Phytophthora root disease and the need for clean nursery stock in urban forests: Part 3. Prevention and management

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MANY URBAN FORESTRY professionals that have backgrounds in horticulture tend to attribute tree decline primarily to cultural issues, such as soil compaction, poor root structure, improper irrigation, salinity, and so forth. Many urban sites do have adverse soil conditions and root structure issues are common in nursery stock, so it is understandable that practitioners often look no further than these factors to explain tree decline. However, Phytophthora root rot can also result in unthrifty, declining, water-stressed trees (Erwin and Riberio 1996). By overlooking the potential for root-infecting *Phytophthora* species as primary or contributing factors in tree decline, urban foresters may compound this disease problem with inappropriate management, such as spreading contaminated soil by soil tillage or replanting susceptible species into *Phytophthora*-infested planting sites.

As discussed in the first part of this series (Swiecki et al. 2018a), an increasing diversity of *Phytophthora* species has been documented in nurseries worldwide, favored by growth in international trade and movement of live plant material (Baker 1957, Bienapfl and Balci 2014, Brasier 2008, Ferguson and Jeffers 1999, Parke et al. 2014, Rooney-Latham et al. 2018, Schwingle et al. 2007, Yakabe et al. 2009, Zentmyer et al. 1952). Root-rotting *Phytophthora* species can readily be introduced into landscapes through planting infected nursery stock. Consequently, an expanding array of *Phytophthora* species have found their way into planted landscapes (Barber et al. 2013, Bourret et al. 2016, Dale et al. 2016, Hulbert et al. 2017, Jung et al. 2015, Rooney-Latham et al. 2015, Sims et al. 2018). These introduced root pathogens adversely affect the growth and survival of the planted stock, and can persist as long-term infestations, affecting other vegetation at the site and future plantings. Spread of *Phytophthora* within a landscape and to new sites can also occur via movement of infested soil and water (Erwin and Ribeiro 1996).

In part 2 (Swiecki et al. 2018b), we discussed how the nursery environment provides ideal conditions for the proliferation of root-rotting *Phytophthora* species and that most infected plants cannot be identified without intensive testing. As a result, Phytophthora root rots are very common in conventionally-produced nursery stock. In this article, we discuss the importance of prevention as a key strategy for managing Phytophthora root rots. Preventing pathogen introduction is critical because options for *Phytophthora* management in infested landscapes are limited.

> *Prevention is the basis for producing nursery plants that are free of root-infecting Phytophthora species.*

Approaches for managing Phytophthora root rots

Phytophthora root rots pose a significant threat to the long-term health of trees and other vegetation. Resource managers, landscape architects, arborists, landowners, and others involved in the planning, design, and maintenance of both natural and horticultural landscapes need to understand how to minimize this threat. Strategies for dealing with Phytophthora root rot in landscapes can be summarized in following three basic approaches (Erwin and Riberio 1996):

- **Prevention**: Avoid introducing *Phytophthora* via infected nursery stock or other contaminated materials such as soil, plant debris, etc.. (**Fig. 1**)
- **Eradication**: Eliminate *Phytophthora* from infested materials. This strategy is mostly used to eliminate *Phytophthora* contamination from soils or organic materials that may be imported to a site. In some situations, it may also be possible to treat localized *Phytophthora* infestations to eradicate the pathogen before it spreads.
- **Suppression**: Where these pathogens have become established, use of appropriate cultural practices can minimize disease development in infected plants. In appropriate high value situations, the use of chemicals that suppress *Phytophthora* may be justified.

Of these three approaches, **prevention** is the most important and applies to all locations and situa-

Figure 1. This nursery illustrates many of the important features of a clean production system to prevent Phytophthora. These include a high degree of general cleanliness; plants on benches high enough to prevent exposure to water splash from the ground, mesh benches that prevent horizontal water flow between plants and are easy to decontaminate; screen enclosure minimizes potential contamination from beyond the growing area.

tions. If these pathogens are not introduced, it will not be necessary to manage them.

