Integrated Pest Management – An Overview and Update

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Integrated pest management, better known as IPM, is a familiar term for those of us working in forest, conservation, and native plant nurseries. An almost synonymous concept is "holistic pest management" that has been the topic of chapters in recent Agriculture Handbooks that would be useful to growers of native plants (see Landis and others 2009; Landis and others 2014). Let us take a quick look at its history and a more in-depth look at applying the concepts.

1. Brief history and definitions

Pests have been around since humans first domesticated crops, which explains the origin of the "pest" concept—any organism that interferes with society's objectives. The Sumerians, who lived in Mesopotamia around 2,500 B.C., were the first to use pesticides. They applied sulfur dust to control insect pests on their grape crops and, closer to our hearts, the Sumerians were the first people to make beer. Around 300 B.C., the Chinese encouraged natural enemies to control crop pests and by 1,100 A.D. they were using soaps as insecticides (Frazier 2014).

Moving ahead to the 1930s, a revolution in pest control occurred when dichloro-diphenyl-trichloroethane, better known as DDT, became the first synthetically produced pesticide. Due to its successful use during World War II to control malaria and typhus among troops its discoverer, Swiss chemist Paul Hermann Müllerg, was awarded the Nobel Prize in Medicine in 1948 (Encyclopedia Britannica 2014). After the war, DDT was widely used as an agricultural and domestic insecticide; it was so effective against mosquitoes that it was routinely sprayed with fogging equipment along municipal streets in the 1950s. It was not long, however, until people began to notice some unforeseen drawbacks to the use of DDT. In 1962, Rachel Carson wrote her environmental classic Silent Spring, which chronicled the adverse impacts of DDT spraying and suggested that the indiscriminate use of DDT was responsible for the death of many birds as well as a possible cause of cancer. This expose resulted in her receiving death threats from chemical companies but generated such a public outcry that DDT was eventually banned from agricultural use in the United States (Frazier 2014).

About that same time at the University of California, a team of entomologists developed the concept of "Integrated Control," which advocated a combination of chemical and biological controls. Integrated control also stressed regular monitoring and introduced the economic threshold for determining when any control is warranted (Warnert 2009). In the years that followed, integrated control was applied to all types of pests and included other tactics such as cultural controls. This more comprehensive concept became known as integrated pest management (IPM). In 1972, President Nixon signed a law that made IPM a national policy and the US Department of Agriculture created IPM programs at state Land Grant universities. Nixon also established the US Environmental Protection Agency that is responsible for reviewing Environmental Impact Statements of other federal agencies (US EPA 2014).

2. Working definition of IPM

IPM is one of those concepts that can mean many things to different people, and much has been written about procedures that just are not practical. An operational IPM program is based on an awareness of potential pests and regular monitoring (scouting). Controls are only applied when damage reaches an intolerable level (economic threshold), and a combination of cultural, biological, and chemical tactics are employed (Alston 2011a; Figure 1). The least toxic chemical that will control the pest is applied only as a last resort (Olkowski and others 1991). IPM programs can target a single species, for example, Fusarium root disease (James and others 1990) and lygus bug (*Lygus lineolaris*) (Bryan 1989), or an entire nursery program (for example, Dumroese and Wenny 1992).

2.1 Based on prevention

One of the first conceptual breakthroughs to using IPM is that the emphasis is on prevention, rather than eradication. For nursery pests such as grey mold, which is caused by the fungus *Botrytis cinerea*, the spores are

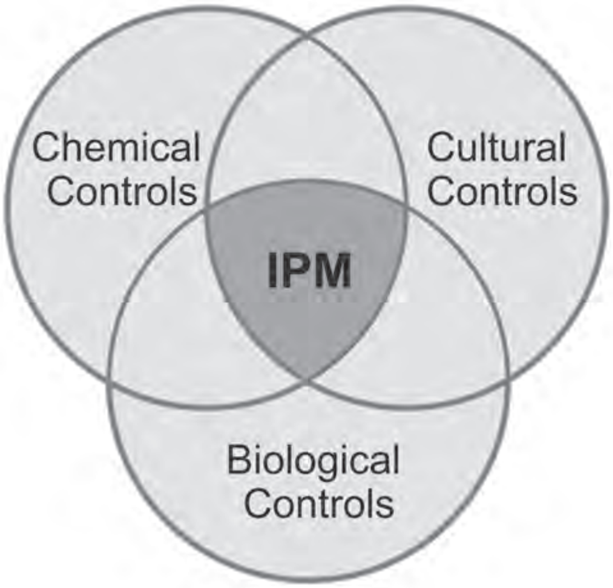

Figure 1 - Integrated pest management uses a combination of cultural, biological, and chemical controls.

always present because this fungus grows on many common weeds. Because it is an excellent saprophyte, grey mold typically gets established on the senescent foliage that develops in dense nursery crops as larger and younger foliage shades out the older cotyledons and primary foliage (Landis and others 1990). Because it also rapidly invades any damaged or stressed tissue, it is impossible to completely eliminate grey mold from your nursery.

2.2 Use least toxic chemicals as a last resort

Damping-off is another fungal disease that has always been common nursery pest (Landis 2013a). Before IPM, controlling a disease like damping-off typically meant spraying chemicals on seedlings that are probably already infected. Many pesticides are labeled for damping-off fungi but they only function as preventative chemicals and cannot cure infected seedlings. Many nurseries just routinely apply pesticides to prevent damping-off because they consider these chemical treatments as cheap insurance. However, the only true way to find out if these protective pesticide applications are effective is to not apply them to part of a crop as a control treatment (Figure 2). You might just find that they are unnecessary. During a 5-year period at the University of Idaho Center for Forest Nursery and Seedling Research, the percentage of container seedlings acceptable for shipment remained constant or even increased slightly when protective pesticide applications were reduced (Dumroese and others 1990). During this same period, the nursery also increased the total number of seedlings produced by 60%, showing that IPM can be scaled up as nurseries expand.

