A Systems Approach for Management of Pests and Pathogens of Nursery Crops

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Nursery Production Systems Are Complex Systems

Horticultural nurseries are exceedingly complex agricultural systems, making pest and pathogen management very challenging. Compared to crop monocultures, nurseries are characterized by extreme heterogeneity in plant material. The typical agricultural row crop contains a single cultivar of a single species, grown over hundreds or even thousands of acres, whereas a single horticultural nursery of 40 acres may grow upward of 500 different plant taxa in any given field season (Fig. 1). The typical agricultural crop is started from a uniform propagative material: seeds, clonally propagated tubers, or cuttings from a single source. In contrast, many nurseries propagate multiple species, each from a variety of sources including seeds, bulbs, tubers, cuttings, scions, grafted rootstocks, and tissue culture. This propagative material may originate from multiple sources including on-site production blocks and domestic and overseas markets and can be comingled in propagation blocks.

Nurseries are also characterized by extreme spatial and temporal heterogeneity. Plants typically undergo repotting several times as they are transferred from micropropagation cells (tissue culture plantlets) or flats (seeds or cuttings), and are moved from the propagation house to production greenhouses to container yards or the field. Plants are densely packed in the early stages of growth, and are spread further apart as the canopies expand. Container stock is constantly moved from place to place in the nursery and comingled with other lots. Different plant species require different potting media with particular biological, chemical, and physical properties. Blocks of plants with similar water use are grouped together, but there may be several different irrigation systems (drip, microsprinklers, overhead spray) in a single nursery, and several different irrigation frequencies. In contrast, the typical monoculture row crop is grown in a fairly uniform growing environment, generally in a single soil type with similar physical, chemical, and biological properties, although slope and aspect may vary within the field. Cropping history, tillage, organic matter management, soil fertility, irrigation regime, sunlight, and plant spacing are also fairly uniform within monoculture crops. Unlike nursery crops, most agricultural crops stay in the same place once planted.

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Complexity Confounds Pest Management

Pest management is complicated by the heterogeneity of production systems typical for nurseries consisting of a large diversity of plant material grown, the variety of cultural methods employed, compounded by the spectrum of microenvironments (3,4,17). Each plant species is host to a range of plant diseases, insect pests, and abiotic disorders. These must be scouted, recognized, and managed using pest management tools and approaches that often differ among plant taxa. For example, a single nursery in Oklahoma trains scouts to recognize 38 different disorders (18). Epidemiological models and forecasting systems so helpful in managing diseases of agricultural crops such as potato late blight, wheat rust, and soybean rust are almost completely lacking for even the most important diseases that affect nursery crops. A predictive model for rose downy mildew is being developed but is not yet applied commercially (1). Disease forecasting models for apple scab and fireblight on fruit trees could be applied to related tree varieties grown as ornamentals, but this is not a common practice in nurseries. For these reasons, nursery personnel with limited training in plant pathology and entomology face a daunting task in responding appropriately to disease and pest outbreaks.

Nursery Plants Can Be Vectors of High-Stake Pests and Pathogens

Despite all these challenges, management of disease and pest outbreaks in nurseries is particularly critical. Nursery stock can be an important long-distance vector for many pests and pathogens, including exotic organisms that threaten not only ornamentals but also agricultural crops and forests (Table 1). There are numerous historical examples of pathogen and pest introductions via the nursery trade, some of which have caused widespread and catastrophic epidemics. For example, *Cronartium ribicola*, the cause of white pine blister rust, was introduced to 226 locations in the U.S. Midwest on German nursery stock, nearly wiping out white pine (21,26). Chestnut blight, caused by *Cryphonectria parasitica*, was introduced from Asia on nursery stock of Japanese chestnut sold by mail order nurseries beginning in the 1890s (7). By 1926, the disease had spread throughout the eastern North American forests, eliminating mature American chestnut throughout its native range. To cite a more recent example, there is compelling evidence that *Phytophthora ramorum*, the cause of ramorum blight and sudden oak death, was introduced to the United States on at least three separate occasions, almost certainly via the nursery trade (Fig. 2) (8,9,12,13). This pathogen, responsible for widespread mortality of oak and tanoak in coastal California and southwestern Oregon, poses a threat to red oak–dominated ecosystems east of the Mississippi (6,24). In 2004, camellia plants from two southern California nurseries were shipped to thousands of locations throughout the continental United States, resulting in detection of *P. ramorum* in 176 nurseries (19). *P. ramorum* continues to be detected at low frequency in U.S. West Coast nurseries and in southeastern locations where infested plants were shipped (12). As is the case for sudden oak death, pathogens of agricultural crops are spread by the nursery trade. *Ralstonia solanacearum* race 2 biovar 3, causal agent of brown rot of potato and bacterial wilt of tomato, was imported several times into the United States on *Pelargonium* cuttings from Guatemala and Kenya during the period 1999 to 2004 (16). This pathogen, designated as a Select Agent under the Agricultural Bioterrorism Protection Act of 2002, is a threat to the $4 billion U.S. potato crop and the $2.2 billion tomato crop (2011 statistics) (28). Another emerging threat is the Australian light brown apple moth (*Epiphyas postvittana*) found first in California in 2006; it was almost certainly imported on live nursery stock (27). In 2007, the annual cost of eradication, quarantine, and damage to fruit crops (apple, pear, grape, and oranges) was estimated at $105 million (5). These select examples provide evidence for introduction of pests and pathogens affecting nursery crops, and movement by nursery crops, with significant detrimental economic and environmental impacts.