Preventing the introduction of additional *Phytophthora* species also remains an important strategy for landscapes already contaminated with one or more *Phytophthora* species. *Phytophthora* species are a diverse group of microscopic plant pathogens, with well over 120 described species, and a number of hybrids (Yang et al. 2017). Hybridization between *Phytophthora* taxa under nursery conditions has been demonstrated. This can cause shifts in host range and pathogenicity that further increase the risks associated with infected nursery stock (Man in 't Veld et. al. 2012, Leonberger, Beckerman et. al. 2013, Leonberger, Speers et. al. 2013, Yang et al. 2014). *Phytophthora* species have varying host ranges, temperature preferences, and other adaptations that can affect their ability to infest an area and infect vegetation. Distinct threats are posed by different *Phytophthora* species, and even different strains within species. Infestations that include multiple *Phytophthora* species have a greater potential to affect a broader variety of plants and may be able to spread more extensively across the landscape.

Phytophthora contamination may be introduced into a site through the movement of contaminated materials. Spores of root-rotting *Phytophthora* are closely associated with live or dead host roots, so any activity that imports soil or roots from infested sources can contaminate a site. As we have discussed in detail in parts 1 and 2 of this series (Swiecki et al. 2018a,b), *Phytophthora*-infected nursery stock is an ideal vehicle for inadvertent transport of multiple *Phytophthora* species to a site. Preventing *Phytophthora* contamination is the basis for producing nursery stock free of *Phytophthora* and using clean stock eliminates a common pathway through which *Phytophthora* species are introduced into native and horticultural landscapes.

Producing nursery plants without *Phytophthora*

Prevention is the basis for producing nursery plants that are free of root-infecting *Phytophthora* species. To manage *Phytophthora* and other pathogens in nurseries, Baker (1957) advised "Don't fight 'em, eliminate 'em". Although nursery conditions are ideal for root-rotting *Phytophthora* species (Swiecki et al. 2018b), *Phytophthora* diseases cannot develop if these pathogens are not present.

The overall strategy for producing *Phytophthora*-free nursery plants can be summarized in two simple principles:

Start clean. All nursery inputs should be free of contamination to begin with, including pathogen-free plant propagules, sanitized or new containers, pasteurized potting media, and uncontaminated water.

Keep it clean. Prevent contamination of the clean inputs throughout the nursery production process. This can be accomplished by setting up and managing the nursery in a way that excludes these pathogens and minimizes potential routes of contamination.

This strategy is best implemented by using a systems approach to sanitation similar to the HACCP (hazard analysis and critical control point) systems that are used to ensure food safety (Parke et al. 2012). The goal of a clean production system is to prevent the introduction of *Phytophthora* into nursery stock rather than attempt to suppress *Phytophthora* after plants are already infected. Soil-borne *Phytophthora* species are introduced and spread through contaminated soil, water, plant material, containers, surfaces, and implements, all of which can be managed in the nursery (Parke et al. 2014, Osterbauer 2014, Junker et al. 2016).

In cooperation with the California Native Plant Society and the Phytophthoras in Native Habitats Work Group (**http://calphytos.org**), we

Table 1. Basic concepts and rules of thumb for clean nursery production. All the nursery *Phytophthora* best management practices (BMPs) are based on applying these concepts and rules to specific situations encountered in nursery plant production.	
Basic concepts	
A.	Contamination by microorganisms like *Phytophthora* cannot be seen. For day to day operations, assume that *Phytophthora* can be introduced anytime that a clean surface or material contacts something that is contaminated.
B.	Clean vs. Contaminated. For the purposes of producing *Phytophthora*-free nursery stock, the nursery system can be divided up as follows:
Clean=no *Phytophthora* present	
Includes:	1. Materials that are innately free of contamination due to manufacturing conditions (e.g., new, uncontaminated plastic or paper, perlite, vermiculite; water from municipal sources or deep wells). 2. Materials treated in a way that effectively eliminates *Phytophthora* (e.g., lethal heat or disinfectants. Note: fungicides do not eliminate *Phytophthora*)
Contaminated=Could have *Phytophthora* present; should be treated as if it is present	
Includes:	Almost everything else. In particular, any non-sanitized surface, especially the ground; untreated water from surface sources; plant material not produced and maintained under these BMPs; container mixes or components (e.g., sand, compost, forest products, and peat moss) that have not been heat-treated.
Basic rules of thumb	
1	**Clean + clean= clean**. If all inputs (plant materials, container mix, pots, water) are clean and there is no contamination during production, the plants will remain clean.
2	**Clean + contaminated = contaminated**. Clean items should never be allowed to come into contact with contaminated materials.
3	**Contaminated plants stay contaminated**. Once contaminated, live nursery plants cannot be made clean again.
4	**If unsure, assume it's contaminated.** Any tool, surface (including benches, hands, and gloves), or input (plant materials, container mix, pots, water) should be considered as contaminated unless you know or have documentation it was sanitized or treated to kill *Phytophthora* and was not subsequently contaminated.
5	**The ground is always contaminated.** The ground surface and any water in contact with it (including water splashed from it) is always considered to be contaminated.
6	**Contamination spreads with water splash**. Clean plants or other materials that receive water splash from contaminated plants or surfaces will become contaminated. Water splash from rainfall-sized droplets in still air can reach a height of about 0.6 m (2 ft) and can spread laterally up to about 1.5 m (5 ft). Splash dispersal distances can be greater under windy conditions or with larger drops (such as runoff from roofs, etc.) or if splash is generated by water under pressure (e.g., hose nozzle) or mechanical forces (e.g., vehicle splashing through a puddle).