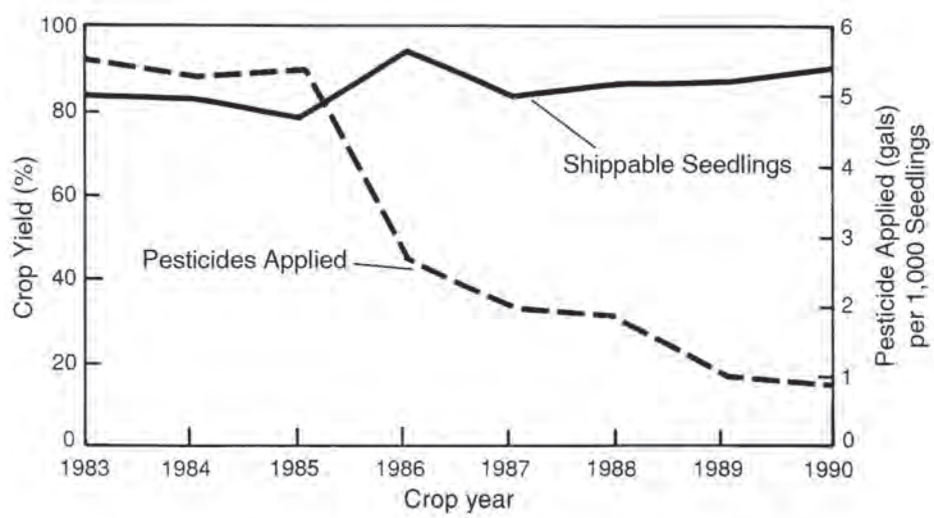

Figure 2 - The true test of whether protective pesticide applications are effective is to stop applying them for a period of time (modified from Dumroese and others 1990).

3. IPM is a systems approach, rather than an incident approach

For an IPM program to be effective, it should be applied as a systems approach rather than a “knee-jerk” response. A comprehensive discussion of a systems approach to managing ornamental nursery pests based on a hazard analysis of critical control points is presented by Parke and Grünwald (2012). A simple but effective systems approach to IPM consists of 6 sequential steps.

3.1 Be vigilant—assign scouting responsibilities

Because an effective IPM program is based on early detection and control, the entire nursery workforce should receive regular pest training so that they are constantly looking for problems. Although all workers must be alert for pests, the best procedure is to designate scouts whose primary responsibility is to monitor for any growth abnormalities. A good disease scout should have the following characteristics:

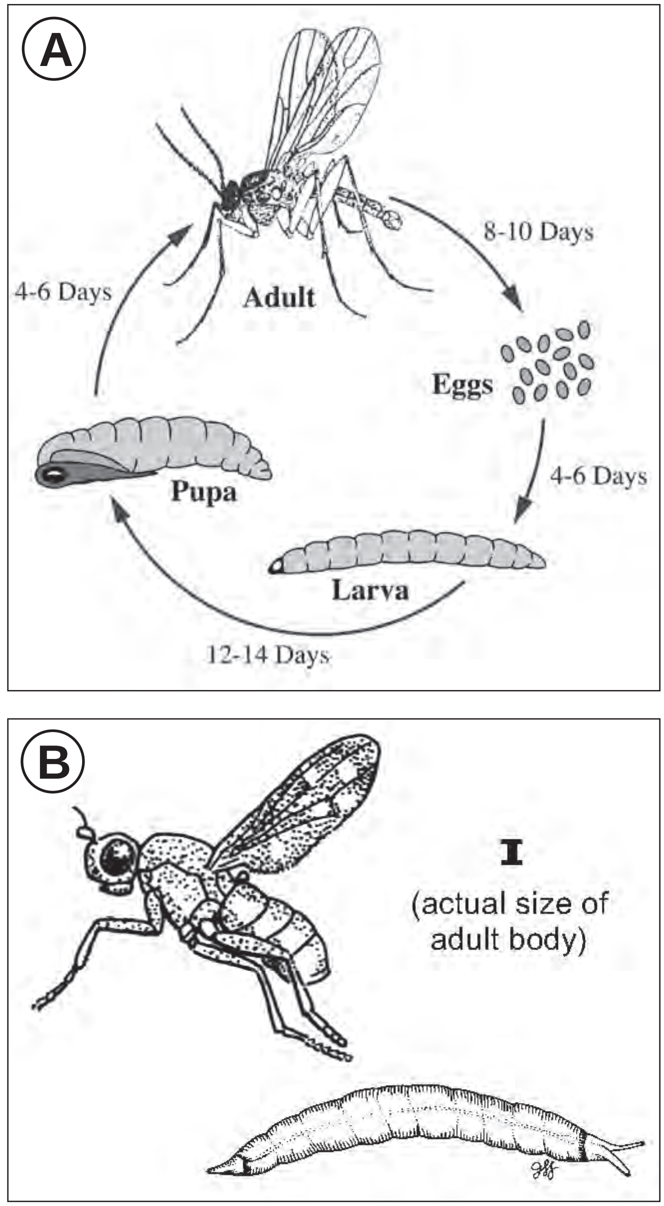

Figure 3 - Fungus gnats are common nursery pests, but understanding the life cycle (A) is critical to good IPM. A Y-shaped wing vein distinguishes common fungus gnats from other common small greenhouse flies (B) that may be a nuisance but don't damage seedlings (modified from Bethke and Dreistadt 2001).

Experience. Scouts should have extensive experience is all phases of the nursery system, and be knowledgeable of the growth phases of all the crops so that they can quickly spot when something is out of the ordinary. Experienced nursery workers, such as irrigators or inventory personnel that are regularly out in the crop, make the best scouts. After several seasons of working with crops, scouts will further refine what is normal and what is not. Scouts should have access to current and past growth records so that they can make comparisons and detect when things just are not looking right.

