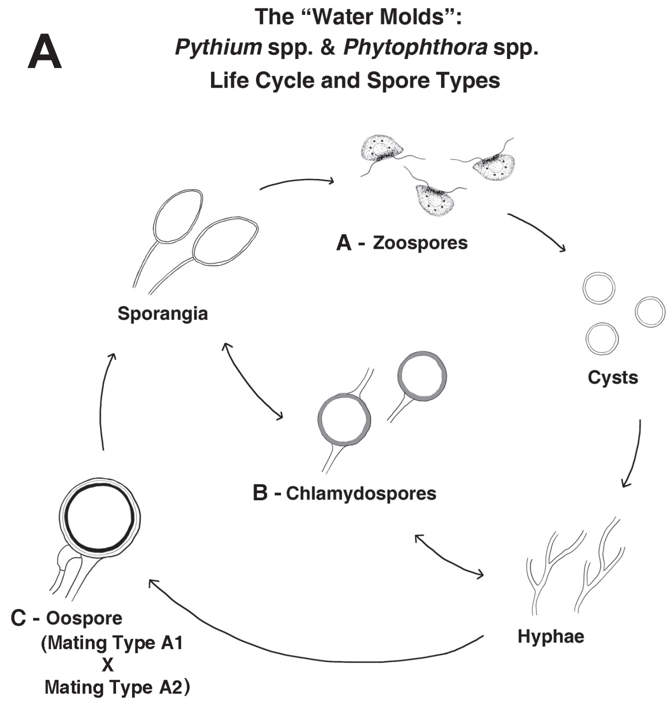
Water does not naturally contain organisms that can cause plant disease but irrigation sources often become contaminated, especially in agricultural areas. The source of your irrigation water is critical to determining whether it might contain pathogens and therefore require treatment. Water from ground wells can be considered pest-free (Fisher and Smith 2007), but ponds, ditches, rivers and other surface waters have been shown to contain propagules of almost every major pathogen group (Hong and Moorman 2005)(Figure 1). However, if well water is stored in unlined ponds, it can still become contaminated (Baker and Matkin 1978). Many nurseries are now recycling or are considering reusing runoff water and this makes the subject of waterborne pathogens even more important. Recycled water has been proven to contain several pathogens, and must be tested and treated before it can be reused (Black 2009).

1.1 Water molds

Pythium spp. and *Phytophthora* spp. are fungus-like pathogens that are uniquely suited for water transport because of their motile zoospore stage. In addition, they have 2 other resting spore stages called chlamydospores and oospores (Figure 2A) that allow them to survive in infected plant material for months or even years. One estimate is that an infected fragment only 1 mm long could contain 50 to 100 resting spores (Wick and others 2008), and organic wastes can be transmitted in nursery runoff. In a review of the literature, 17 species of *Phytophthora* and 26 species of *Pythium* have been identified from water samples (Hong and Moorman 2005). Therefore, control of water molds in irrigation and especially in recycled nursery water has been getting a lot of recent attention (Meador and others 2012).

1.2 Fungi

More than 25 fungal genera including *Botrytis* spp. and *Rhizoctonia* spp. have been found in nursery irrigation water (Baker and Matkin 1978), but their relationship to actual nursery diseases is sometimes hard to prove (Hong and Moorman 2005). *Fusarium* spp., on the other hand, has been confirmed to spread between plants in greenhouse water (Wick and others 2008). *Botrytis cinerea*, *Cylindrocladium candelabrum*, and *Ralstonia solanacearum* are the fungi most associated with diseases in Brazilian forest nurseries and have been shown to be transmitted through water (Machado and others 2013). Obviously, much depends on the type of irrigation system; spores from pathogenic root fungi would



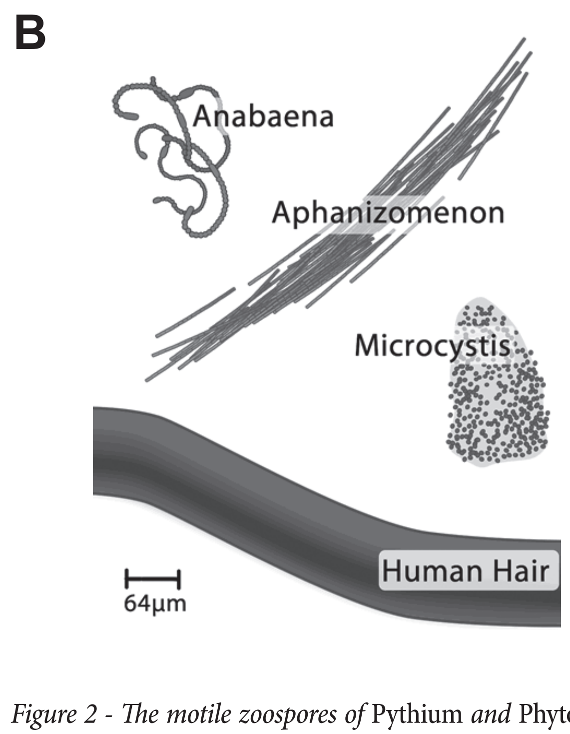


Figure 2 - The motile zoospores of Pythium *and* Phytophthora *are especially suited for water transport, and the resting oospores and chlamydospores can be transported in organic suspensions (A). Propagules of algae (B) and liverworts can also be introduced in irrigation water from surface sources (A modified from* Phytophthoras *of the World 2013; B courtesy Lakes of Missouri Volunteer Program 2013).*

be more likely to spread in recycled water or under subirrigation systems.

1.3 Bacteria

Although bacterial diseases are not common in most woody plants in forest, conservation and native plant nurseries, 8 different species of bacteria have been confirmed in nursery irrigation water. The pathogenic bacteria *Erwinia* spp. and *Xanthomonas* spp. have been shown to spread through water, and to cause disease in ornamental crops (Hong and Moorman 2005). *Xanthomonas axonopodis* is a pathogenic bacterium that is introduced in irrigation water in eucalyptus nurseries in Brazil (Machado and others 2013).

1.4 Nematodes

Plant parastic nematodes can be carried in muddy water but usually settle to the bottom of storage ponds (Baker and Matkin 1978). In a search of the literature, 13 species of plant parasitic nematodes were confirmed in nursery irrigation water. However, several nematode species identified in a water source did not survive when applied through a sprinkler irrigation system (Hong and Moorman 2005).