Current Pest and Pathogen Prevention Systems Are Inadequate

Current methods to prevent the movement of pests and pathogens via the domestic nursery trade are based on certification, endpoint inspections, and quarantines. These methods, although well intentioned, have failed to prevent contaminated plants from being shipped. There are many reasons why: for example, plants may be infected but not express symptoms; fungistatic materials may suppress disease temporarily; and pots or potting media may be infested but go unnoticed. Pathogens are particularly easy to miss when infecting roots. Furthermore, symptoms may not be recognized by plant inspectors, especially if they are caused by a new pathogen. The cost of inspection is also very high. For example, to comply with federal regulations, the Oregon Department of Agriculture spent approximately $3.2 million over a 5-year period (2001 to 2006) to survey nurseries that ship hosts of *P. ramorum* (6). Despite many practices such as prenotification, twice yearly inspections, and certification programs, *P. ramorum* has persisted at a low level since it was first detected in Oregon nurseries in 2003. Thus, the current system is both economically unsustainable and inadequate from a regulatory standpoint.

It is highly likely that additional exotic pests and pathogens will threaten agricultural, forest, and ornamental crops at an unprecedented rate. Live plant imports into the United States have increased more than 500% since 1967 (20), and the sheer volume of imports (43 million plants per inspector per year in FY 2010) precludes an effective inspection-based protection scheme. It is estimated that a substantial percentage of actionable pests and pathogens arriving at U.S. ports of entry for live plant imports are missed (20). The geographic sources of these imported plants have

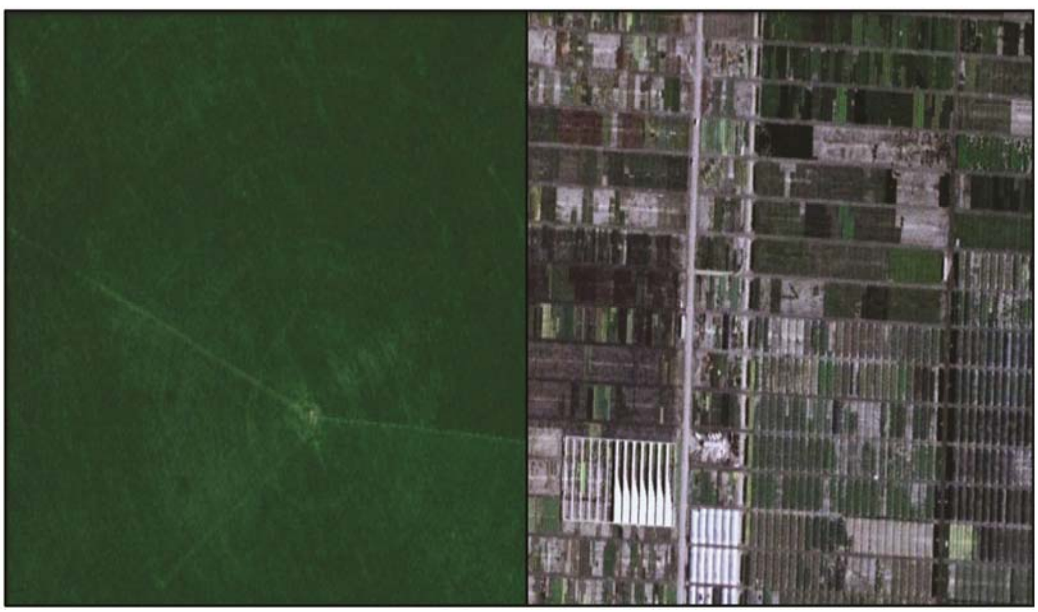

Fig. 1. A contrast of the environmental heterogeneity observed in typical row crop versus nursery production systems. Aerial photo of a potato field (left) and a horticultural nursery (right) as viewed from an altitude of 2,000 ft.

Table 1. Examples of quarantine pathogens and pests dispersed by the U.S. nursery trade that are of current concern to crop production, urban landscapes, or forests

Pest or pathogen	Ornamental host(s)	Threatens
Ralstonia solanacearum biovar 3 race 2	*Pelargonium*	Food crops (potato, tomato, eggplant)
Light brown apple moth	Many	Food crops, urban landscapes, forests
Phytophthora ramorum	Many	Forests, urban landscapes
Emerald ash borer	*Fraxinus* spp.	Forests, urban landscapes

also changed dramatically. While most live plants entering the United States continue to come from Canada or Europe, there has been a large increase in plants shipped from China, New Zealand, Australia, and Costa Rica, exposing U.S. plants to a new array of exotic pests and pathogens. The current piecemeal approach to managing individual pests and pathogens, especially those not yet discovered, is obviously inadequate for preventing the establishment of invasive pests and pathogens.

End-point inspections are similarly unsatisfactory for nursery growers. If a disease is discovered at the loading dock just before shipping, the grower doesn't know where the problem occurred, when or how contamination occurred, and how to correct the problem. There is a great risk of persistent or recurrent infestation if the source of contamination is not known. If the pathogen is of quarantine significance, this exposes the grower to potentially catastrophic economic risk. A lack of understanding about the source, persistence, and spread of a quarantine pathogen also causes uncertainty and risk for the nursery industry for the state or region in which it is found. Buyers in other states are reluctant to purchase nursery stock from locations where a quarantine pathogen has been detected and where end-point inspections have not prevented shipment of infected stock.

The purpose of this article is to introduce to plant pathologists a new conceptual framework for managing plant disease in agriculture, referred to here as a systems approach that is modeled after an approach widely used in other industries.

The Hazard Analysis of Critical Control Points System

Other industries and government agencies have had to develop practices to minimize risk associated with product contamination, and these could serve as a model for minimizing the risk of pathogen contamination of nursery stock. A team from NASA, including food scientists, engineers, and microbiologists, developed a method for reducing the risk of foodborne illness among astronauts in the 1960s (25). In 1971, when Pillsbury baby cereal was contaminated with broken glass, Pillsbury sought a systematic approach to ensure the safety of processed foods based on their prior experience with NASA. Meanwhile, in other food processing plants and restaurants, there continued to be several breaches of food safety, including botulism from low-acid canned foods. The National Canners Association petitioned the FDA for stiffer regulations, fearing consumer backlash. Pillsbury conducted the first training sessions on the new method, called Hazard Analysis of Critical Control Points (HACCP), for U.S. Food and Drug Administration inspectors in 1972. In the 1980s, when interest waned, a report produced by the National Academy of Sciences on microbial criteria for food production provided a strong endorsement of HACCP. This led to the formation of the National Advisory Committee on Microbiological Criteria for Foods, established in 1988. The HACCP program is now required for juice, meat, poultry, and seafood processing facilities in the United States and is recommended for all other food products (29).