Observant. Scouts must be patient and take the time to look at each crop, and be inquisitive enough to check into any growth abnormalities. Allow scouts to have a flexible work schedule so that they can come into the nursery before and after normal working hours, and occasionally on weekends. Being away from the pressure of nursery work projects eliminates distractions and allows time for patient observation.

Well-trained. Scouts should be trained in disease diagnosis and identification, and be allowed to attend training sessions. Scheduling visits to other nurseries and talking to other nursery workers is a great way to learn and share experiences.

3.2 Identify pests promptly and accurately

"Know Your Enemy" is one of the major precepts in the classic book *The Art of War* that was written by Sun Tzu, an ancient Chinese military strategist. The analogy works for nursery pests too. All nursery workers should be given regular training on what pests could occur and the type of damage to look for. Understanding the life cycles of nursery pests is critical to good IPM. For example, fungus gnats (*Bradysia* spp.) are a common greenhouse pests that can affect many different greenhouse crops. Scouts must realize that the adult fungus gnat may be a nuisance but the larvae are what cause damage (Figure 3A) by eating seeds and fine roots of seedlings (Landis and others 1990). Scouts must be able to distinguish between adult fungus gnats and harmless shore flies (*Scatella* spp.) (Figure 3B), and realize that damaging populations of fungus gnats are usually an indication of excessive, and wasteful, irrigation.

Many nursery problems can be diagnosed by unique signs and symptoms but this is not the case with the newest and most serious nursery disease, *Phytophthora ramorum*. Signs and symptoms of this fungus-like pest are can vary considerably among hosts and are impossible to distinguish from other plant pathogens (including other *Phytophthora* species), insect damage, or abiotic injury (Kliejunas 2010). The presence of the pathogen can only be confirmed by experts using sophisticated and specialized techniques (Landis 2013b). This stresses the fact that good nursery scouts must know when to ask for expert advice.

3.3 Monitor your crops and keep good records

Monitoring your crop by using history plots can serve many purposes in the nursery, but one of their best uses is to detect and diagnose problems. These plots can be established in portions of bareroot seedbeds or container tables and can help identify when losses occur (for example, during specific growth phases) and focus observations to find the cause (see Landis 1997 for establishing history plots). Sometimes, history plots will reveal the cause of poor seedling growth may not be a pest. Often, for example, the first symptom that something is wrong is that plants don't grow or develop at a normal rate. This hidden stunting is not diagnostic in that it cannot identify the specific problem, but it is an early "heads-up". The only way that this stunting can be diagnosed is by taking good growth measurements from history plots, charting them manually or by computer, and then comparing current growth rates with those from previous crops. As an example, when a crop of blue spruce (*Picea pungens*) container seedlings showed early stunting compared to past crops, switching to a high nitrogen fertilizer at week 8 solved the problem (Figure 4). Note, however, that crops response was not immediate but the additional fertilizer took another 4 weeks to increase the shoot growth rate.

Another example is lygus bug, where critical observations recorded for consecutive years on pest occurrence and seedling damage identified the specific interval in the pine crop cycle when damage was likely to occur. Then, pesticide applications could be applied during the most opportune time to prevent damage, which was subsequently reduced from 17 to 6% (Bryan 1989).

3.4 Prevent pests through strict sanitation

The old adage "prevention is the best cure" certainly applies to nursery pest problems. The simplest approach to pest prevention is to make a list of your most significant nursery pests, and do some research into how they occur. Then, you can develop techniques to keep them from entering or spreading in your nursery. A wealth of good information has been published about nursery pests. For example, Forest Nursery Pests (Cram and others 2012) contains excellent information on the most common pest problems that you might encounter in your nursery, and well as other useful information on diagnosis and integrated pest management.

A more systematic approach to pest prevention is to develop a hazard analysis of critical control points (HACCP). A control point is any step in a production system that can be measured, monitored, controlled, and corrected, and a critical control point is the best step at which significant hazards can be prevented or reduced. The HACCP system consists of a series of logical steps to identify, evaluate, and correct sources of hazards (USFDA 2012). The HAACP approach has been developed to prevent the spread of pests and diseases in ornamental nurseries in Oregon (Parke and Grunwald 2012), and the same concepts can be applied in forest, conservation, and native plant nurseries.

A good bareroot nursery example of how the HAACP process can be applied is the transplanting operation. The introduction of transplants has been shown to be a significant risk for introducing pests, especially root rot

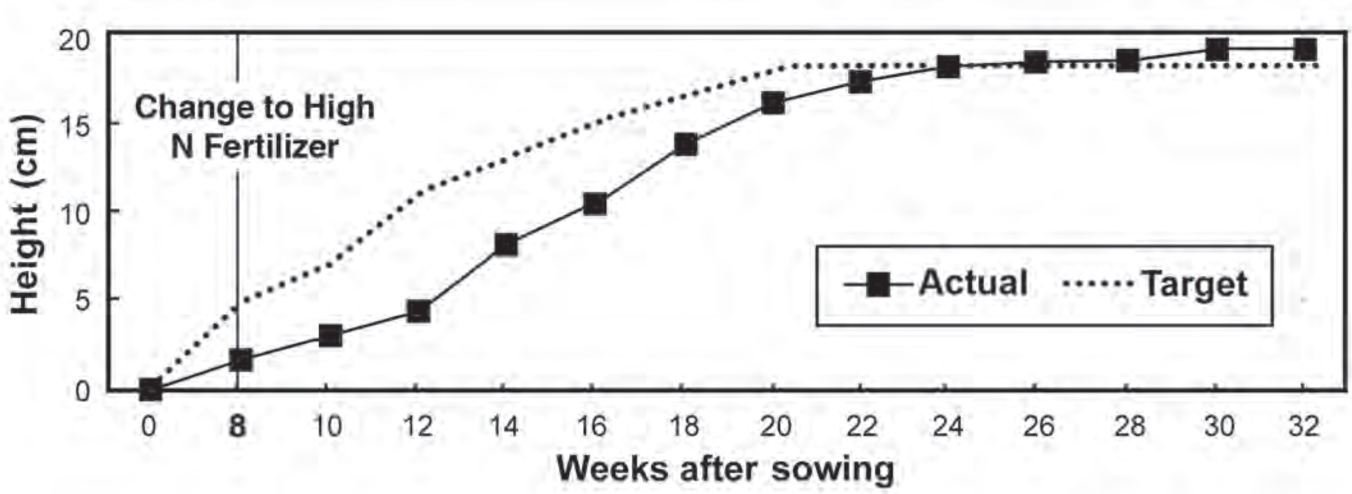

Figure 4 - Early stunting of this blue spruce container crop was only diagnosed by comparing the shoot growth to target growth curves, which were developed from past crop performance (modified from Landis and others 1999).