1.5 Algae, mosses, and liverworts

Although not widely appreciated, propagules of algae (Figure 2B), mosses, and liverworts are easily spread through irrigation water. Even though they are not considered classical pathogens, these primitive plants can cause serious problems in nurseries. Mosses and liverworts can become so thick on the top of container plants that they interfere with water absorption (Svenson and others 1998). In Oregon, liverworts were rated as the worst container nursery weed problem (Hester and others 2013). Harmful algal blooms can develop in irrigation storage ponds or ditches, especially when fed with surface waters high in nitrogen and phosphorus. Certain blue algae, such as *Microcystis aeruginosa* (Figure 2B), produce toxins when they die that can be harmful to humans and pets (Wikipedia 2013). Algal blooms have resulted in legal action in one forest nursery, and even nontoxic algae can plug irrigation nozzles (Haman 2013). Algal mats on the surfaces of container plants create ideal conditions for fungus gnats, which can become a serious plant pest (Landis 2007). Algal slime can create a safely hazard on walkways and create unsightly and unsanitary conditions that give nursery customers a bad impression (Merrill and Konjoian 2006).

1.6 Viruses

At least 10 plant pathogenic viruses have been documented in irrigation water (Hong and Moorman 2005) but none have been associated with diseases in forest, conservation, or native plant nurseries.

2. Detecting and monitoring waterborne nursery pests

As we have just discussed, water from wells is much less likely to contain pathogens than water from rivers, ponds, or other surface sources and recycled irrigation water is particularly suspect. So, how can you test your water source and determine if pest populations are present and are high enough to cause problems? A pathological evaluation of your irrigation water should determine whether the pathogen can be detected (the detection threshold) and whether populations are high enough and for sufficient time (the biological threshold) to pose a real threat to your crops (Hong and Moorman 2005).

It is important to obtain an accurate evaluation of your water quality because treating irrigation water can be an expensive operation. The first step is to determine what pests you are looking for because sampling and testing procedures can vary considerably. A recent national survey tested irrigation water quality at 5 points including the source, storage tanks, subirrigation, furthest outlet, and catchment basins. However, because the researchers only assayed the water samples for "aerobic bacteria" and "yeasts and molds" (Meador and others 2012), this general information really does not help detect which could be causing problems.

No single test will detect all potential waterborne pests, so irrigation water should be assayed by specific diagnostic techniques. Laboratory tests are available from some water treatment companies, university plant pathology laboratories, and private microbiology laboratories. For example, the Soil and Plant Testing Laboratory at the University of Missouri at Columbia will perform a basic water quality test for about $35 (Schultheis 2013).

2.1. Microscopic examination

Light microscopy is the classical method for detecting and enumerating algal species, and detection of nematodes requires direct examination and counting under a microscope (Baker and Matkin 1978). Identifying algal species and determining population levels requires specialized training and standard protocols, such as Standard Methods for the Examination of Water and Wastewater, must be followed. Although microscopic examinations provide important visual confirmation of which algal species are found in water samples and generates reasonably accurate population information, it is tedious and time-consuming (Sellner and others 2003). Therefore, laboratories specializing in algal analysis, such as Phyco Tec should be consulted if a problem exists; their website is a wealth of information on identifying and treating algae in irrigation systems (http://www.phycotech.com/).

2.2 Culturing on selective media

Water molds, fungi, and bacteria must be identified after culturing on selective agar or in liquid culture, and the number of colonies that grow from one milliliter of water can then be counted in terms of colony forming units per milliliter of water (cfu/ml) (Fisher and Smith 2007). One of the oldest tests for waterborne pathogens is the use of apples, pears, or other plant tissues as baits for water molds. The zoospores of both *Phytophthora* spp. and *Pythium* spp. are attracted to the baits, penetrate the tissue, and cause small circular decayed areas (Figure 3). Castor bean (*Ricinus communis*) leaf discs were used to bait *B. cinerea* and *C. candelabrum* from nursery irrigation water in Brazil (Machado and others 2013). The number of lesions per bait give a rough estimate of the pest population (Baker and Matkin 1978), but culturing on selective media is required for specific information. A wide variety of plant tissues or seedlings have been used as baits for *Phytophthora* spp, but leaves of rhododendron plants have proven to be the most effective (Orlikowski and Ptaszek 2010). Recent research into detecting and monitoring *Phytophthora ramorum* in and around nurseries has resulted in specific protocols for this important waterborne pest (USDA APHIS 2013).

Vacuum filtration of irrigation is a new technique that was found to be more effective for detecting *Phytophthora* species in streams, and also provided information on inoculum density (Hwang and others 2008).

2.3 Serological tests

The enzyme-linked immunosorbent assay (ELISA) test uses antibodies and color change to identify a substance, and is basically the same as home pregnancy tests. However, due to cross reaction with other closely-related species, it can be difficult to positively confirm a specific pathogen. But, if large numbers of samples

Figure 3 - Fruits, leaves and other baits attract the zoospores of water molds, and then the lesions can be cultured to identify individual species.

are to be processed, ELISA can be used as a low-cost prescreening to reduce the number of samples that will need to be processed for subsequent tests (Kliejunas 2010). In the Pacific Northwest, the recommended procedure for detecting water molds is to bait irrigation water sources with *Rhododendron* spp. leaves for one week and then test the leaves with ELISA kits (Parke and Fisher 2013):

> Phytophthora ImmunoStrip® is a dipstick on-site kit that can be used to detect *Phytophthora* spp. and *Pythium* spp. (Agdia 2013).
>
> Alert LF™ lateral flow devices can be used to detect the oomycete and fungal pathogens including *Phytophthora* spp., *Pythium* spp., *Rhizoctonia* spp. and *Botrytis* spp. (Neogen Europe 2013)

2.4 Molecular tests

Several different DNA-based molecular techniques have been used to detect *Phytophthora ramorum*, and new variations are continually being developed (Kliejunas 2020). Both real-time and nested polymerase chain reaction (PCR) based molecular diagnostic assays have proven useful for detecting *Phytophthora* spp. from leaf baits, and greatly reduce the turnaround time (Colburn and Jeffers 2011). PCR-based tests are being developed to detect algal species in irrigation water, and would represent a big improvement over the lower and more labor intensive light microscopy (Sellner and others 2003).

3. Treating water for pests

Any good water treatment system always begins with filtration, which not only removes suspended inorganic particles that can damage fertilizer injectors or plug irrigation nozzle but can also filter many waterborne pests from the irrigation water.