compiled best management practices (nursery *Phytophthora* BMPs) for producing nursery stock that is free of *Phytophthora* (**http://phytosphere.com/BMPsnursery/index.htm**). These BMPs are based on principles described by Baker (1957). The same practices are included in other long-established systems for producing *Phytophthora*-free nursery stock, such as the Avocado Nursery Voluntary Accreditation Scheme (ANVAS), initiated by the Australian avocado industry in 1978 (Ernst et al. 2013). These nursery *Phytophthora* BMPs are based on recognizing the potential routes of contamination and providing procedures to eliminate them (**Table 1**).

A systems approach to BMPs

Baker (1957) established that an integrated and comprehensive approach is needed to produce healthy nursery stock. The nursery *Phytophthora* BMPs are based on the using an integrated approach. No individual practice or subset of BMPs is sufficient to achieve and maintain a clean production system. Plants infested with multiple *Phytophthora* species have been detected at many nurseries that have followed some but not all of the practices described in the nursery *Phytophthora* BMPs. A partial approach to sanitation is like deciding to patch only some of the holes in a very leaky bucket. Even if some of the largest holes are filled, the bucket is not going to hold water if other holes remain. Similarly, if nursery practices do not consistently and thoroughly address all the potential routes of contamination, *Phytophthora* is likely to be introduced. Once present, *Phytophthora* can then spread rapidly in the highly conducive nursery environment via splash between containers and contamination in runoff, on tools and surfaces, etc.

For this reason, nursery BMPs that omit critical components are unlikely to approach a *Phytophthora*-free standard. For example, three nursery certification programs designed to produce pest and disease free plants for commerce, the USDA US Nursery Certification (USNCP) program, the Oregon Department of Agriculture's Grower Assisted Inspection program (GAIP), and the standard Shipping Point Inspection (SPI) program, allow one or more of the following: use of untreated recycled irrigation water, reuse of pots without cleaning, placement of potted plants on native soil, and placement of potting mix on native soil (Osterbauer et al. 2014). All these are known pathways for *Phytophthora* introduction into container plants (Parke et al. 2014, Osterbauer 2014, Junker et al. 2016). In one study, the average incidence of Phytophthora root rot in nurseries followings these protocols over a two-year period was 19% for USNCP, 17% for GAIP, and 31% for SPI (Osterbauer et al. 2014). Due to false negatives possible in the study's testing protocols, these reported infection rates likely underestimate actual disease levels (Swiecki et al. 2018b).

In contrast, Sims at al. (2019) conducted a two-year study in which a common set of *Phytophthora* host plants was sampled in native plant nurseries. Sampling was done before and one year after nurseries adopted a simplified version of the nursery *Phytophthora* BMPs. In nurseries that followed the BMPs, *Phytophthora* infection rates in sampled host species fell from 22% to 0% (no detections) in one year. Among nurseries that were sampled in the first year but did not adopt the BMPs, *Phytophthora* infection rates remained high (32% in year 2).