fungi, into the transplant nursery. The major problem is when bareroot seedlings are transplanted into another nursery (Cram and Hansen 2012); the risk of spreading root disease on container transplants is much less because of sterile growing media. So, in a typical transplanting operation, there are 2 critical control points (Figure 5A). First, the transplant stock; many nurseries either purchase seedlings for transplanting from other nurseries or they are supplied by a customer. It is very easy for pathogenic fungi to be transported on small soil particles adhering to the roots. Second, root rot fungi and nematodes can also be introduced into a bareroot nursery on cultivation or transplanting equipment. For this reason, nursery managers insist that operators clean and sterilize their equipment (Figure 3C) when it is moved from one field to another, and especially when equipment is leased or borrowed from other nurseries.

3.5 Keep crops healthy

Another important aspect of IPM is that many nursery problems can be avoided just by keeping your plants healthy. Vigorous nursery stock is much more resistant to pests, and also recovers more rapidly from environmental stresses. Root diseases are an excellent example. Although they frequently occur in bareroot and container nurseries, most common root disease fungi, such as *Pythium* spp., *Fusarium* spp., and *Cylindrocarpon* spp., are not aggressive pathogens. In a comprehensive study of *Fusarium* species on damping-off and root disease of Douglas-fir seedlings, the common nursery pathogen *F. oxysporum* only had an average rating of around 5 on a pathogenicity scale of 1 to 10 (James and others 1989). In Sweden, the fungal pathogen *Cylindrocarpon destructans* causes root rot problems of container pine seedlings. Researchers discovered that *C. destructans* does little harm to healthy seedlings but typically invades dead or dying roots. The fungus then uses these sites as a base for further invasion of healthy roots (Unestam and others 1989). Predisposing environmental factors are also important in bareroot nurseries. For example, Fusarium root disease only developed where tillage pans, caused by rotary cultivators, impeded water drainage and predisposed the seedlings to invasion by the pathogen (Juzwik and others 1998). Therefore, because opportunistic pathogens do not cause disease unless seedlings are under stress (Figure 6), it only makes sense to keep your crops healthy.

Your seedlings may not be healthy just because you don't see symptoms. Even though root pathogens, such as *Fusarium* and *Cylindrocarpon*, may not cause