3.1 Filtration

Filtration is a prerequisite for all types of water treatment. Ultraviolet light requires clear water to to penetrate pathogen cell walls whereas oxidizing compounds like chlorine react with all types of suspended organic material (Fisher and others 2008a). One recommendation is that the total suspended solids should be less than 20 ppm (Parke and Fisher 2012). Any filtration system is a trade-off between removing suspended solids and waterborne pests while allowing enough water flow and pressure so that your irrigation system will operate properly. New nurseries should do a series of water tests before selecting on a filtration system, keeping in mind that the quality of surface sources may change during the year. For example, algae levels will increase during the summer so the filtration system must be able to handle the worst water quality (Bartok 2000).

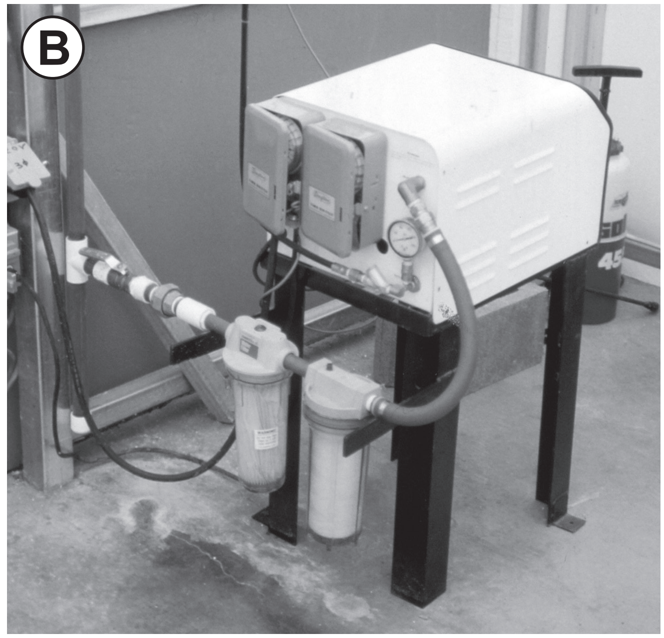
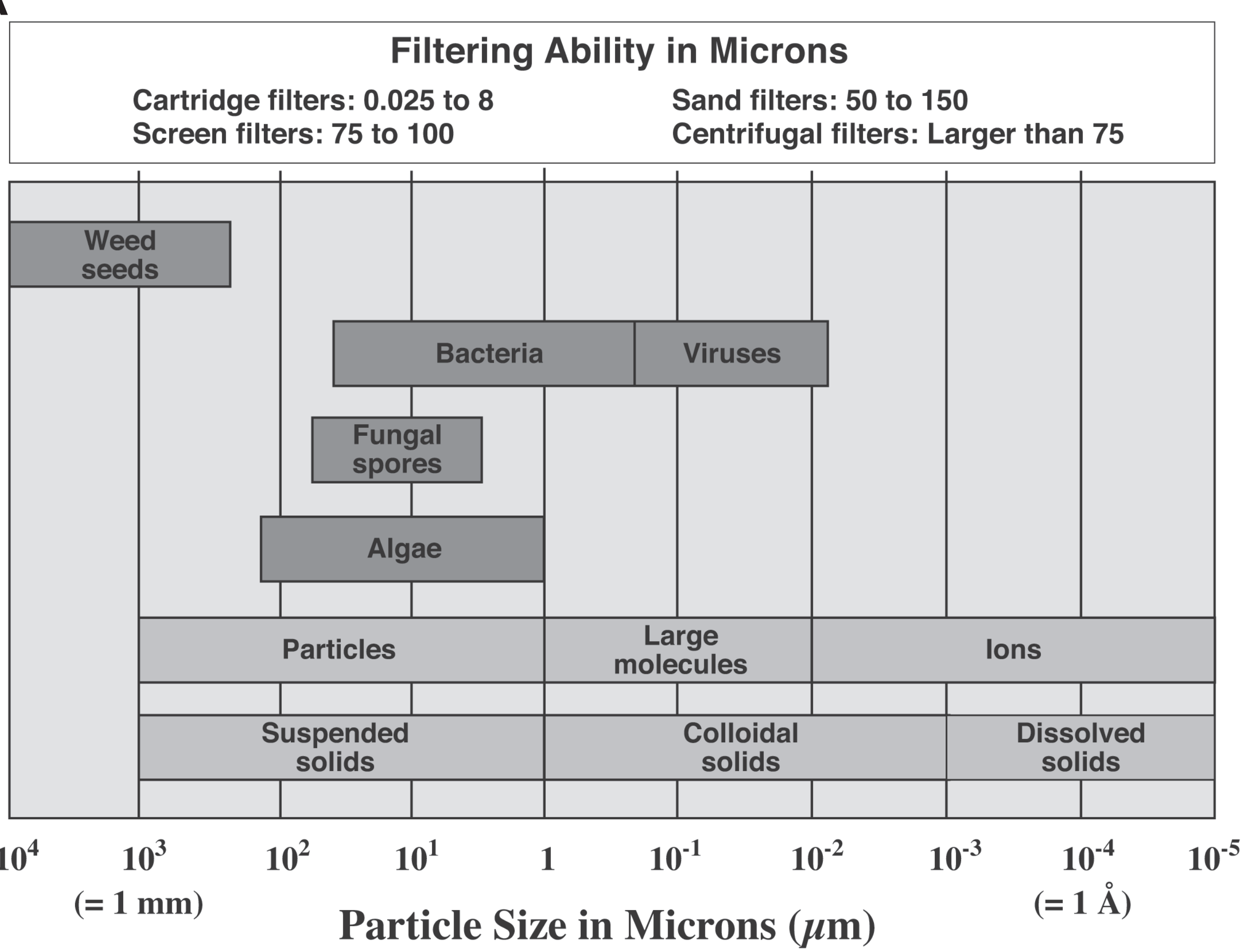


Figure 4 - The first step in any water treatment is filtration and several types of filters have been used (A). Cartridge filters are easy to use and are available in different pore sizes and filtering ability (B) (A modified from Taylor and Wiesner 1999).

A



Several types of filters are commonly used in forest and conservation nurseries (Figure 4A), and the best choice depends on irrigation water source and quality.