The HACCP approach consists of a prescribed series of logical steps to identify, evaluate, and correct sources of hazards (Sidebar).

Steps required for Hazard Analysis of Critical Control Points

1. Conduct a hazard analysis
2. Identify the critical control points
3. Establish critical limits
4. Establish monitoring procedures
5. Establish corrective actions
6. Establish record-keeping procedures
7. Establish verification procedures

Source: U.S. Food and Drug Administration (29).

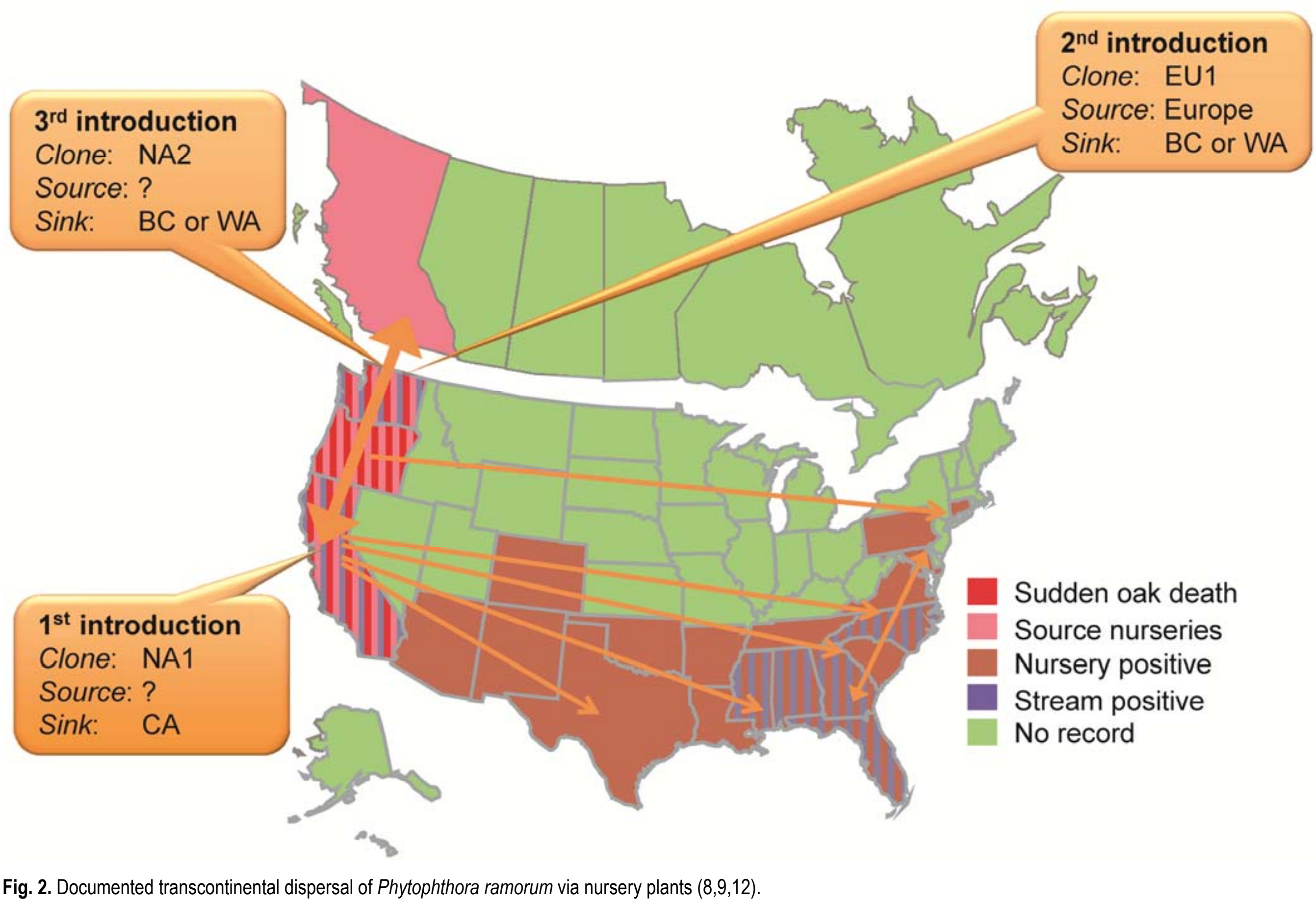

Fig. 2. Documented transcontinental dispersal of *Phytophthora ramorum* via nursery plants (8,9,12).

In the food processing industry, three types of hazards to public health have been identified: physical, chemical, and biological. HACCP requires that the production process be systematically and rigorously examined to identify potential hazards that may affect the final product. A control point is defined as any point, step, or procedure at which biological, physical, or chemical factors can be controlled. A critical control point (CCP) is a point, step, or procedure at which control can be applied and a hazard can be prevented, eliminated, or reduced to acceptable levels (29). It is important to note that HACCP is not a stand-alone program. For the food-processing industry, Good Manufacturing Practices (GMPs) and Standard Sanitation Operating Procedures (sSOPs) are prerequisites for having a successful HACCP program. Once potential hazards and CCPs have been identified, the production process is changed to manage hazards instead of relying on end-point inspection or testing of the final product, which could result in rejection of the product, or even worse, products actually posing a hazard such as being contaminated by a pathogen.

HACCP has also been adapted by the U.S. Fish and Wildlife Service as a mechanism for preventing the spread of nontarget, invasive species such as aquatic weeds, nondesirable fish, and invertebrates during fish stocking efforts. An online template, called the HACCP Wizard (www.haccp-nrm.org), assists natural resource managers in anticipating and preventing contamination by nontarget species. Several hospitals around the world are using the HACCP approach to reduce the spread of pathogens and foodborne illnesses (11), as are producers of pharmaceuticals and cosmetics. The HACCP approach has only recently been applied to plant production systems. The horticultural industry in Australia implemented a HACCP-based program, BioSecure HACCP (2), to ensure that their plants are free of pests. Nurseries certified to comply with these guidelines have greater access to international export markets.