Starting in 2015, a number of California native plant nurseries that produce plants for habitat restoration began to voluntarily implement the version of the nursery *Phytophthora* BMPs adopted by the Phytophthoras in Native Habitats Work Group (**http://calphytos.org**). In nurseries that have rigorously followed these BMPs, *Phytophthora* has not been detected in BMP-compliant stock over multiple years of extensive testing. The data clearly indicate that *Phytophthora* can be excluded from container stock if the nursery *Phytophthora* BMPs are carefully observed.

Role of testing in clean plant production

The nursery *Phytophthora* BMPs require that nurseries conduct their own internal testing to monitor for *Phytophthora* that may result from an unintended departure from the BMPs. If an issue is detected, the nursery can then take steps to identify the source(s) of the contamination, eliminate infected material, and reestablish clean production in affected areas. Clients having BMP-compliant plants produced under contract should also conduct independent pre-delivery testing to provide a final check that the plant material is free of detectable *Phytophthora*. The prospect of pre-delivery testing provides an added incentive to the nursery to be vigilant about BMP compliance and internal testing, because a *Phytophthora* detection near the delivery date is highly undesirable.

Researchers are working to develop sensitive, nondestructive testing protocols that can be used to detect contamination while levels are still low and spread within the nursey is limited (Swiecki et al. 2019). Swiecki et al. (2019) describes a method for baiting water that leaches from plants in a series of repeated irrigations. (**Fig. 2** also see **http://phytosphere.com/BMPsnursery/test3_4bench.htm**). This method has been used successfully by nurseries for their internal testing. Like other tests, the leachate test needs to be performed properly to maximize sensitivity, and false negative results are possible. Hence, testing plays a supporting role to help confirm that *Phytophthora* is below detectable levels. As previously noted (Swiecki et al. 2018b), testing should not be the only basis for assessing whether nursery plants may be infected with *Phytophthora*. Consistent, documented adherence to the BMPs provides the primary assurance that plants are free of *Phytophthora* to the maximum extent attainable.

Steps toward certification of *Phytophthora*-free nursery stock

Introducing destructive exotic pathogens such as *Phytophthora* into native habitats is clearly incompatible with the concept of habitat restoration and threatens the long-term sustainability of native habitats. Consequently, many organizations that have perpetual stewardship responsibilities over lands where habitat restoration is conducted have a strong interest in using nursery stock that has a very low risk of *Phytophthora* contamination.

The BMPs and testing methods outlined above form the basis of a system to identify nurseries capable of producing plants free of *Phytophthora.* First, the nursery documents that it adheres to the nursery *Phytophthora* BMPs. Second, *Phytophthora* should not be detectable in the resultant plant material using a sensitive testing protocol. These elements have been combined in the pilot project "Accreditation to Improve Restoration and Native Plant Nursery Stock Cleanliness", or AIR. Nurseries participating in the AIR program complete an extensive online evaluation form that documents how they manage production in accordance with the nursery *Phytophthora* BMPs. The form is reviewed by qualified evaluators, who assess whether implementation of each specific BMP is adequate to minimize contamination risk. The evaluators also visit the facility, assess specific nursery layout features, and conduct testing using the leachate method to detect *Phytophthora*. (**Fig. 2**) Testing conducted by the nursery, as well as third-party testing of BMP-compliant stock, also become part of the nursery's testing record.

Based on the evaluation and test results, the evaluator can issue a certificate valid for one year indicating that the nursery complies with AIR program standards. If shortcomings are noted, the evaluators recommend changes and modifications needed to bring the nursery into compliance. Once the nursery makes and documents the changes, the evaluators review the information. Based on the information submitted, evaluators may conduct another site visit and further testing, make additional recommendations, or revise the nursery's rating to "compliant". The program helps nurseries that are making good-faith efforts to fully comply with the BMPs identify any weaknesses in their production systems and make the changes that will allow them to reliably produce clean plant material. Although material from accredited nurseries is not guaranteed to be free of all pest and diseases, plants produced under the *Phytophthora* BMPs will be free of *Phytophthora* to the maximum extent attainable and are likely to be free of many other soil-borne diseases.