Cartridge filters are made of paper or a spun fiber (Figure 4A) and are most appropriate for container nurseries that have irrigation water with a light sediment load such as that from wells or domestic sources. They would not be practical for bareroot nurseries using irrigation water containing suspended solids or if algae is present because the filters will quickly clog and have to be replaced. Cartridge filters come in a wide variety of pore sizes from 0.025 to 8 microns (µm), which can remove several waterborne pathogens (Figure 4B). Zoospores of *Pythium* spp. and *Phytophthora* spp. were also found to pass through membranes with pores of 0.40 to 0.45 µm (Hong and others 2003),

Screen filters come in all sizes and shapes and can be made of slotted PVC, perforated or mesh stainless steel, and nylon mesh, and should have a filtering capacity of 75 to 100 µm (Schultheis 2013). Most have to be manually cleaned but some self-cleaning models use high pressure water or brushes (Bartok 2000).

Disc filters consist of a stack of grooved wafers over which the water passes, and the degree of filtration is determined by the size and spacing of the grooves. They are best for irrigation water with a low concentration of suspended solids. Disc filters are cleaned and are cleaned by backflushing — by reversing the water flow into a separate drain (Bartok 2000).

Granular media filters, like the common swimming pool sand filter, are best for removing organic matter such as algae and suspended silt and clay particles (Bartok 2000). Depending on their construction, media filters are capable of removing suspended particles from 50 to 150 µm in diameter (Bisconer 2011), and are cleaned by backflushing.

Centrifugal filters are needed to remove sand and other heavy organic matter so would only be need for irrigation water from surface sources. Water is filtered with a spinning motion inside a steel cone, and particles larger than 75 µm are spun to the outside and then collect along the bottom where they can be cleaned out (Bartok 2000).

Biofilters or slow-flow filters are the newest category and researchers in Europe and Australia have shown they can remove waterborne pathogens including *Phytophthora* spp. , *Pythium* spp., and *Fusarium* spp. Biofilters are similar to granular media filters but the substrate is inoculated with beneficial microorganisms such as *Pseudomonas* spp. or *Trichoderma* spp. This substrate captures the waterborne pathogens and holds them long enough for the beneficials to attack and neutralize them. As the name implies, flow rates are relatively slow and the treatment tanks must be large; rates 25 to 80 gallons per hour per square foot of substrate are effective (Svenson 1999).

Ultra-filtration, with a membrane pore size of 0.02 to 0.10 µm, was effective in removing fungal and bacterial pathogens from irrigation water under laboratory conditions but would not be practical for the irrigation water quality in operating forest nurseries (Machado and others 2013).

3.2 Disinfection of irrigation water through chemical oxidation

My memories of oxidation-reduction reactions from chemistry class are something about oxygen's ability to strip electrons from other chemicals. Now, after all these years, I can finally see how that tidbit of chemical knowledge can actually be put to good use. In water treatment, the term oxidation refers the addition of chemicals to kill waterbone pathogens and chemicals that are strong oxidizers, such as chlorine, bromine, and ozone, are excellent disinfectants. These oxidizing compounds "burn" the pathogens and other suspended organic matter in irrigation water but leaves only harmless chemicals as by-products. The oxidation reduction potential (ORP) of any treatment solution is dependent on the concentration of the oxidizer, and its activity can be can be measured in millivolts (mV) (Newman 2004).

3.2.1 Chlorine. Chlorination is by far the most common water treatment for nurseries wanting to prevent pests that are introduced through the irrigation system (Fisher and others 2008a). Chlorine comes in many formulations, which differ considerably in safety and ease of use.

Chlorine compounds can be gas (chlorine or chlorine dioxide), solid (calcium hypochlorite or chlorine dioxide), or liquid (sodium hypochlorite). All chlorine products supply hypochlorous acid (HOCl), which is the sanitizing form of chlorine when dissolved in water (Table 1).

Chlorine gas. This is the traditional method of chlorination but many nurseries may not consider chlorine gas due to safety concerns. Chlorine gas is toxic at low concentrations, as well as corrosive. However, one large ornamental nursery that used 1.3 million gallons of water per day installed REGAL gas chlorinators and found this system very effective. Not only were they easy to install

Table 1 - Sources of chlorine for irrigation water treatment (modified from Newman 2004; Fisher and others 2008a).

Chemical	Form	Formulation	Injection Method	Target Chlorine Concentration	Safety Considerations
Chlorine	Gas	Cl_2	Chlorine gas is bubbled through the water, where it combines with the water to form hypochlorous acid: (HOCI) and hydrochloric acid (HCL)	1 to 2 ppm	Chlorine gas is very toxic, so requires protective clothing, masks, and must be handled carefully.
Sodium hypochlorite	Liquid or soluble tablets	NaOCl - Household bleach is 3% to 6% NaOCl; industrial bleaches are 10% to 12% NaOCl	Liquids require a special injector that is resistant to corrosion and has a high injection ratio. Tablets are gradually dissolved in flow-through feeders.	1 to 2 ppm	Splash hazard for liquids so protective clothing and masks should be used. Tablets are least hazardous option.
Calcium hypochlorite	Soluble tablets	$Ca(OCl)_2$	Tablets are gradually dissoved in a flow-through feeders	1 to 2 ppm	Tablets are least hazardous option.
Chlorine dioxide	Soluble tablets	ClO_2	Injectors using tablets are now available.	0.25 ppm	Tablets are least hazardous option.

and maintain, but they paid for the injectors the first year and it cut their fungicide use by 50% (Majka and others 2008).

Chlorine dioxide. Although it is 25 times more effective than chlorine gas as a biocide, chlorine dioxide can be 5 to 10 times more expensive. Originally, generating chlorine dioxide on-site was problematic, but several commercial products are now available. The Ultra-Shield™ Chlorine Dioxide Water Treatment System features tablets that dissolve in water in less than 20 minutes to release chlorine dioxide and can be used for treating irrigation water. The AquaPulse System is a fully automated chlorine dioxide generator that produces chlorine dioxide for injection into irrigation systems (Fisher and others 2009).

Sodium hypochlorite. One of the oldest disinfectants, sodium hypochlorite was first used to kill disease-causing microorganisms by Louis Pasteur. Ordinary household bleach contains 3% to 6% NaOCl, whereas industrial bleaches are more concentrated (10% to 12% NaOCl). Due to this relatively low concentration, high volume injectors are needed that are also resistant to corrosion (Newman 2004). Still, sodium hypochlorite has been to treat nursery irrigation water (Fisher and others (2008b).

Calcium hypochlorite. Commonly available as tablets (Figure 5), calcium hydroxide is much easier to use and store than liquid bleach (Newman 2004). From a handling and safety standpoint, tablets were considered superior to other formulations (Ferraro and Brenner 1998). Chlorine tablets are not as corrosive and can be applied with injectors similar to those commonly used for swimming pools. A typical applicator schematic can be found in Fisher and others (2008b).