Implementing a Systems Approach to Improve Nursery Production Systems: The Oregon Experience

With concepts borrowed from HACCP, we modified and applied a proactive, preventative systems approach to nursery plant production in Oregon with the goal of minimizing the hazard of plant contamination by *Phytophthora* species (22).

HACCP implementation begins with an analysis of hazards (Sidebar), which includes identification of all potential hazards that can be introduced, increased, or controlled at each step of the process (29). We chose to focus a priori on a single hazard, the pathogen genus *Phytophthora,* which is well known to be a serious problem in Oregon nurseries. For three years, we worked with four commercial nurseries that specialize in the production of woody ornamentals, many of which are hosts to *Phytophthora* spp. We developed flowcharts (Fig. 3) for each nursery's production system, mapping the stages and location of each growing phase, then listed all the known, possible sources of *Phytophthora* contamination at each stage of production. Although each nursery is unique, they all followed the general production sequence shown. For this study, we deliberately chose nurseries that did not purchase plants off-site; it would not have been possible to monitor plants for *Phytophthora* contamination each time a shipment was received. Im-

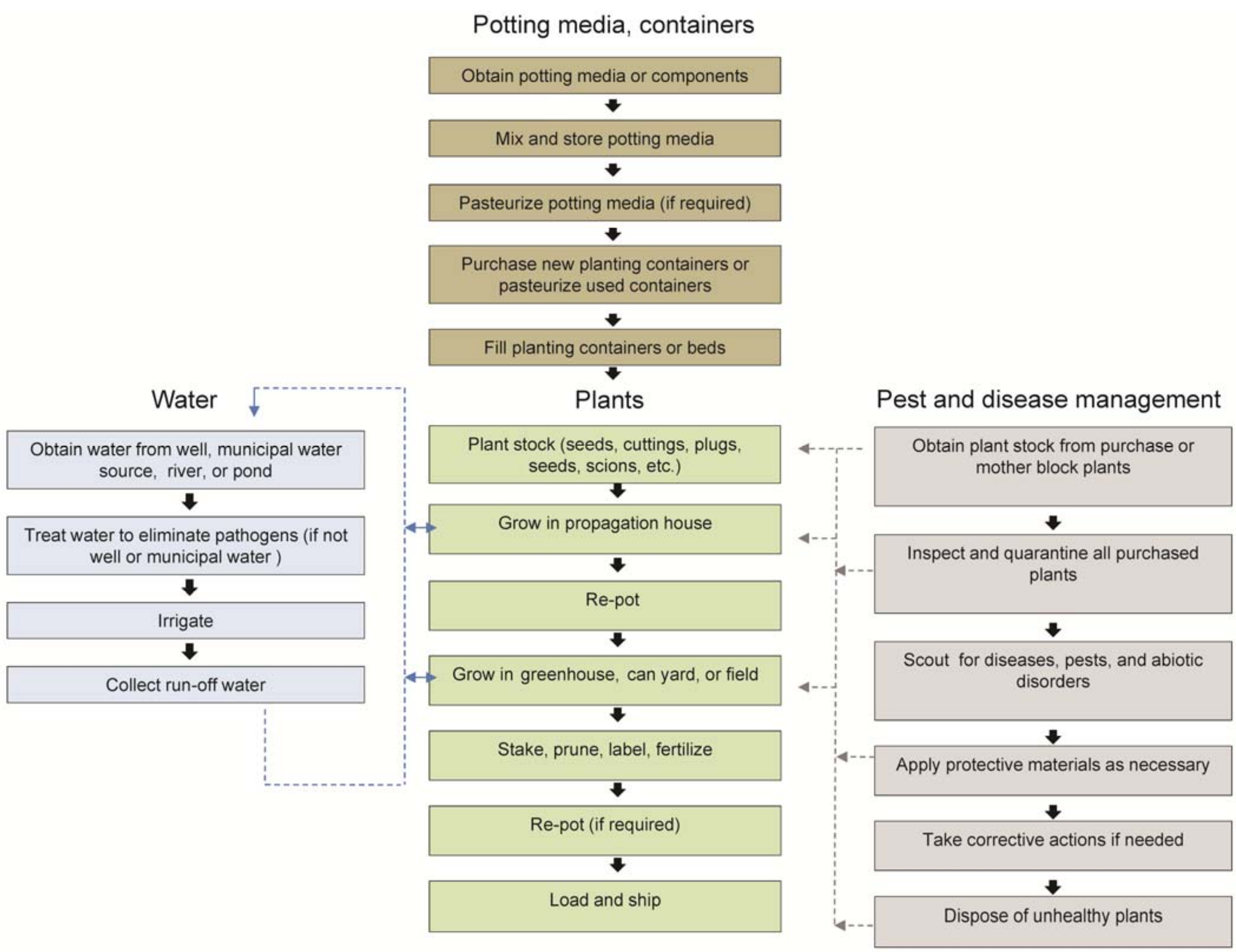

Fig. 3. An example of a simple production flow chart for a typical production container nursery. Each step in the process should be evaluated for contamination hazards by pests and pathogens.

portantly, two of the four nurseries recycled their water, whereas two nurseries used water from deep-water wells or municipal sources.