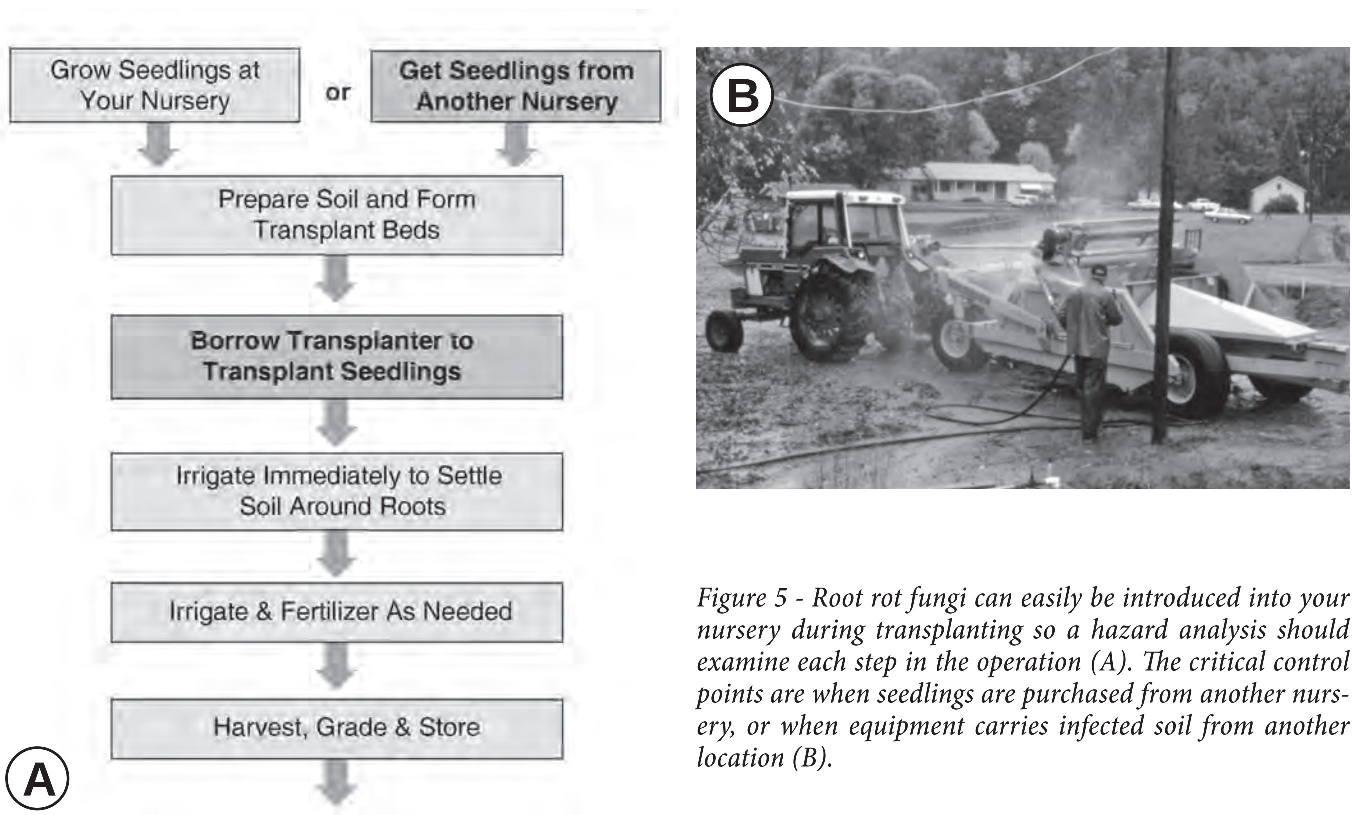

Figure 5 - Root rot fungi can easily be introduced into your nursery during transplanting so a hazard analysis should examine each step in the operation (A). The critical control points are when seedlings are purchased from another nursery, or when equipment carries infected soil from another location (B).

typical disease symptoms, such as shoot chlorosis or necrosis, they may still be reducing seedling growth. Dumroese and others (2002) found that containers reused for several growing seasons without proper sanitation allowed inoculum levels to increase and this was, despite no typical root rot symptoms, associated with significant reductions in growth and an increase in culls. Seedlings in containers that had been used for 5 crops but treated with hot water to remove inoculum were 16% taller with 10% more stem diameter and, 13% more seedlings made specification compared to those growing in non-sanitized containers.

3.6 Encourage beneficial organisms

One way to keep your crops healthy is to foster beneficial microorganisms, such as free-living fungi antagonistic to pathogenic fungi, helpful soil bacteria, and mycorrhizal fungi. Soil fungi, such as those in the genus *Trichoderma*, can help protect seedlings against root disease (Mousseaux and others 1998; Dumroese 2008) and several *Trichoderma*-based products are available commercially. The beneficial relationship between mycorrhizal fungi and nursery crops has been well known for more than 100 years (Koide and Mosse 2004). Healthy mycorrhizae confer many advantages to nursery crops including increased access to water and mineral nutrients but the one that is often overlooked is disease prevention (Whipps 2004). Microbial relationships in the rhizosphere often involve one or more “helper bacteria” that stimulate mycorrhizal formation with partner fungi (Garbaye 1994). Mycorrhizal fungi can protect roots against fungal pathogens and nematodes in four different ways (Marx 1972):

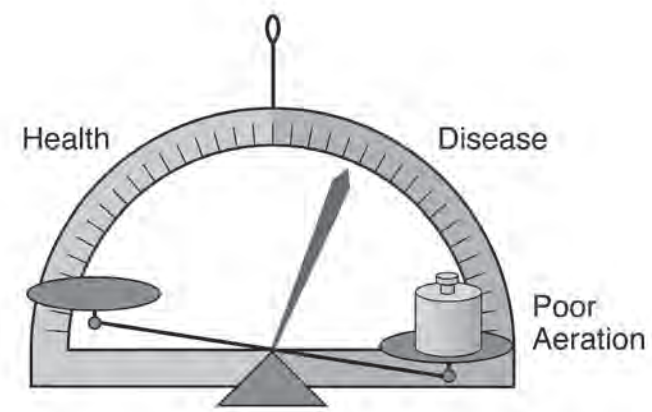

Figure 6 - Many nursery diseases are caused by environmental stresses, which stress plants and make them more susceptible to opportunistic pests. In this example, compaction of the soil or growing medium reduces aeration and provides an entry point for root diseases (Landis 2000).

Pathogen exclusion. This is the best known and most obvious benefit and is most easily seen with ectomycorrhizae that form a protective sheath around plant root tips (Figure 7). When young seedlings are inoculated with mycorrhizal fungi at the time of germination, a fungal mantle surrounds plant root tips and prevent damping-off during establishment, and root rot fungi later in the growing cycle. For example, when red pine (*Pinus resinosa*) container seedlings were inoculated with the mycorrhizal fungus, *Paxillus involutus* and subsequently with *Fusarium oxysporum*, damping-off disease was effectively prevented (Table 1) and seedling growth improved (Chakravarty and others 1990).

Enhanced plant vigor. Mycorrhizal fungi help produce larger, healthier seedlings that will be more resistant to pathogens and environmental stresses. For example, broadleaf tree seedlings inoculated with appropriate ectomycorrhizal fungi were better able to maintain physiological activity during water stress

Table 1 – Red pine seedlings inoculated with mycorrhizal fungi were protected from a subsequent inoculation with the fungal pathogen Fusarium oxysporum *(modified from Chakravarty and others 1990).*

Seedling characteristics	Non-mycorrhizal control	Pre-inoculated with *Paxillus involutus* mycorrhizae
Mortality (%)	40	0
Shoot height (cm)	3	6
Root length (cm)	5	14
Shoot dry weight (mg)	200	610
Root dry weight (mg)	92	251
Total dry weight (mg)	291	862
Mycorrhizal roots (%)	13	90

compared to non-inoculated plants (Fini and others 2011).

Production of antibiotics. Mycorrhizal fungi have also been shown to produce chemicals that repel pathogenic fungi. For example, the ectomycorrhizal fungus *Leucopaxillus cerealis* was found to produce antibiotics that were effective in controlling infections by the root pathogen *Phytophthora cinnamomi* (Marx 1970).

Mycorrhizae are not a pesticide (legally). A final reason why you probably haven't heard about the IPM benefits of mycorrhizal fungi is that the complicated and expensive legal requirements for pesticide registration are the main reason that mycorrhizal inoculum may never be considered a pesticide (Whipps (2004).

