Chemical treatments as alternatives to heat or fumigation for minimizing phytosanitary risks of wood products in commerce

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Introduction

It has been estimated that over 4,500 new species have been introduced into North America (NA) in the past two centuries (Dubensky *et al,* 2001; Windle 1996; and United States Congress 1993), and more than four hundred of these species are known to feed on trees or shrubs (Haack 2003). Between 1906 and 1991, the 79 most damaging of the 4,500 introduced species caused documented losses exceeding $97 billion (Windle 1996).

The number of species introduced into the United States each year has steadily increased (Windle, 1996; United States Congress, 1993). The elevated number of species introductions is most likely due to a variety of factors including a rapidly expanding global economy, more rapid and efficient movement of materials around the globe and reduced trade barriers due to free trade agreements (Dubensky *et al,* 2001). Researchers have found that species travel the world using many different pathways. The most relevant materials to forest pests include fruits and vegetables, logs, chips, unseasoned lumber, solid wood packaging material (SWPM), and live plants (Dwinell, 2001a). SWPM is used in ninety-five percent of all international shipments (Dubensky *et al,* 2001), and its potential to harbor wood pests has attracted increasing attention. An estimated 88% of all scolytid interceptions made by APHIS during 1985 and 2001 were made on SWPM. This material is especially attractive because it remains biologically viable during its service life (Haack, 2003).

Since the mid 1980s, a number of different regional and national organizations have implemented phytosanitary standards to deal with SWPM. However, a coordinated global response to this invasive species pathway was not formulated until 2002 when the International Plant Protection Convention (IPPC) of the United Nations Food and Agriculture Organization (FAO) formulated International Standard for Phytosanitary Measures (ISPM) Number 15. This measure recognized SWPM as an invasive species pathway and suggested the use of heat treatment and fumigation with methyl bromide as methods to prevent invasive species introductions. A majority of large exporting and importing countries around the world have adopted ISPM #15 into their legal codes. However, research has shown that some fungi are heat tolerant allowing them to survive the temperatures specified in ISPM #15 (Morrell 1995). While methyl bromide is a well understood and widely used fumigant, it has also been shown to contribute to global warming by depleting the ozone layer. This chemical is scheduled to be phased out by 2015 under the Montreal Protocol (CSIRO 2001). In addition, these sanitation methods cannot be directly verified by importing countries, since neither heat treatment nor fumigation alter the wood. Likewise, re-infestation of SWPM is possible, since wood moisture content is not significantly reduced during heat treatment and methyl bromide has no longterm protective effect.

Wood preservatives may be a promising alternative to heat treatment or fumigation. These chemicals have been specially formulated to control fungal growth on wood products exposed to decay prone environments. Wood preservatives also contain chemicals that prevent insect infestation. These attributes of wood preservatives would give lasting protection against invasive species introductions, and since wood preservatives alter the wood substrate, their use could be verified by importing countries. Further, the use of wood preservatives and the methods used to deploy them effectively are well understood and have been used since 1838 (Hunt and Garratt 1938). However, the ability of wood preservatives to eliminate established insect populations has not been investigated, nor has it been determined if adequate wood and gallery penetration can be achieved when these systems are applied to wood products above the fiber saturation point.

The use of large, modern cargo ships and aircraft along with the advent of shipping containers has increased the likelihood of introducing exotic species with SWPM. In the past, SWPM dried during shipping or the time required to complete the voyage allowed the flora and fauna residing in the material to complete their life cycles and emerge. A majority of the time, the environment faced by the emerged species was not suitable for survival, resulting in their demise. Modern ships and aircraft reduce the time needed to move material and, thus, reduce the amount of drying. They also increase the chances that the flora and fauna found within the SWPM have not emerged. Both of these factors increase the likelihood of a species being inadvertently introduced into a new ecosystem at a life stage more capable of survival. Shipping containers have also aided the movement of invasive species. These air and watertight containers increase the rate at which vessels can be loaded and unloaded. The containers are often lined with wooden panels, and wood is used as blocking, pallets, and in other forms within the containers. The material used for these purposes is often low grade and, thus has a great likelihood of containing insects and fungi. The shipping container protects insects and fungi from the harsh environments experienced during shipping, increasing the risk of introduction of viable organisms into the importing country (McNamara and Kroeker, 2001; Dobensky *et al,* 2001). A combination of refrigerated containers and the rapid movement of material also allow for the importation of large quantities of perishable items (APL Limited, 2004), creating another pathway used by non-native species.