Mode of action. Hypochlorous acid oxidizes all forms of organic material, not just fungal pathogens or algae. For this reason, irrigation water must be prefiltered to remove other types of suspended organic material so that the hypochlorous acid is more effective for pathogen control. Chlorine is most effective in irrigation water with a slightly acid to neutral pH (6.0 to 7.5), and its activity drops off rapidly at either lower or higher pH values. For example, almost 3 times the amount of sodium or calcium hypochlorite would be needed at pH 8 to have the same effectiveness in water with a pH of 7 (Fisher and others 2008c). One advantage of

Figure 5 - Tablets are considered the safest way to supply chlorine or bromine for disinfecting irrigation water (Ferraro and Brenner 1998).

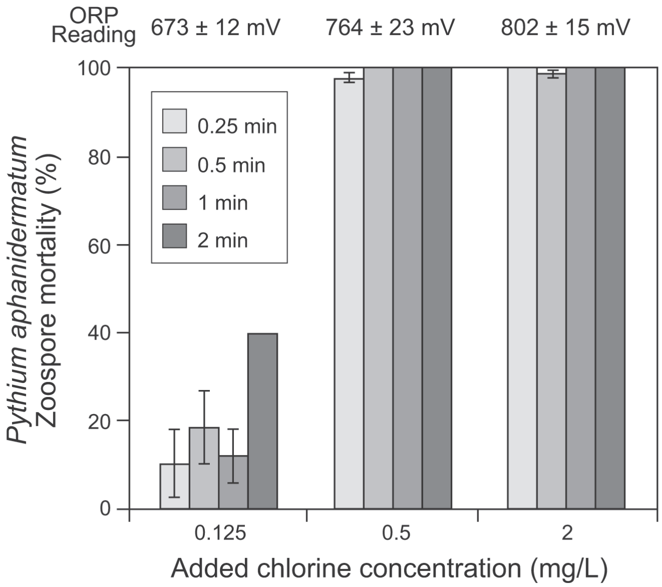


Figure 6 - All Pythium *spp. zoospores were killed after 0.5 min exposure to 0.5 ppm chlorine, which produced an oxidation reduction potential (ORP) meter reading of 764 mV (modified from Lang and others 2008)*

chlorine dioxide is that it is effective at a much wider pH range (Fisher and others 2009).

Target concentration. Chlorine activity is typically reported as free residual chlorine or total chlorine. Free residual chlorine is the more practical measurement because it reflects the chlorine available for disinfection after the background demand of suspended organic matter and biofilm has been satisfied (Fisher and others 2008c). In a controlled research trial, 100% of the *Pythium aphanidermatum* zoospores were killed after 0.5 min exposure to 0.5 ppm chlorine after the water pH was reduced to 6; this produced an oxidation reduction potential (ORP) meter reading of 764 mV (Lang and others 2008) (Figure 6). Operational research has shown that 1 to 2 ppm residual free chlorine is required at the farthest sprinkler head, which may require an initial injection of up to 6 ppm of chlorine. Although 2 ppm free chlorine effectively controls zoospores of *Pythium* and *Phytophthora* species in irrigation water, the more resistant fungal structures such as chlamydospores, oospores and hyphae in suspended organic matter may not be controlled at this concentration (Wick and others 2008). Control of mycelial fragments of *Phytophthora* required 8 ppm chlorine compared with 2 ppm for zoospores, whereas 12 to 14 ppm free chlorine were required to control *Fusarium oxysporum* conidia and *Rhizoctonia solani* mycelia (Hong and others 2003). For algae control, injecting enough chlorine to maintain at least 1 to 3 ppm of free chlorine at the end of the irrigation line was found to be effective (Nye 2013).

Phytotoxicity. Maintaining free residual chlorine levels at no more than 2 ppm should avoid phytotoxicity, but testing on your specific crop is always recommended. A research trial with a variety of ornamental shrubs, showed that a 5 minute exposure to 2.4 ppm free chlorine killed waterborne pathogens without reducing the plant value (Cayanan and others 2009).

Monitoring. A chlorine meter can be purchased for $150 to $300; be sure that the meter measures free chlorine, rather than total chlorine. An ORP meter, which costs $100 to $400, is better way to monitor the disinfecting power in your irrigation water – the higher the millivolts reading, the greater the sanitizing power. In tests at the University of Florida, commercially available Extech and Hanna Instruments ORP meters produced results similar to a higher-cost laboratory sensor (Fisher and others 2008b). Lang and others (2008) consider ORP meters to be essential for nursery managers using chlorination. When the irrigation water of a greenhouse using chlorine injection was measured at the sprinkler head, it had an ORP reading of 825 mV with 1.4 ppm free chlorine and 2.25 ppm total chlorine (Newman 2004).

3.2.2 Bromine. Although bromine (Table 2) has an oxidation potential 21% lower than chlorine (Newman 2004); it is reported to have a higher activity against algae, bacteria, fungi, and viruses (Austin 1990);. Bromine reacts more quickly than chlorine and this may provide some benefits in reducing the required contact periods (De Hayr and others 1995). Agribrom™ is available in tablet form (Figure 5), and can be applied through a inexpensive pool chlorinator in which water gradually dissolves the tablets and disperses bromine into the irrigation water. One nursery that propagated cuttings with a mist system installed a pool chlorinator

Table 2 - Bromine compounds used to disinfect irrigation water (modified from Fisher and others 2008a).

Form	Active Ingredient	Solubility	Injection Method	Target Concentration
Tablets or granules	1-Bromo-3-chloro-5,5-dimethyl-2,4-imadazolidinedione	Slowly	Tablets or granules are slowly dissolved and the supernatant injected into the irrigation system	5 to 35 ppm bromine

for around $100 and used Agribrom tablets to maintain 5 to 25 ppm of bromine (Klupenger 1999). Typically, 5 to 10 ppm of bromine is needed to inactivate most microorganisms, and research has shown very little phytotoxicity even on sensitive plants at bromine rates as high as 100 ppm. One comparison with the use of chlorine concluded that bromination was the least expensive, most effective method of disinfecting irrigation water (Ferraro and Brenner 1998).