The next phase of a HACCP plan is hazard evaluation, where the severity and probability of each hazard occurrence is reviewed and assessed. To evaluate the hazard of contamination by *Phytophthora* spp., we sampled each nursery every two months for three years, including plants at all stages of the production cycle from propagation, greenhouse-grown liners, container plants of various sizes, and field-planted stock (Fig. 4). We sampled symptomatic and asymptomatic plant leaves, stems, and roots; container media and media components; used pots; water used for irrigation; and the ground upon which containers were placed. Plant tissue was plated onto *Phytophthora*-selective media for pathogen isolation. Pure cultures of putative *Phytophthora* isolates were identified to species by direct sequencing of the internal transcribed spacer (ITS) rDNA and blast searches at www.phytophthora-id.org (14). Over 700 *Phytophthora* isolates were retrieved and identified to species. Data generated from the hazard analysis allowed determination of the most important points of contamination in the nurseries. Detailed results on *Phytophthora* species found and their sources will be described elsewhere. We analyzed all these hazards and chose four core hazards that yielded the greatest recovery of *Phytophthora* isolates: contaminated ground, contaminated irrigation water (in the two nurseries that did not treat recycled water), used pots, and contaminated potting media (Fig. 5).Our effort is a first attempt to systematically define *Phytophthora* hazards within nurseries and to monitor them over time.

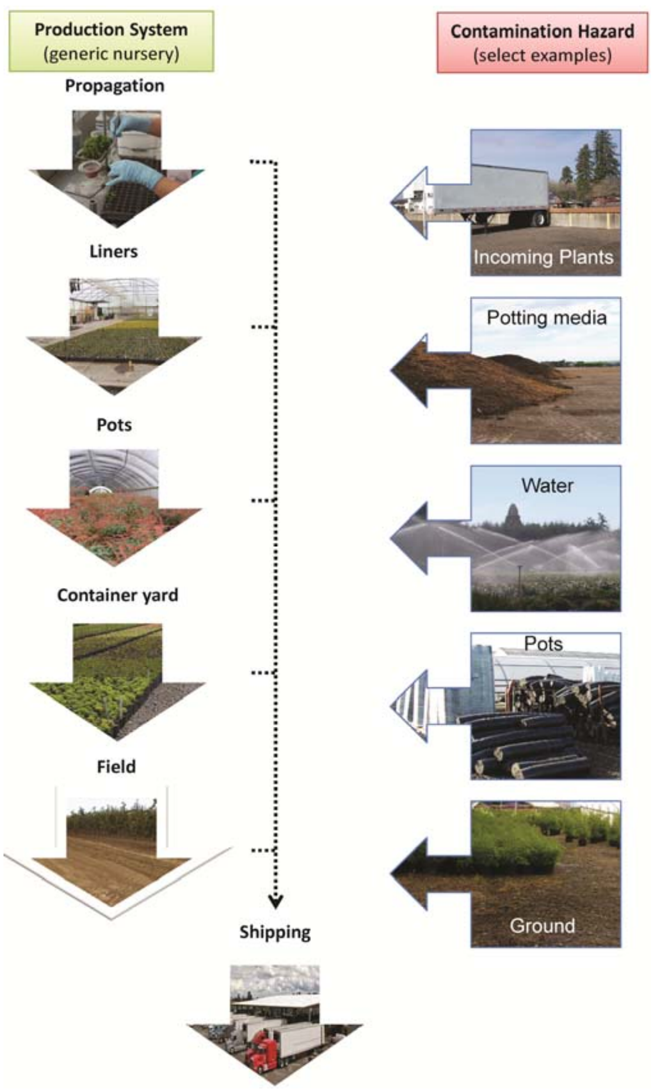

Fig. 4. Examples of contamination hazards for *Phytophthora* contamination in a generic nursery.

Defining Critical Control Points

The next stage in the process was to identify CCPs, the points, steps, or procedures at which control can be applied and *Phytophthora* hazards can be prevented, eliminated, or reduced to acceptable levels. We worked with nursery managers to develop CCPs for each of our four core hazards established above as common sources of contamination. For example, for the hazard "contaminated ground", several possible CCPs were designated (Table 2). We then met with nursery managers to brainstorm and develop best management practices targeting each CCP. These interactions with growers were particularly productive because the growers' insights, creativity, and innovation as well as the science could be applied to solve the problem.

From this point on, our approach differed from the HACCP approach. We were able to establish critical limits for some, but not all, CCPs. For example, we were able to advise growers on the time and temperature requirements for pasteurizing media and containers, and we advised them of effective means for disinfesting contaminated irrigation water (10). However, we did not establish monitoring procedures, record-keeping, and verification. Implementation of an effective systems approach in a nursery situation should eventually include these elements as well.

We had intended to compare the frequency of recovery of *Phytophthora* isolates in our cooperating nurseries *before* and *after* implementation of a systems approach, thereby assessing efficacy in reducing disease based on multiple samples to account for seasonal variability and changes in host plant inventory. This was not possible. As the nursery managers learned about specific sources of contamination in their nurseries, they gradually, and at different rates and to different extents, began to modify their practices during this study. Sources of contamination became a "moving target" as growers improved sanitation practices, water treatment and management, and other cultural practices. While our results are not quantitative, we were also not able to find quantitative analysis of efficacy for any domestic phytosanitary system in the scientific literature.

A few case studies may illustrate the effectiveness of a systems approach and show how our interactions with growers resulted in the development of feasible yet flexible problem solving.

Case Study 1: One grower experienced repeated crop failures when placing container-grown *Kalmia latifolia* plants on a large, well-drained, gravel-surfaced container yard. Plants consistently developed foliar blight from *Phytophthora syringae.* The pattern of infection indicated splash dispersal of inoculum from the underlying gravel during winter rain events. The gravel had become infested from decomposed leafy debris from infected plants, and it was difficult to develop a way to disinfest it. The grower suggested laying down fabric mesh over the gravel and removing the leafy debris between crops with a riding lawn mower with a bag attachment, a strategy that proved to be both practical and effective in eliminating *P. syringae* foliar blight.

Case Study 2: Another grower, upon learning that we detected *Phytophthora* species in containers designated for re-use, decided to build his own steam chamber. Although he was motivated to treat pots because of the *Phytophthora* contamination problem, steam treatment also killed weed seeds, reducing his expenses for herbicides and labor. This practice more than paid for the cost of the pot steaming operation.

Case Study 3: Another grower who wanted to disinfest used containers built a large bin with walls and a lid made of clear polyethylene. Solarization of the dark-colored, used pots, loosely piled in the bin for several weeks, resulted in disinfestation of the containers.