The rapid movement of cargo and the use of low-grade wood for packaging material have resulted in the introduction of the pinewood nematode (PWN) into Portugal. In 1984, Scandinavian authorities found wood chips imported into Finland from North America (NA) were infested with PWN. This was of great concern to the authorities since the PWN is known to be the causal agent for pine wilt disease (Dwinell and Nickle, 1989). The PWN was introduced previously into Japan, South Korea, Taiwan, and the People's Republic of China with disastrous results. Researchers learned from the introduction of PWN into Japan that the species not native to NA were highly susceptible to this nematode, while species native to the PWN's home range were only attacked if the tree was already stressed (Linit, 2001). The discovery of the PWN in Finland resulted in swift legislative action by both the Scandinavian countries and Europe as a whole. By July of the following year, all Scandinavian countries had banned the importation of raw wood products from areas of the world known to have PWN. The European Plant Protection Organization (EPPO) likewise made the recommendation to its members in July 1985 that only kiln dried softwood lumber should be imported from NA and Southeast Asia (Dwinell and Nickle, 1989). The ban on the import of raw softwood products from NA into the European Union (EU) resulted in large economic losses for softwood lumber exporters as well as individuals exporting pulp chips to the Scandinavian countries. These actions resulted in the development of pasteurization processes to allow the import of green products. Unprocessed wood products once again came into the spotlight in 1999 during an extensive survey conducted throughout Europe. During this survey, the PWN was located in a small area (30km radius) of southern Portugal. The cause of the PWN outbreak has not been determined, but SWPM was believed to be the source and The Plant Quarantine Service of Finland confirmed these fears. The Finish agency found that 5% of all SWPM from NA or China tested was infested with PWN or its vector, the long horned beetle *Monochamus* spp. (McNamara and Kroeker, 2001; Dwinell and Nickle, 1989). In response to the outbreak, the EU passed an emergency measure for coniferous SWPM. The measure required that all coniferous SWPM be treated using heat, fumigation, or chemical pressure treatment. After treatment, the SWPM must be marked indicating compliance with the measure. This ruling went into effect in October of 2001 (USDA APHIS, 2003). Following the incidents associated with the PWN, other nations started to regulate the importation of non-manufactured wood products.

Legislation

Import and export of agricultural products has been regulated since the beginning of the twentieth century. It was recognized early on that the unregulated import of fruits and vegetables along with animals and animal products could lead to the introduction of unwanted species (U.S. Department of Homeland Security, 2004). The idea that most invasive species are associated with fresh agricultural products still holds true today. APHIS spends a majority of its time inspecting the vast numbers of shipments into the United States that contain fruits and vegetables or animal products. Since the early

1900s, APHIS has also recorded pest interceptions. Between 1985 and August 2001, 577,829 interceptions were made by the agency with an average of 36,882 interceptions per year. However, the agency currently inspects only two percent of all international shipments. Of the total number of interceptions between 1985 and 2000, 6,827 were scolytids or other wood boring insects (Haack, 2003). The importation of raw wood products as cargo has been regulated for some time both in the United States and around the world. Examples include the ban on the importation of raw wood materials into Europe, and similar restrictions put in place by NA, Australia and New Zealand. All of these restrictions are intended to prevent the importation of species that may damage the local forest ecosystems.

The idea that SWPM is also a pathway for the introduction of exotic species has only been recognized in the past ten years. The Australian Quarantine and Inspection Service was the first to introduce legislation dealing with SWPM. The agency stated that it preferred shipments which did not contain any wood products, specifically any non-manufactured wood products such as SWPM (Australian Quarantine and Inspection Service 2004). Since then, other countries have followed suit. Most major importing and exporting countries currently have legislation in place dealing with SWPM. However, the rules imposed vary greatly between different countries or regions. Some countries have also claimed that the rules imposed to deal with SWPM claiming that they are being used to limit trade in place of tariffs and other trade barriers. The General Agreement on Tariffs and Trade (GATT) prohibits these types of trade barriers. The issues surrounding phytosanitation as a trade barrier were discussed during the Uruguay Round of Negotiations in 1986. The result of these negotiations was The Agreement of the Application of Sanitary and Phytosanitary Measures which was signed in early 1994. This agreement gave authority to the International Plant Protection Council (IPPC) to establish guidelines associated with phytosanitary measures and resulted in the establishment of international standards of phytosanitary measures. During the 2002 meeting of the IPPC, the organization ratified International Phytosanitary Measure 15 (IPSM #15), which addresses SWPM (Griffin, 2001; FAO, 2002).