3.3 Other options for disinfecting irrigation water

3.3.1 Activated peroxygen. This stabilized mixture of hydrogen peroxide (H_2O_2) and peracetic/peroxyacetic acid is injected directly into irrigation lines, but requires an injector with a high injection ratio and that is resistant to corrosion (Parke and Fisher 2013). Several commercial products are available such as ZeroTol®, which has been used by container nurseries for many years and GreenClean®,which is particularly effective against algae (BioSafe Systems 2013). Although Zero Tol® can be used by organic growers, its high cost may be prohibitive for continual water treatment (Newman 2004).

3.3.2 Copper ionization. Copper solutions have been used to control plant disease since Bordeaux mixture was developed in the late 1800s. For treating irrigation water, copper ions are generated by applying a direct electrical current across copper electrodes as water passes through a series of pipe chambers (Emmons 2002). Copper ionization has strong residual activity, which means the copper ions travel with the water and attack pathogens throught out the irrigation system and even in the soil or growing medium. Research has shown that 0.5 to 1.0 ppm of free copper significantly reduced *Pythium* spp. *Phytophthora* spp. and other waterborne pathogens, while 1.0 to 2.0 ppm effectively reduced algae. A variety of copper ionization systems are commercially available from around $5,000, but it is important to select one designed for nurseries instead of swimming pools. Copper ionization systems can be designed for water flow rates from a few gallons to thousands of gallons per minute. The electrical conductivity (EC) of the water would obviously affect the ionization process so, where EC can fluctuate frequently as in water recycling systems, precise monitoring is required (Fisher and others 2008d). The Aqua-Hort® system features controls that control ionization based on water quality and flow rate, and uses magnetic coils to increase the copper ion activity (Aqua-Hort 2013). One nursery generated 20 to 25 ppm copper into a stock tank, and then injected this treated solution at a ratio to maintain the desired 0.5 ppm level in the irrigation lines (Emmons 2002). The issue of copper pollution of leached irrigation water is a concern but has not proven to be a problem when copper ionization systems are properly designed and operated.

3.3.3 Heat. Pasteurization is one of the oldest methods of disinfesting water, and maintaining a temperature of around 200 °F (93 °C) for 30 seconds is sufficient to kill most plant pathogens. However, due to the high energy demand, heat treatment is much too expensive for the large volumes of water required for most irrigation systems (Parke and Fisher 2013).

3.3.4 Ozone. The first discovery of ozone was in 1839, and the name comes from the Greek word "ozein," which means "to smell." Ozone is the strongest oxidizer and has an oxidation potential that is 52% higher than chlorine (Newman 2004). The first application of ozone generation for water treatment was in France in 1906 and today most European and some US cities use ozone for drinking water treatment instead of chlorine. Several ozone generators are available commercially (Zeitoun 1996). A corona ozone generator that uses electrical energy to produce ozone, which is then dissolved into the irrigation system with a venturi system, has been recommended; typical swimming pool generators that use ultraviolet light to generate ozone are not (Hayes and others 2009). Ozone is effective against all waterborne pathogens including nematodes and viruses but needs at least 4 minute contact time. Ozone has a half life of 4 to 20 minutes and so the generator should be installed in the irrigation line (Ferraro and Brenner 1998). Water filtration before treatment is absolutely necessary. Dissolved ozone residual levels in the range of 0.01 to 0.05 ppm control algae, but should be below 1 ppm to avoid phytotoxicity. Dissolved ozone can be measured with test kits or commercial monitors. Because it is a strong oxidizer, ozone activity can be most effectively and economically monitored with an oxidation-reduction potential meter (Hayes and others 2009). Unlike the chemical water treatments, ozone does not leave behind any by-products; instead, ozone molecules break down to oxygen. As a bonus, ozonated irrigation water was found to have a suppressive effect on existing liverworts in container stock (Graham and Dixon 2012). In a comparison between ozone and chlorination, one nursery found that operating costs were less with ozonation and that the investment in a generator was amortized in 2 to 3 years (Roberts 1993). For worker safety, ambient ozone gas monitors can be programmed to automatically shut down the generator if a leak occurs and if ozone is used indoors, safety criteria set by the Occupational Safety and Health Administration must be met (Hayes and others 2009).

3.3.5 Ultraviolet radiation. Electromagnetic radiation in the 100 to 400 nanometers (nm) wavelengths is considered ultraviolet (UV), so named because it is closest to violet light but beyond the light sensitivity of the human eye. Not all UV light is the same, however, and only radiation known as UV-C (240 to 280 nm) is useful for disinfecting irrigation water. Because UV light must hit each microorganism, water turbidity must be very low — a maximum of 2 nephelometric turbidity units (Fynn and others 2009). Water is treated in a disinfection chamber where it passes by special lamps that generated the UV light (Figure 7); because suspended minerals or other matter can be deposited on the lamp housing, many UV water treatment systems feature some sort of automatic wiping system. Effectiveness of disinfection depends on UV light intensity and duration of exposure; 250 mJ/cm^2 (250,000 $\mu watt\text{-}sec/cm^2$) will eliminate most waterborne pathogens (Newman 2004). Because UV radiation has no residual effects, it is often combined with chlorination or ozone treatment, which produces a synergistic effect. When UV light combines with ozone, the sanitizing effect is increased. If you are considering UV light water treatment be sure to consult with experts to make certain that it is properly designed for your conditions (Fynn and others 2009).

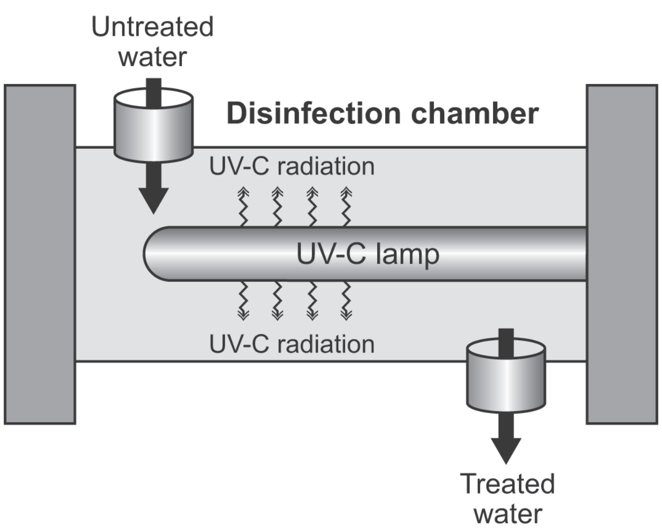


Figure 7 - Ultraviolet (UV) lamps create high energy radiation that kills waterborne organisms as they pass through a disinfection chamber (modified from Newman 2004).