3.7 Apply timely and appropriate control measures

One of the key tenets of the IPM approach is that no control measures should be initiated until pest damage has reached a point where significant economic damage is occurring (Alston 2011b). This "economic threshold" was first applied with insect pests where population levels could be easily monitored and then correlated with economic damage. The economic threshold must be determined for each different pest and, for relatively minor problems, may never be reached. Most nurseries utilize an oversow factor of 5 to 10% to account for these minor losses (Thompson 1984). For particularly aggressive pathogens like *Phytophthora ramorum* that require quarantine, however, the economic threshold is zero. Once this pest is detected in a nursery, their crops are subject to rigorous testing and restrictive and expensive quarantine measures must be implemented (Suslow 2006). Determining economic thresholds for your nursery and your crops is a good opportunity to fully assess your overall cultural program in context with pest management. A list of nursery-specific pests, threshold levels, and control measures can then be made (Table 2).

Table 2. Examples of pest threshold damage levels and subsequent treatments (modified from Dumroese and Wenny 1992).

Pest	Pest attributes	Damage threshold	Preventative treatment(s)	Treatment(s) when threshold surpassed
Mice	Eat freshly sown seeds. Clip seedlings in fall for bedding.	Any damage exceeds threshold.	Maintain vegetation-free and junk-free buffer zone around greenhouse and headhouse.	Continual baiting and trapping.
Fungus gnats	Larvae feed on organic matter and seedling roots.	Ten adults per block per week.	Set out yellow sticky-cards to trap and monitor adults.	Reduce irrigation frequency if possible. Soil drench with parasitic nematodes once each week for 3 consecutive weeks.
Algae	Algae on floor makes them hazardous to employees and guests.	More than 20% of area is covered.	Power-scrub floors each spring to remove build-up from previous crop.	Treat floors with diluted bleach solution and/or power scrub.
Damping-off	This disease is often an association of many fungi.	15% of the trays in a seedlot have 3 to 5% of their cells with disease.	Surface sterilize seeds before stratification with a bleach solution. Rogue dead and dying seedlings to prevent spread. Refrain from excessive irrigation and avoid high rates of nitrogen fertilizer during germination.	Treat affected seedlot with fungicide.

Table 3 - Pesticides and modes of action for controlling fungus gnats (modified from Fisher and others 2006).

Trade name	Active ingredient	Type of pesticide
Traditional pesticides		
DuraGuard™	Chlorpyrifos	Contact Insecticide
Adept®	Diflubenzuron	Growth regulator
Distance®	Pyriproxyfen	Growth regulator
Marathon®	Imidacloprid	Systemic insecticide
Citation®	Cyromazine	Growth regulator
Safari™	Dinotefuran	Systemic insecticide
Organic pesticides		
Azatin®	Azadirachtin	Growth regulator from neem
Nemasys®	*Steinernema feltiae*	Parasitic nematode

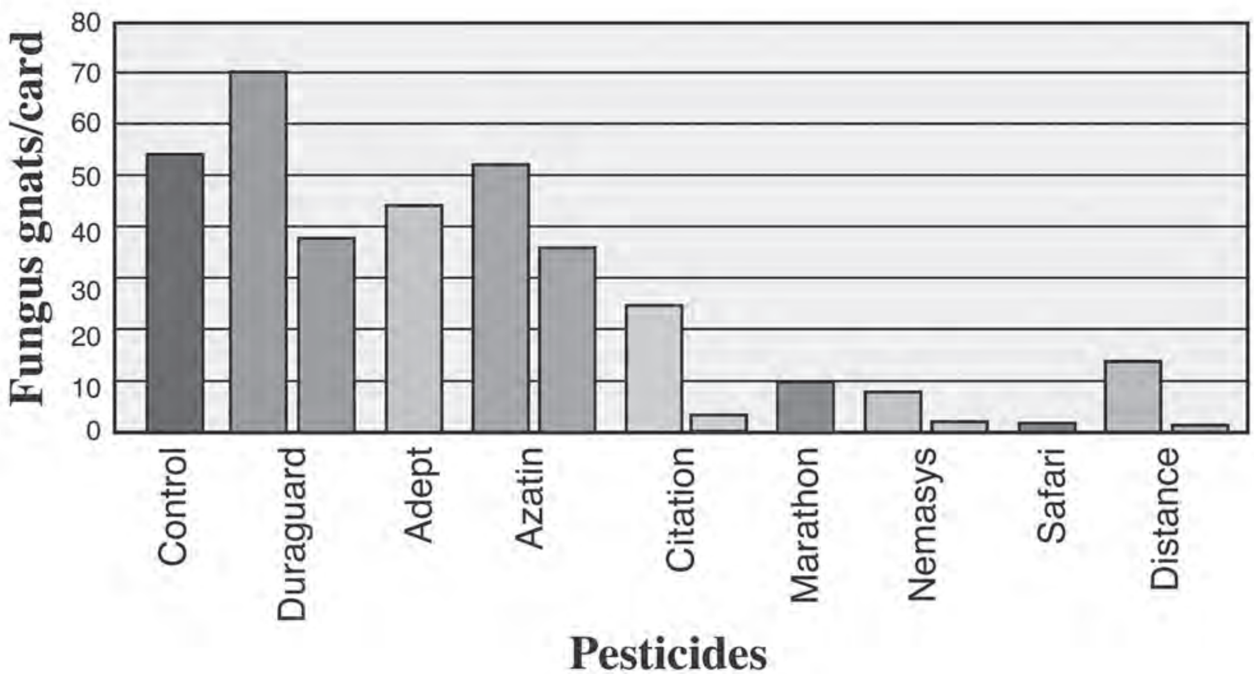

Figure 8 - Pesticide efficacy for fungus gnats after 1 or 2 drenches (modified from Fisher and others 2006)

Pesticide mode of action. Each pesticide has a unique mode of action that must be considered when developing an IPM program. For example, a range of pesticide drenches was tested as a control for fungus gnats; their modes of action ranged from contact and systemic pesticides, growth regulators, and biocontrol agents (Table 3). While one application of a chemical insecticide (Safari™) was the most effective, a biocontrol that consisted of parasitic nematodes (Nemasys®) was equally effective after two applications (Figure 8). To achieve a goal of minimal chemical use, side-by-side comparisons such as this are critically important.