Case Study 4: A large growing operation that otherwise practiced excellent sanitation used untreated recycled irrigation water for watering plants on the shipping dock. The pond with untreated water, a significant source of *Phytophthora* isolates, was closer to the shipping dock than were reservoirs with treated water. When this was pointed out to the manager, he immediately instructed his crew to switch to using treated water, which eliminated the problem.

Case Study 5: In this large nursery, field workers frequently removed and destroyed symptomatic plants without bringing them to the attention of their nursery managers for diagnosis and corrective action. The field workers felt that it was disrespectful to their supervisors to point out plant "failures". Once the nursery began following a systems approach, the production manager discussed the importance of scouting and encouraged field workers to bring all symptomatic plants to him. According to the nursery manager, the field workers were empowered by his recognition that their skills as early detectors were highly valued. The CCP illustrated here is effective scouting.

Discovery of CCPs in these nurseries led the Oregon Department of Agriculture to develop a pilot nursery certification program called the Grower-Assisted Inspection Program (GAIP). Each nursery choosing to participate in this program agreed to develop a manual, requiring the Oregon Department of Agriculture's (ODA) approval, which specified how they would employ best management practices to address each of the four CCPs. The nurseries are also subject to twice yearly audits and plant inspections by ODA, exceeding the federal requirement for annual inspection. Finally, select personnel at each nursery were required to pass a test after completing a free online training course about *Phytophthora* diseases. The online course (see http://pne.oregonstate.edu/course/phytophthora-training-nursery-growers) was developed at Oregon State University in collaboration with USDA Agricultural Research Service and ODA (23). Individuals who pass the test receive a certificate indicating mastery of the subject. The overall effectiveness of the GAIP program remains to be determined through scientific analysis, but it has been well received by the growers and particularly the out-of-state customers.

Traditional Approaches versus Systems Approaches to Management of Pests and Diseases

Traditional approaches are essentially *reactive*; they rely on end-point inspections to detect infested plants and do not address unknown pathogens or pests. In contrast, systems approaches are *proactive*; they aim to reduce the risk of infestation by correcting unsafe nursery practices for all pathogens and pests (Table 3).

Fig. 5. Examples of the four core hazards of *Phytophthora* contamination in commercial production nurseries studied in Oregon followed by best management practices (BMP). (Clockwise from upper left) **A,** Propagation trays placed directly on the ground can become infested with *Phytophthora* spp. BMP: place plants on elevated clean surfaces that are not subject to splash-dispersed inoculation. **B,** Recycled pots were found to be a source of *Phytophthora* spp. BMP: clean and sterilize pots if reused or use new pots. **C,** Planting media became contaminated with *Phytophthora* spp. by muddy field equipment used for mixing and loading. BMP: Use clean equipment to mix or load planting media and store media in an area free of contamination. **D,** Water from ponds, particularly recycled water, can be infested with *Phytophthora*. BMP: disinfest water before irrigating plants.

Table 2. A few examples of *Phytophthora* contamination hazards, critical control points, and best management practices; discovery of contamination hazards and critical control points should drive the development of best management practices

Contamination hazard	Critical control points	Best management practices
Ground	Direct contact between containers and contaminated ground	Raise containers off the ground or add a rock or gravel barrier between containers and the ground
	Splash dispersal of pathogen from contaminated ground	Prevent standing water by not overwatering and correcting drainage problems
	Movement of contaminated soil by tools and equipment	Clean equipment (shovels, pruning shears) and vehicles (trucks, loaders, carts) before moving from contaminated areas to other areas
	Movement of soil by staff and visitors	Disinfest shoes before entering propagation areas
	Contamination of soil by infested fallen foliage	Prevent leafy debris from accumulating on the soil surface
Water	Contamination of plants by use of infested irrigation water	Disinfest irrigation water using an approved method[a] or use water from deep wells or municipal sources
	Splash dispersal of pathogen	Prevent standing water by not overwatering and correcting drainage problems, or by raising containers off the ground
	Contamination of waterways	Recapture runoff water and subsequently treat it with an approved method[a]
Containers	Contamination by reused containers	Use new containers or properly disinfest used containers
Planting media	Contamination by infested media ingredients	Ensure that all media ingredients are free of *Phytophthora* spp. or disinfest ingredients before use
	Contamination by infested soil, water, or plant material	Store media in an area free of contamination
	Contamination by infested soil	Use clean equipment to mix or load planting media

[a] Griesbach et al. (10).

Table 3. Comparison of approaches to reduce physical, chemical, or biological contaminants in industrial applications

Traditional approach	Systems approach
Reactive	Proactive
Conduct end-point inspections	Audit process to ensure compliance
Produce and test	Correct unsafe practices
Detect contaminants	Prevent contaminants

Because systems approaches emphasize safe production practices that result in healthy plants, nurseries that document these practices can gain access to national and international markets that otherwise might be unavailable to them. The cost of implementing a systems approach is often outweighed by the benefits of accessing these markets. Additional advantages of using the systems approach are that growers learn where their sources of contamination occur so that they can treat the "root" of the problem, not just the symptom. One of the appeals of the systems approach to growers is its flexibility. In our experience, flexibility is crucial as each nursery has its own logistical and economic constraints, and one-size-fits-all approaches are not feasible. A customized implementation of measures to control pests and pathogens at a given CCP allow for easier adoption by the grower community. For example, if used pots are contaminated, multiple strategies are available for eliminating this as a source of contamination, including the use of new pots, treatment of used pots with aerated steam, use of disinfectants, or solarization.

Our study focused on *Phytophthora* species. The prospect of developing CCPs for each individual pest and pathogen may seem daunting, but there are likely to be CCPs that are common to many pests and pathogens so that a proactive, preventative approach for one may influence several. At the request of USDA-APHIS, a technical working group of plant pathologists, entomologists, and horticulture industry representatives recently developed a set of "minimum standards" for managing pests and pathogens in greenhouse and nursery crops intended for interstate trade (J. L. Parke, *personal communication*). These minimum standards are based on CCPs for all pests and pathogens affecting nursery and greenhouse crops. If embraced by the nursery and greenhouse industry and state and federal regulatory agencies, the minimum standards could be the first step in the long process of implementing a systems approach nationally.