Importance of clean stock in urban forestry

Like organizations that manage native habitats, urban forestry programs also have perpetual responsibility for the resources they manage. Introducing *Phytophthora* via infected nursery stock not only compromises the performance and survivability of the affected planting stock, but can permanently degrade the planting site, leading to ongoing plant health problems. For trees planted in small cutouts or islands, relocating the planting site is typically not an option, so it is critical to avoid introducing these persistent pathogens.

Figure 2. Testing plants for *Phytophthora* infection by capturing irrigation leachate and baiting it with a green pear. Upward swimming *Phytophthora* zoospores accumulate near the top of the plastic vessel, where they can infect a floating green pear; excess water drains from the bottom. *Phytophthora* species are among the few organisms that infect unwounded green pears.

In diverse urban forests, tree species or cultivars have historically been treated as replaceable. Tree species that develop a host-specific pest or disease problem (e.g., Dutch elm disease in elms, anthracnose in Modesto ash) have been replaced over time with species that lack these particular problems, though this process is often costly and disruptive. However, tree species replacement may not be a viable strategy against many root-rotting *Phytophthora* species because of their wide host ranges, especially in sites infested with multiple *Phytophthora* species.

Urban trees suffer relatively high rates of mortality, especially among small diameter size classes (< 8 cm DBH), many of which are recently-planted (Roman 2014). Phytophthora root rot is likely to be a significant contributor to the mortality seen in these trees. One important symptom we have observed in planted nursery stock infected with *Phytophthora* is a lack of root exploration into the soil beyond the original rootball. Such plants remain dependent on water applied to the original rootball area, so plants tend to grow slowly and have chronic drought stress. Phytophthora root rot is enhanced if such plants are irrigated more frequently to ameliorate drought stress symptoms (Blaker and MacDonald 1981). Hence, the use of *Phytophthora*-free planting stock in urban forests has the potential to improve establishment and initial survival of new plantings, increase longevity, and improve long-term performance.

Beyond the risks to urban forest health, the expanding suite of introduced *Phytophthora* species puts native forest species at risk, especially in the urban-wildland interface. In many locations, including Europe (Jung et al. 2015) and the eastern US (Balci et al. 2007, Reed et al. 2019, Meadows and Jeffers 2011, Zentmyer 1980), root-rotting *Phytophthora* species have become established in many native forests. Unlike many of the exotic trees grown in the urban forest, native forest species are not readily replaceable. As more *Phytophthora* species become established in native forests, many more native forest species may be killed or debilitated, permanently degrading forest health and productivity. In the worst cases, dominant native tree species may no longer be able to grow in infested areas in either native or urban forest stands, leading to a loss of important ecosystem functions (e.g. *Phytophthora lateralis* root disease of Port Orford Cedar along the Pacific Coast of southern Oregon and northern California), Betlejewski et al. 2011).

The movement towards clean plant production among California native plant nurseries has been fueled largely by the risks posed by use of *Phytophthora*-infected nursery stock in restoration areas and native ecosystems (Frankel et al. 2018). Many native plant nursery owners are philosophically committed to environmental stewardship. As a group, they have proved to be motivated to make changes once they understood the adverse environmental impacts of using conventional nursery practices. Nurseries producing plants for restoration are a specialized industry segment and are subject to different market forces than the general horticultural nursery trade. Many of these nurseries do most of their business with a few large institutional clients, such as public agencies or districts. These client organizations have begun to establish a specific market for *Phytophthora*-free nursery stock, understanding that they need to pay more for higher-quality stock that will meet their needs (Frankel et al. 2018).