Timing of pesticide application. The timing and frequency of pesticide applications must coincide with the damage threshold (Figure 9). Applying pesticides too early (A) is uneconomical, whereas applications when pest levels or economic damage have reached a critical point (B) are ideal. Applying "revenge" pesticide treatments when pest populations are already declining (C) may make growers feel better but are a waste of money as serious damage has already occurred. In other words, the cost of the chemical and labor to apply it may be greater than the cost of the damage caused by the pest if the economic threshold is not crossed. And, similarly, applying revenge treatments is just wasting money because the damage is done and the financial lost already incurred.

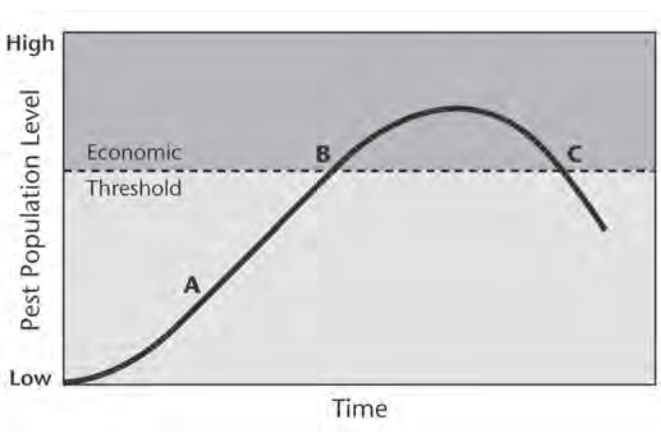

Figure 9 - Pesticide applications should be made based on when crop damage reaches the economic threshold: Application A is too early, Application B is perfect, Application C is too late ("revenge treatment") (modified from Daar and others 1992).

4. Developing and following an IPM plan

Developing an IPM program for each nursery pest is a systematic approach that is effective and economic. Many nursery managers already practice IPM without formally calling it that. IPM is a management philosophy that reflects the goals and values of the nursery manager; therefore, it is impossible to provide an IPM "recipe" for all nurseries as each nursery has unique goals and different ideas of what constitutes acceptable pest populations or economic damage thresholds (Dumroese 2012). An IPM plan should be dynamic, evaluated and updated each year as more data becomes available from history plots, new pests emerge, and new control methods become available.

5. References

Alston DG. 2011a. The integrated pest management (IPM) concept. Logan (UT): Utah State University Cooperative Extension. Utah Pests Fact Sheet IPM-014-11. URL: http://www.utahpests.usu.edu (accessed 16 Jan 2014).

Alston DG. 2011b. Pest management decision-making: the economic-injury level concept. Logan (UT): Utah State University Cooperative Extension. Utah Pests Fact Sheet IPM-016-11. URL: http://www.utahpests.usu.edu (accessed 28 Apr 2014).

Bethke JA, Dreistadt SH. 2001. Fungus gnats, shore flies, moth flies, and march flies: integrated pest management in the home, interior plantscapes, greenhouses, and nurseries. Davis, (CA): University of California, Agriculture and Natural Resources. Pest Notes Publication 7448. 6 p.

Bryan H. 1989. Control of the tarnished plant bug at the Carters nursery. Tree Planters' Notes 40(4):30-33.

Chakravarty, P., Peterson, R. L., and Ellis, B. E. 1990. Integrated control of Fusarium damping-off in red pine seedlings with the ectomycorrhizal fungus *Paxillus involutus* and fungicides. Canadian Journal of Forest Research 20:1283-1288.

Cram MM, Frank MS, Mallams KM, technical coordinators. 2012. Forest nursery pests. Washington (DC): USDA Forest Service, Agriculture Handbook 680. 202 p.

Cram MM, Hansen EM. 2012. Phytophthora root rot. In: Cram MM, Frank MS, Mallams KM. technical coordinators. Forest nursery pests. Washington (DC): USDA Forest Service, Agriculture Handbook 680: 126-128.

Daar S, Olkowski H, Olkowski W. 1992. IPM training manual for wholesale nursery growers. Berkeley (CA): Bio-Integral Resource Center. 84 p.

Dumroese RK. 2008. Observations on root disease of container whitebark pine seedlings treated with biological controls. Native Plants Journal 9:92–97.

Dumroese RK. 2012. Integrated nursery pest management. In: Cram MM, Frank MS, Mallams KM, technical coordinators. Forest nursery pests. Washington (DC): USDA Forest Service, Agriculture Handbook 680: 5-12.

Dumroese RK, Wenny DL. 1992. Forest Research Nursery wastewater management plan, integrated pest management plan, and pesticide safety. Moscow (ID): University of Idaho, Idaho Forest, Wildlife and Range Experiment Station. Contribution 665. 10 p. URL: http://rngr.net and http://www.fs.fed.us/rm/pubs_other_NONTS/1992_dumroese.pdf (accessed 30 Apr 2014).

Dumroese RK, Wenny DL, Quick KE. 1990. Reducing pesticide use without reducing yield. Tree Planters' Notes 41(4): 28-32.

Dumroese RK, James RL, Wenny DL. 2002. Hot water and copper coatings in reused containers decrease inoculum of *Fusarium* and *Cylindrocarpon* and increase Douglas-fir seedling growth. HortScience 37:943–947.

Encyclopædia Britannica. 2014. Paul Herman Müller. URL: http://www.britannica.com/EBchecked/topic/396883/Paul-Hermann-Muller (accessed 30 Apr 2014).

Fini A, Frangi P, Amoroso G, Piatti R, Faoro M, Bellasio C, Ferrini F. 2011. Effect of controlled inoculation with specific mycorrhizal fungi from the urban environment on growth and physiology of containerized shade tree species growing under different water regimes. Mycorrhiza 8:703-719.

Fisher P, Eaton A, Cloyd R. 2006. Fungus gnat management. Greenhouse Grower 24(11): 20, 22, and 24.