4. Additional information and training

Obviously, treating irrigation water to prevent waterborne pathogens from entering your nursery is a complicated subjects and there are many options. An excellent source for learning more about water treatment methods is the educational center of the Water Education Alliance for Horticulture website (www.watereducationalliance.org). Applied research and efficacy tests for different water treatment technologies can be explored by selecting "grower tools" and "waterborne solutions." Many articles and videos about water treatment technologies are available, and growers can register for upcoming webinars and workshops on this website.

For specific information about the waterborne pathogen *Phytophthora* spp. and especially the new threat of *Phytophthora ramorum*, nursery managers can take a Phytophthora Online Course: Training for Nursery Growers at URL: http://oregonstate.edu/instruct/dce/phytophthora/module2.html.

5. References

Agdia. 2013. URL: https://orders.agdia.com/InventoryD.asp?attribute_Size=5&collection=ISK+92601&loc=IN (Accessed May 29 2013).

Aqua-Hort. 2013. Copper fertilization and electromagnetic treatment of nutrition water. URL: http://www.aqua-hort.dk/ (accessed 10 June 2013).

Austin B. 1990. Brominization vs. chlorination. International Plant Propagators' Society, Combined Proceedings (1989) 39:310-311.

Avila FJ, Schoedel B, Abad ZG, Coffey MD, Blomquist C. 2010. ELISA and ImmunoStrip® for Detection of *Phytophthora ramorum*, *P. kernoviae*, and other *Phytophthora* species. In: Frankel SJ, Kliejunas JT, Palmieri KM, technical coordinators. Proceedings of the Sudden Oak Death Fourth Science Symposium. Albany (CA): USDA Forest Service, Pacific Southwest Research Station. General Technical Report PSW-GTR-229:95-96.

Baker KF, Matkin OA. 1978. Irrigation water: detection and control of pathogens in water. Ornamentals Northwest 2(2):12-14..

Bewley WF, Buddin W. 1921. On the fungus flora of glasshouse water supplies in relation to plant diseases. Annals of Applied Biology 8: 10–19.

BioSafe Systems. 2013. Horticulture. URL: http://www.biosafesystems.com/Industry-Home-GreenhouseNursery.asp (accessed 10 Jun 2013).

Bisconer I; Boswell MJ. 2011. Microirrigation system fundamentals. In: Stetson LE, Mecham BQ, eds. Irrigation, 6th Edition. Falls Church (VA): Irrigation Association: 387-452.

Black, R. 2009. Recycled irrigation water chlorination and pathogen prevention. International Plant Propagators' Society, Combined Proceedings (2008) 58:508-511.

Cayanan, D. F., Dixon, M., Zheng, Y., and Llewellyn, J. 2009. Response of container-grown nursery plants to chlorine used to disinfest irrigation water. HortScience 44(1):164-167.

Chastagner G, Oak S, Omdal D, and 7 others. 2010. Spread of *P. ramorum* from nurseries into waterways—implications for pathogen establishment in new areas In: Frankel SJ, Kliejunas JT, Palmieri KM, tech. coords. Proceedings of the sudden oak death fourth science symposium. Albany (CA): USDA Forest Service, Pacific Southwest Research Station. General Technical Report PSW-GTR-229: 22-26

Colburn G, Jeffers S. 2011. Use of real-time and nested PCR to detect *Phytophthora ramorum* in infested nursery container mixes and soils. Phytopathology 101:S38.

Emmons M. 2002. Ionized copper as an effective control of problematic pathogens. International Plant Propagators' Society, Combined Proceedings (2001) 51:504-506.

Ferraro, B. A. and Brenner, M. L. 1998. Disinfection of nursery irrigation water with chlorination, bromination, and ozonation. International Plant Propagators' Society, Combined Proceedings (1997) 47:423-426.

Fisher P, Argo B, Huang J, and 6 others. 2009. Using chlorine dioxide for water treatment. URL: http://www.aquapulsesystems.com/ChlorineDioxideforWaterTreatment.pdf (accessed 6 Jun 2013)

Fisher P, Argo W, Fischer R, Konjoian P. 2008a. Water treatment series: choose the best water-treatment method for your operation. Greenhouse Management and Production 28(3):19, 21-24.

Fisher P, Argo B, Hong C, Huang J. 2008b. Water treatment series: sodium, calcium hypochlorite can treat irrigation water. Greenhouse Management and Production 28(6):21-22, 24-25.

Fisher P, Huang J, Looper A, Minsk D. 2008c. Water treatment series: water sanitation using chlorine. Greenhouse Management and Production 28(7):15-16, 19-20, 22.

Fischer R, Fisher P, Frances, A. 2008d. Water treatment with copper ionization. Greenhouse Management and Production 28(12):18, 20-21

Forest Phytophthoras of the World. 2013. URL: http://www.forestphytophthoras.org/ (accessed 24 Apr 2013).

Fynn, R. P., Fisher, P., Frances, A., and Argo, B. 2009. Using ultraviolet light for water treatment. Greenhouse Management and Production 29(2):16, 18-21.

Ghimire SR, Richardson PA, Moorman GW, Lea-Cox JD, Ross DS, Hong CX (2009) An in situ baiting bioassay for detecting *Phytophthora* species in irrigation runoff containment basins. Plant Pathology 58(3):577–583.

Graham T, Dixon MA. 2012. Liverwort control: an ancillary role for ozone-based irrigation water treatment systems? HortScience 47(3):361-367.

Haman DZ. 2013. Causes and prevention of emitter plugging in microirrigation systems. Publication BUL258. Gainesville (FL): University of Florida. URL: http://edis.ifas.ufl.edu (accessed 27 May 2013).

Hayes C, Evans L, Fisher P, Frances A, Vetanovetz R, Zheng, Y. 2009. Combat pathogens, algae with ozone treatment. Greenhouse Management and Production 29(1):16-18, 20.

Hester K, Vea E, Palmer CL. 2013. IR-4 Ornamental Horticulture Program Liverwort Efficacy. URL: http://ir4.rutgers.edu/ir4_pdf/default aspx?pdf= http://ir4.rutgers.edu/Ornamental/SummaryReports/LiverwortDataSummary2012.pdf (Accessed May 27 2013).

Hong, C. X., Richardson, P. A., Kong, P., and Bush, E. A. 2003. Efficacy of chlorine on multiple species of *Phytophthora* in recycled nursery irrigation water. Plant Disease 87(10):1183-1189.

Hong CS, Moorman GW. 2005. Plant pathogens in irrigation water: challenges and opportunities. Critical Reviews in Plant Sciences, 24:189–208.