Although systems approaches offer many potential benefits, there are some information gaps that currently limit its application to the horticultural industry. Data comparing the effectiveness of systems approaches to end-point inspections in preventing dissemination of contaminated plants are not available. The cost of implementing systems approaches to growers and regulatory agencies is also not known. Hazards may differ significantly between nurseries in different geographic regions, requiring adaptation. Training of nursery growers and field personnel in recognizing, correcting, and documenting unsafe practices will be required. The extent of regulatory oversight required is not known. There is an absence of data on critical limits. Our study only detected the presence or absence of *Phytophthora* species without any attempt to quantify inoculum, but knowledge of dose–response relationships will be essential for assessing hazards. For example, we do not know what concentration of waterborne inoculum of *Phytophthora* species is required to initiate disease, leading to establishment of a "zero tolerance" for this group of pathogens.

Systems Approaches in Restaurants and Horticultural Nurseries

Restaurants, like nurseries, are privately managed businesses that must conform to requirements to ensure product safety for the public. Whereas restaurants have a responsibility to prevent spread of human foodborne diseases, nurseries have a responsibility to prevent the spread of plant pests and diseases that affect agriculture and natural resources. Food handlers are required to undergo training to prevent disease, and they must pass a competency test. Nursery growers have no such training requirement. Restaurants, like nurseries, are audited by a regulatory agency, usually at the county or state level. But unlike nurseries, restaurants rely on a systems approach to ensure the safety of their product. Their processes for handling foods have specific requirements that minimize the risk of contamination, e.g., minimum water temperature for dishwashers and maximum temperatures for refrigerating foods. It would be impractical to employ end-point inspections of every meal that is served.

Introducing the Concept of a Systems Approach to Nursery Growers: An Analogy to Human Health

Growers may be wary of the concept of a systems approach. We have found it useful to draw analogies between management of

Table 4. Comparison of currently existing nursery certification programs

Component	Pelargonium Offshore Clean Stock Program[a]	U.S. Nursery CertificationPilotProgram (USNCP)[b]	Oregon Grower-Assisted Inspection Program (GAIP)[c]	Australian Biosecure HACCP[d]
Systems approach	√	√	√	√
Science-based guidelines	√	√	√	√
Flexible	√	√	√	√
Standards defined	√	√	√	√
Audit-based	√	√	√	√
Education/training	√	√	√	√
Incentives	√	√	√	√
Effectiveness demonstrated	√	-	-	-

[a] http://www.aphis.usda.gov/plant_health/plant_pest_info/ralstonia/downloads/ralstoniaworkplan.pdf
[b] http://www.aphis.usda.gov/plant_health/acns/downloads/USNCP-Standards.pdf
[c] http://www.oregon.gov/ODA/PLANT/NURSERY/gaip.shtml
[d] Bagshaw et al. (2).

nursery health and human health (10). We ask growers to consider the difference between following a wellness program or visiting the doctor only when one is sick. A wellness program emphasizes disease prevention through healthy lifestyle choices including a nutritious diet and regular exercise, childhood vaccinations, and annual check-ups and lab tests. In contrast, only visiting the doctor when one is sick may require emergency treatment for catastrophic illness, expensive surgeries, and prescription medications. The wellness program is a holistic, systems approach to managing human health, whereas only visiting the doctor when one is sick is essentially a piecemeal, reactive approach to managing health. Likewise, a systems approach in nurseries can prevent the need to respond with a spray program, crop destruction order, or quarantine when a problem develops in the field or the greenhouse.

International and Domestic Trends in the Plant Trade

The potential introduction of quarantine pests and pathogens on infested nursery stock remains a major barrier for domestic and international trade. The North American Plant Protection Organization (NAPPO) is a regional phytosanitary organization that develops agreements on plant health, facilitating trade between Canada, the United States, and Mexico. The NAPPO Standards for Plants for Planting were adopted in 2005. International standards for the production of live plants ("plants for planting") in international trade were recently ratified (15). These two standards both call for implementation of a systems approach, heightening the urgency to develop uniform domestic standards. There is an international trend toward the development of nursery certification programs that would, in theory, prevent contamination of nurseries and preclude shipment of exotic pests. Proposed nursery certification programs require strict adherence to specific management practices, extensive record-keeping, and periodic audits by regulatory personnel rather than requiring inspection of individual shipments. APHIS, the National Plant Board, and state departments of agriculture are looking at potential alternative strategies to end-point inspections, which are both costly and ineffective. There are a number of different domestic and international nursery certification systems that are based on a more holistic approach to producing and shipping healthy plants (Table 4).

Conclusions

The HACCP-based systems approach shows promise as a means of improving control of pathogens and pests in nursery production systems and preventing movement of exotic pathogens or pests in the nursery trade. While it may be premature to abandon our current system of end-point inspections, it should be possible to transition within a few years to a systems approach, analyzing hazards, identifying critical control points, obtaining data on best management practices that are effective in mitigating CCPs, and gathering data on effectiveness and costs. A systems approach is also a process that is always subject to improvement by continued learning and reassessment of CCPs followed by implementation of new and revision of existing control strategies.