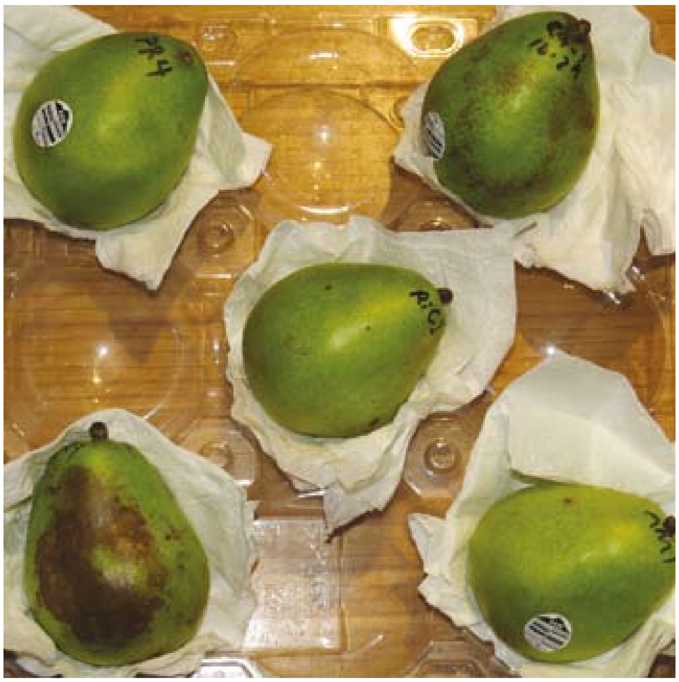

Figure 3. Green pears from 5 different irrigation leachate tests for *Phytophthora*. Lesions caused by *Phytophthora* are usually distinctive and initially only affect the skin of the pear. Lesions are often brown with irregular margins. Pears at upper right and lower left are infected with *Phytophthora*. Note the ring of lesions formed by zoospores which infected at the waterline on pear at upper right. Pure cultures used to identify *Phytophthora* to species can be obtained by placing lesion tissue into sterile media. Green pears can also be used to detect *Phytophthora* in soil/root samples.

This example may provide a model for developing a nursery segment that could similarly provide clean stock to municipal urban forest clients. Production practices needed to exclude *Phytophthora* are not the norm in commercial nurseries in part because they raise production costs. If nursery stock contracts are awarded to low bidders, a grower following nursery *Phytophthora* BMPs would be at a competitive disadvantage. This disadvantage can be overcome if the specifications for the plant material require that material be produced according to a *Phytophthora*-free standard. However, adopting and maintaining these clean production practices have capital and ongoing costs, so nurseries would need to have the guarantee of an ongoing market for *Phytophthora*-free stock to justify their investments. To create a large enough market to support clean production in one or more nurseries, requirements for *Phytophthora*-free stock would have to be adopted at a regional level. To ensure a uniform standard, and simplify nursery certification, a third-party system such as the AIR program could be implemented to document BMP compliance and conduct quality assurance testing.

Although buyers would pay more for clean stock, these up-front costs will be offset by improved plant survival, growth, and performance, reduced need for replanting, and other avoided costs related to having *Phytophthora*-infested sites. Even if only small segments of the nursery industry converted to producing *Phytophthora*-free stock, purchasers of urban forest nursery stock would have the option to purchase clean stock, which is not currently available.

Using clean stock in sites with *Phytophthora* infestations

Compared with most habitat restoration sites, many urban planting sites have a much higher potential of being infested with one or more *Phytophthora* species due to previous plantings. Consequently, planting clean stock alone is not a guarantee for success if the site is already infested with *Phytophthora*. Clean stock prevents introduction of additional *Phytophthora* species and helps improve plant establishment, but additional measures are needed to manage contaminated landscapes.

The logical solution would be to eradicate existing *Phytophthora* infestations, but this is very difficult to achieve in practice. The use of lethal heat is the most practical method for eradicating *Phytophthora* in most landscape situations. Heating moist soil to a temperature of 140°F (60°C) for 30 minutes will kill propagules of *Phytophthora* and other water molds, as well as most plant pathogenic fungi, but will not destroy many beneficial soil microorganisms (Baker and Cook 1974).

Due to costs and logistics, heat treatments are typically limited to small soil volumes. For instance, in a small planting site where *Phytophthora* has been introduced via contaminated stock, it may be possible to excavate and dispose of the rootball (in a sanitary landfill) to remove the most highly-contaminated material. The remaining soil within the infested site can also be carefully excavated to avoid spreading contamination and sent to a sanitary landfill and replaced with known clean or heat-treated soil. Alternatively, the excavated soil can be heat-treated and returned to the hole. Various types of equipment can be adapted to heat excavated soil to the necessary temperature. It is also possible to heat soil in place using steam. However, most in-situ soil steaming equipment (e.g., Fennimore et al. 2014) has been designed primarily for agricultural fields in which soils are not highly compacted.