Frazier M. 2014. A short history of pest management. University Park, (PA): Pennsylvania State University, Penn State Extension. URL: http://extension.psu.edu/pests/ipm/schools/educators/curriculum/contents/shorthistory (accessed 13 Jan 2014).

Garbaye J. 1994. Helper bacteria: a new dimension to the mycorrhizal symbiosis. Tansley Review No. 76. New Phytologist 128: 197-210.

James RL, Dumroese RK, Gilligan CJ, Wenny DL. 1989. Pathogenicity of *Fusarium* isolates from Douglas-fir seed and container-grown seedlings. Moscow (ID): University of ldaho, College of Forestry, Wildlife and Range Sciences. Bulletin 52. 10p.

James RL, Dumroese RK, Wenny DL. 1990. Approaches to integrated pest management of *Fusarium* root disease in container-grown seedlings. In: Rose R, Campbell SJ, Landis TD, editors. Target seedling symposium: proceedings, combined meeting of the Western Forest Nursery Association and Intermountain Nursery Association. Fort Collins (CO): USDA Forest Service, Rocky Mountain Forest and Range Experiment Station. General Technical Report RM-200: 240–246.

Juzwik J, Gust KM, Allmaras RR. 1998. Influence of cultural practices on edaphic factors related to root disease in *Pinus* nursery seedlings. Plant and Soil 207:195-208.

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

Koide RT, Mosse M. 2004. A history of research on arbuscular mycorrhiza. Mycorrhiza 14:145–163

Landis TD. 1997. History plots as an IPM tool. In: Forest Nursery Notes (July 1997). Portland (OR): USDA Forest Service, Pacific Northwest Region, State and Private Forestry, Cooperative Programs. Publication R6-CP-TP-25-97. p 22-25.

Landis TD. 2013a. Forest nursery pests: damping-off. Forest Nursery Notes 33(1):25-32.

Landis TD. 2013b. *Phytophthora ramorum*: impacts on forest, conservation and native plant nurseries. Forest Nursery Notes 33(1):15-24.

Landis TD. 2000. Holistic nursery pest management: a new emphasis on seedling health. In: Proceedings of the 4th meeting of IUFRO Working Party 7.03.04 - Diseases and insects in forest nurseries. Suonenjoki, Finland: Finnish Forest Research Institute. Research Paper 781: 5-15.

Landis TD, Tinus RW, Barnett JP. 1999. Seedling propagation, volume 6. The container tree nursery manual. Washington (DC): USDA Forest Service. Agriculture Handbook 674. 167 p.

Landis TD, Tinus RW, McDonald SE, Barnett JP. 1989. The biological component: nursery pests and mycorrhizae, volume 5. The container tree nursery manual. Washington (DC): USDA Forest Service. Agriculture Handbook 674. 171 p.

Landis TD, Luna T, Dumroese RK. 2009. Chapter 15: Holistic pest management. In: Dumroese RK, Luna T, Landis TD, editors. Nursery manual for native plants: a guide for tribal nurseries. Volume 1: nursery management. Washington (DC): USDA Forest Service. Agriculture Handbook 730: 262–275.

Landis TD, Luna T, Wilkinson KM, Dumroese RK. 2014. Chapter 14: Problem prevention and holistic pest management. In: Wilkinson KM, Landis TD, Haase DL, Daley BF, Dumroese RK., editors. Tropical nursery manual: a guide to starting and operating a nursery for native and traditional plants. Washington (DC): USDA Forest Service. Agriculture Handbook 732: 273-291.

Marx DH. 1972. Ectomycorrhizae as biological deterrents to pathogenic root infections. Phytopathology 10:429-454.

Marx DH. 1970. The influence of ectotrophic mycorrhizal fungi on the resistance of pine roots to pathogenic infections. V. Resistance of mycorrhizae to infection by vegetative mycelium of *Phytophthora cinnamomi*. Phytopathology 60:1472-1473.

Mousseaux MR, Dumroese RK, James RL, Wenny DL, Knudsen GR. 1998. Efficacy of *Trichoderma harzianum* as a biological control of *Fusarium oxysporum* in container-grown Douglas-fir. New Forests 15:11–21.

Olkowski W, Daar S, Olkowski H. 1991. Commonsense pest control. Newton (CT): Taunton Press. 715 p.

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

Suslow K. 2006. *Phytophthora ramorum* – Economic impacts and challenges for the nursery industry. Frankel SJ, Shea PJ, Haverty MI, technical coordinators. Proceedings of the Sudden Oak Death Second Science Symposium: The State of Our Knowledge. Albany (CA): USDA Forest Service, Pacific Southwest Research Station. General Technical Report PSW-GTR-196: 41-44.

Thompson BE. 1984. Establishing a vigorous nursery crop: bed preparation, seed sowing, and early seedling growth. In: Duryea ML, Landis TD, editors. Forest nursery manual: production of bareroot seedlings. Hingham (MA): Kluwer Academic Publishers. p 41-49.

Unestam T, Beyer-Ericson L, Strand M. 1989. Involvement of *Cylindrocarpon destructans* in root death of *Pinus sylvestris* seedlings: pathogenic behaviour and predisposing factors. Scandinavian Journal of Forest Research 4:521-535.

[US EPA] US Environmental Protection Agency. 2014. National environmental policy act (NEPA). Washington, DC. URL: http://www.epa.gov/compliance/basics/nepa.html (accessed 30 Apr 2014).

[USFDA] US Food and Drug Administration. 2012. Hazard analysis & critical control points (HACCP). Washington, DC. URL: http://www.fda.gov/food/guidanceregulation/haccp/default.htm (accessed 28 Mar 2014).

Warnert J. 2009. The 50th anniversary of a great idea. California Agriculture 63(4):160-161.

Whipps JM. 2004. Prospects and limitations for mycorrhizas in biocontrol of root pathogens. Canadian Journal of Botany 82:1198-1227.