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Literature Cited

1. Aegerter, B. J., Nuñez, J. J., and Davis, R. M. 2003. Environmental factors affecting rose downy mildew and development of a forecasting model for a nursery production system. Plant Dis. 87:732-738.
2. Bagshaw, J., Rogers, M., and McDonald, J. 2008. BioSecure HACCP Guidelines for Managing Biosecurity in Nursery Production. Nursery & Garden Industry Australia, Sydney.
3. Daughtrey, M. L., and Benson, D. M. 2005. Principles of plant health management for ornamental plants.Annu. Rev. Phytopathol. 43:141-169.
4. Dreistadt, S. H. 2001. Integrated pest management for floriculture and nurseries. University of California System, Division of Agriculture and Natural Resources Pub. 3402.
5. Fowler, G., Garrett, L., Neeley, A., Borche, R. D., and Spears, B. 2007. Economic analysis: Risk to U.S. apple, grape, orange and pear production from the light brown apple moth, *Epiphyas postvittana* (Walker). Online. http://www.aphis.usda.gov/planthealth/plantpestinfo/lbamoth/
6. Frankel, S. J. 2008. Sudden oak death and *Phytophthora ramorum* in the USA: A management challenge. Australas. Plant Pathol. 37:19-25.
7. Freinkel, S. 2007. American Chestnut: The Life, Death, and Rebirth of a Perfect Tree. University of California, Berkeley.
8. Goss, E. M., Larsen, M., Chastagner, G. A., Givens, D. R., and Grünwald, N. J. 2009. Population genetic analysis infers migration pathways of *Phytophthora ramorum* in US nurseries. PloS Pathogens 5:e1000583
9. Goss, E. M., Larsen, M., Vercauteren, A., Werres, S., Heungens, K., and Grünwald, N. J. 2011. *Phytophthora ramorum* in Canada: Evidence for migration within North America and from Europe. Phytopathology 101:166-171.
10. Griesbach, J. A., Parke, J. L., Chastagner, G. C., Grünwald, N. J., and Aguirre, J. 2012. Safe procurement and production manual: A systems approach for the production of healthy nursery stock. 2nd ed. Oregon Association of Nurseries, Wilsonville, OR. http://oan.org/associations/4440/files/pdf/SafeProduction.pdf
11. Griffith, C. J. 2006. Food safety: Where from and where to? Br. Food J. 108:6-15.
12. Grünwald, N. J., Garbelotto, M., Goss, E. M., Heungens, K., and Prospero, S. 2012. Emergence of the sudden oak death pathogen *Phytophthora ramorum*. Trends Microbiol. 20:131-138.
13. Grünwald, N. J., Goss, E. M., and Press, C. M. 2008. *Phytophthora ramorum:* A pathogen with a remarkably wide host range causing sudden oak death on oaks and ramorum blight on woody ornamentals. Mol. Plant Pathol. 9:729-740.

14. Grünwald, N. J., Martin, F. N., Larsen, M. M., Sullivan, C. M., Press, C. M., Coffey, M. D., Hansen, E. M., and Parke, J. L. 2011. Phytophthora-ID.org: A sequence-based *Phytophthora* identification tool. Plant Dis. 95:337-342.
15. International Plant Protection Convention (IPPC). 2012. Integrated Measures for Plants for Planting adopted Mar. 23, 2012. International Standards for Phytosanitary Measures (ISPM). https://www.ippc.int/index.php?id=13399
16. Jones, J. 2010. Recovery plan for *Ralstonia solanacearum* race 3 biovar 2 causing brown rot of potato, bacterial wilt of tomato, and southern wilt of geranium. Online. http://www.ars.usda.gov/SP2UserFiles/Place/00000000/opmp/RalstoniaR3b2May2010.pdf [Accessed April 28, 2011]
17. Jones, R. K., and Benson, D. M. 2001. Diseases of Woody Ornamentals and Trees in Nurseries. American Phytopathological Society, St. Paul, MN.
18. Jones, R. K., Simone, G. W., von Broembsen, S. L., and Dutky, E. 2001. Integrated disease management. Pages 376-383 in: Disease of Woody Ornamentals and Trees in Nurseries. R. K. Jones and D. M. Benson, eds. American Phytopathological Society, St. Paul, MN.
19. Kliejunas, J. T. 2010. Sudden Oak Death and *Phytophthora ramorum*: A Summary of the Literature. U.S. Dep. Agric., For. Serv., Pacific Southwest Res. Stn., Albany, CA.
20. Liebhold, A. M., Brockerhoff, E. G., Garrett, L. J., Parke, J. L., and Britton, K. O. 2012. Live plant imports: The major pathway for forest insect and pathogen invasions of the United States. Frontiers Ecol. Evol. 10:135-143.
21. Maloy, O. C. 1997. White pine blister rust control in North America: A case history. Annu. Rev. Phytopathol. 35:87-109.
22. Parke, J. L., Lewis, C., and Grünwald, N. J. 2008. Tracing the path of pathogens. Digger 12:43-51.
23. Parke, J. L., Pscheidt, J., Regan, R., Hedberg, J., and Grünwald, N. J. 2008. *Phytophthora* Online Course: Training for nursery growers. Online. http://pne.oregonstate.edu/course/phytophthora-training-nursery-growers [Accessed July 2, 2012]
24. Rizzo, D. M., Garbelotto, M., and Hansen, E. M. 2005. *Phytophthora ramorum:* Integrative research and management of an emerging pathogen in California and Oregon forests. Annu. Rev. Phytopathol. 43:309-335.
25. Ross-Nazzal, J. 2007. From farm to fork: How space food standards impacted the food industry and changed food safety standards. Pages 219-236 in: Societal Impact of Spaceflight, NASA, Washington, D.C.
26. Spaulding, P. 2010. The Blister Rust of White Pine (1911). Reprinted 2010. Kessinger Publishing. Whitefish, MT.
27. Suckling, D. M., and Brockerhoff, E. G. 2010. Invasion biology, ecology, and management of the light brown apple moth (Tortricidae). Annu. Rev. Entomol. 55:285-306.
28. U.S. Department of Agriculture Economic Research Service. 2012. Data Set Catalog Listing. Data sets: Vegetables, melons, and pulses. Online. http://www.ers.usda.gov/Catalog/CatalogByTopicID.asp?SON=TRUE&SBY=TITLE&PDT=1&ARC=C&TID=660 [Accessed April 17, 2012]
29. U.S. Food and Drug Administration. 2012. Hazard analysis and critical control point principles and applications guidelines. http://www.fda.gov/Food/FoodSafety/HazardAnalysisCriticalControlPointsHACCP/HACCPPrinciplesApplicationGuidelines/default.htm [Accessed April 17, 2012]

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