Because heat treatments are expensive, they are most applicable to small, high value sites. These sites are subject to recontamination through maintenance practices unless carefully managed. Tools, vehicle tires, and other items that could carry soil or root fragments from infested areas need to be cleaned and disinfested before they are used in an uncontaminated area. Precautions to avoid transferring *Phytophthora* from landscape sources into uninfested areas are the subject of other BMPs not covered here (Swiecki and Bernhardt 2018, WGPNH 2016).

In areas where existing *Phytophthora* infestations cannot be eradicated, the use of clean stock needs to be coupled with other disease management tactics. Most of these tactics are related to suppressing disease by modifying other factors in the plant disease pyramid (Swiecki et al. 2018b).

Host factors: Infested areas should be planted with tree species that are resistant to the *Phytophthora* species present, but this is easier said than done. To begin with, the *Phytophthora* species present at the planting site must be determined. This may take several rounds of sampling and testing, typically by baiting. Furthermore, the host ranges of most *Phytophthora* species are not well characterized. An online database maintained by the USDA lists many known host/*Phytophthora* species associations (Farr and Rossman 2019), but this database is far from complete. More information may be available in the scientific literature, but the pathogenicity of *Phytophthora* species to most landscape plants has not been studied. Nonetheless, information from the literature and observations of past performance of plant species in an infested site can be used to identify highly susceptible hosts that should be avoided.

Abiotic environment factors: Because *Phytophthora* reproduction is favored by periods of soil saturation, new infections can be minimized by reducing the duration of soil saturation. This can be achieved by designing planting sites to drain quickly and avoid ponding, especially from rain or irrigation. Prolonged periods of soil saturation can also be avoided by adjusting irrigation system output and using short run times. However, Phytophthora root rot can be severe in dry upland sites that receive only natural rainfall (Swiecki et al. 2011), so water management can limit but not prevent disease.

Biotic environment factors: Phytophthora root rot is suppressed through the activity of microbial antagonists in some natural soils (Broadbent and Baker 1974, Weste and Marks 1987). To duplicate this effect, certain organic mulches or amendments have been used to suppress *Phytophthora* diseases, though results are variable (Erwin and Ribeiro 1996, Drenth and Guest 2004). Although the suppressive effects of organic mulches and amendments are primarily related to increases in microbial antagonists, these materials may also affect disease development by altering the chemical or physical properties of the soil or changing the soil microclimate. These treatments do not eliminate *Phytophthora* and repeated additions of the organic materials are needed to sustain disease suppression.

Suppressive chemicals: Chemicals that suppress *Phytophthora* diseases commonly inhibit pathogen growth and reproduction, but some (phosphonates) may also increase host resistance. As noted previously (Swiecki et al. 2018b), these chemicals are classified as fungicides, though they are more accurately described as systemic oomycete suppressive (SOS) chemicals. Because these chemicals do not actually kill *Phytophthora,* treatments need to be repeated indefinitely to maintain disease suppression. Not all *Phytophthora* species or isolates are equally susceptible to these various materials, and resistance to many of these materials can develop in situations where the chemicals are used repeatedly (Dobrowolski et al 2008, Hamm et al 1984, Hu et al. 2008, Rupp. et al 2016).

Conclusions

None of the options for dealing with established *Phytophthora* infestations are easy to implement or inexpensive. Hence, it is always preferable to prevent *Phytophthora* introductions if possible and starting with clean plant material is a critical part of prevention. Although the use of nursery-grown plants is considered a necessity in the highly altered urban forest environment, native plants have evolved to establish and grow without first being started in nurseries. Some trees, such as native oaks, can be successfully started from seed in some urban sites (Bernhardt and Swiecki 2015). While nursery-grown plants provide many benefits, the prevalence of root-rotting *Phytophthora* in nursery stock is an unintended consequence of conventional plant production practices. Although clean production practices can remedy this problem, the supply of clean plant material will be driven by demand. To create a supply of *Phytophthora*-free stock, urban forestry professionals can follow the lead of habitat restoration agencies that require such stock for their projects. If the long-term costs of dealing with the consequences of *Phytophthora* invasions on the health, management, and sustainability of urban and natural landscapes are considered, it is clear that the increase in cost required to produce clean stock is a bargain (Garbelotto et al. 2018).

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