Hong CS, Richardson PA, Kong P. 2002. Comparison of membrane filters as a tool for isolating pythiaceous species from irrigation water. Phytopathology. 92: 610-616.

Hwang, J.; Oak, S.W. and Jeffers, S.N. 2008. Detecting *Phytophthora ramorum* and other species of *Phytophthora* in streams in natural ecosystems using baiting and filtration methods. Proceedings of the Sudden Oak Death Third Science Symposium General Technical Report PSW-GTR-214: 55–58.

Kliejunas, John T. 2010. Sudden oak death and *Phytophthora ramorum*: a summary of the literature. 2010 edition. Gen. Tech. Rep. PSW-GTR-234. Albany (CA): USDA Forest Service, Pacific Southwest Research Station. General Technical Report PSW-GTR-234. 181 p.

Klupenger D. 2000. Cleanliness in propagation with the use of Agribrom. International Plant Propagators' Society, Combined Proceedings (1999) 49:602-603.

Landis TD. 2013. Phytophthora ramorum: Impacts on forest, conservation and native plant nurseries. Lincoln (NE): USDA Forest Service, Forest Nursery Notes 33(1): 15-24.

Landis, TD. 2007. Managing fungus gnats in Container Nurseries. Central Point (OR): USDA Forest Service, Forest Nursery Notes, Winter 2007 (R6-CP-TP-01-2007): 16-19.

Lakes of Missouri Volunteer Program. 2013. Blue green algae in Missouri. URL: http://www.lmvp.org/bluegreen/index.html (accessed 5 Jun 2013).

Lang JM, Rebits B, Newman SE, Tisserat N. 2008. Monitoring mortality of Pythium zoospores in chlorinated water using oxidation reduction potential. URL: http://ghex.colostate.edu/pdf_files/Pythium.pdf (accessed 5 Jun 2013).

Machado P da S, Alfenas AC, Coutinho MM, Silva CM, Mounteer AH, Maffia LA, Freitas RG, Freitas, C. 2013. Eradication of plant pathogens in forest nursery irrigation water. Plant Disease 97(6): 780-788.

Majka, J. M., Argo, B., Fisher, P., and Hong, C. 2008. Water treatment series: gas chlorination can sanitize water. Greenhouse Management and Production 28(8):17-19.

Meador DP, Fisher PR, Harmon PF, Peres NA. 2012. Survey of physical, chemical, and microbial water quality in greenhouse and nursery irrigation water. HortTechnology 22(6):778-786.

Merrill L, Konjoian P. 2006. How critical is greenhouse water treatment? Greenhouse Management and Production 26(6):88-94.

Neogen Europe (2013). Alert-LF. URL: http://plant.neogeneurope.com/protype.asp?strParents=100&CAT_ID=103&numRecordPosition=1 (accessed 29 May 2013).

Newman, SE. 2004. Disinfecting irrigation water for disease management. San Jose (CA): 20th Annual Conference on Pest Management on Ornamentals, February 20-22, 2004. URL: http://ghex.colostate.edu/pdf_files/DisinfectingWater.pdf (accessed 24 Apr 2013).

Orlikowski LB, Ptaszek M. 2010. Water as the important source of *Phytophthora* species in horticulture and natural environment. In: Lutsenko A, Palahniuk V, editors. Water microbiology: types, analyses, and disease-causing microorganisms. Hauppauge (NY): Nova Science Publishers: 281-294.

Parke J, Fisher P. 2013. Treating irrigation water to eliminate water molds. Pscheidt JW, Ocamb CM, editors. Pacific Northwest Plant Disease Management Handbook. URL: http://pnwhandbooks.org/plantdisease/pesticide-articles/treating-irrigation-water-eliminate-water-molds (accessed May 28 2013).

Parke JL, Grünwald NJ. 2012. A systems approach for management of pests and pathogens of nursery crops. Plant Disease 96(9): 1236-1244.

Roberts DR. 1993. How to use ozone to eradicate pathogens. Nursery Manager 9(6):74.

Schultheis RA. 2013. Maintenance of drip irrigation systems. Marshfield (MO): University of Missouri Extension. URL: http://extension.missouri.edu/webster/irrigation/Maintenance_of_Drip_Irrigation_Systems.HDT.pdf (accessed 27 May 2013).

Sellner KG, Doucette GJ, Kirkpatrick GJ. 2003. Harmful algal blooms: causes, impacts and detection. Journal of Industrial Microbiology and Biotechnology 30(7): 383-406.

Svenson SE, Smith B, Briggs B. 1998. Controlling liverworts and moss in nursery production. International Plant Propagators' Society, Combined Proceedings (1997) 47:414-422.

Stewart-Wade, SM. 2011. Plant pathogens in recycled irrigation water in commercial plant nurseries and greenhouses: their detection and management. Irrigation Science 29(4):267-297.

Taylor JS, Wiesner M. 1999. Chapter 11: Membranes, In: Letterman RD, technical editor. Water quality and treatment: a handbook of community water supplies. New York (NY): McGraw Hill Inc: 1 to 71.

[USDA-APHIS] USDA Animal and Plant Health Inspection Service. 2013. In vitro water sampling with host material leaf baits—bottle of bait (BOB) technique. URL: http://www.aphis.usda.gov/plant_health/plant_pest_info/pram/ (accessed 19 May 2013).

Whitsell WJ, Lee RD, Hockman EL, Keech DK, Briggs GF, Norman E. 1982. Manual of individual water supply systems. US Environmental Protection Agency. EPA-570/9-82-004. 155 p.

Wick RL, Fisher PR, Harmon PF. 2008. Water treatment series: waterborne pathogens affect water treatment. Greenhouse Management and Production 28(4):16-18.

Wikipedia. 2013. Algal bloom. URL: http://en.wikipedia.org/wiki/Algal_bloom (accessed 21 May 2013).

Zeitoun FM. 1996. Ozone: an effective nursery runoff treatment? Farwest Magazine 40(8):39, 41-43.

Pesticide Precautionary Statement

This publication reports research involving pesticides. It does not contain recommendations for their use, nor does it imply that the uses discussed here have been registered. All uses of pesticides must be registered by appropriate State and/or Federal agencies before they can be recommended.

CAUTION: Pesticides can be injurious to humans, domestic animals, desirable plants, and fish or other wildlife—if they are not handled or applied properly. Use all pesticides selectively and carefully. Follow recommended practices for the disposal of surplus pesticides and pesticide containers.