During 1996, the ALB was discovered in New York and two years later in Chicago. This beetle is a great threat to tree species of significant industrial and urban forestry importance. The pathway used by the ALB was investigated; researchers found that the beetle was imported into the United States in both instances within SWPM from China. In the years following the discovery of the ALB, nearly 59 million dollars were spent on eradication (Haugen and Iede, 2001; McNamara and Kroeker, 2001; Dwinell, 2001a; and United States Department of Agriculture 2006). In addition, an interim rule was passed requiring heat treatment or fumigation of all SWPM originating or passing through China by amending section 319 of article 7, the same legislation originally introduced to prevent the unregulated importation of raw wood products (USDA APHIS, 2004). The number of scolytidae interceptions made by APHIS in packaging material originating from China following the introduction of this interim rule greatly decreased, proving the effectiveness of such legislation (Haack, 2003). U.S. legislation pertaining to the importation of SWPM with cargo was revised further in 2003 to reflect IPSM #15 by extending the restriction on the importation of SWPM to all countries except Canada (United States Department of Agriculture 2006).

Treatment Requirements

ISPM 15 has a number of requirements including bark removal and visual inspection to detect obvious pests, but its two most important features are the requirement that wood be either subjected to a heating period at 56 C for a minimum of 30minutes at the center or that the wood be subjected to fumigation. While both heating and fumigation are effective mitigation processes for many pests, neither is completely effective. More importantly, it is impossible to verify that either process has been completed and treatment has little or no effect on the potential for reinvasion. There remains a critical need for development of improved mitigation tools for limiting the risk of pest introduction on wood in global trade.

One attractive approach to wood protection is chemical treatment. Wood has long been protected from fungal and insect attack by application of chemicals using dipping, soaking or pressure treatment. While there is a wealth of data on the efficacy of chemical treatment for wood protection, there is surprisingly little on its use for pest mitigation. In this report, we summarize the potential for chemical mitigation of wood in global commerce.

As noted, wood can be treated by dipping, soaking or pressure treatment

Dip Treatment: Dip treatment is widely used for short term protection of freshly cut lumber from fungal stain and mold. The treatment is rapid and simple, but also tends to produce the lowest chemical uptakes that result in the shallowest depth of penetration. The wood is generally debarked (both logs and lumber) prior to milling and this reduces phytosanitary risks and increases wood quality while enhancing treatment efficacy (IFQRG, 2007 report). There are a range of chemicals used for this purpose that include: copper-8-quinolinolate, 3-iodo-2- propynyl butyl carbamte, diiodomethyl-p-tolyl sulfone, didecyldimethyl ammonium chloride, propiconazole and boron (Morrell, 2001a; Schauwecker and Morrell, 2008a). Dip treatment produces a thin layer of chemical around the protected wood surface. The aim is to protect against further insect and fungal attack and kill organisms that are on or near the surface. Some treatments may also prevent pest emergence depending on the insect and dosage of chemical. Dip treatments are largely ineffective for wood that is seriously pre-infected. Thus, dip treatment with a combination fungicide/insecticide might be a useful for limiting reinvasion following heat or fumigant treatment. The process might also be useful for protecting chips, particles or other smaller dimension wood articles. Application of a fungicide/insecticide to freshly cut chips prior to shipping sharply reduced the incidence of fungi and insects on the chips when they arrived at their destination. The lower levels of fungal attack also resulted in reduced chemical consumption during pulping. While these results highlight the potential for using dip treatments, the process is probably only useful for smaller dimension wood

Dip-diffusion methods: Dip-diffusion involves application of concentrated chemicals to the surface of the material by spraying, dipping or soaking the material in a solution containing one or more biocides. These chemicals produce a surface layer that prevents insect and fungal attack or some component diffuses throughout the wood. Dip treatments may also directly kill any insects and fungi found near the surface of the wood product, while inhibiting insect emergence. The initial depth of treatment varies widely, from less than 1mm in some species to complete penetration in others depending on the wood species, percentage of heartwood, MC and the chemical formulation. The depth of the treatment within the same piece of lumber also varies widely since the cross sections absorb more chemical than radial or tangential faces. Differences in the depth of the protective layer created by this method pose one of the challenges that must be overcome by researchers before dip diffusion is commercialized for SWPM treatment (Morrell, 2001a).

Dip-diffusion treatments have some distinct advantages including rapid treatment, low capital costs for equipment, the ability to be verifiable and the ability to provide protection that outlasts that provided by fumigation or heat treatment. In the past, broadly toxic pesticides and fungicides have been used for dip treatments. Increased concerns relating to human and environmental health effects have encouraged the use of less broadly toxic chemicals. Boron compounds are of greatest interest since they pose a low mammalian hazard, affect most insects and fungi and, most importantly, have the ability to diffuse deeply into many woods. Boron is also well understood. Borate diffusion can be achieved even in hard to treat species such as Douglas-Fir (*Pseudotsuga menziesii*) (Fowlie *et al,* 1988); however, the treatment must be done shortly after milling for the material to reach boric acid concentrations that will prevent decay (Carr, 1955). The same studies have also found that the time required for adequate diffusion to occur normally exceeds one month, which would be a problem when treating SWPM (Fowlie *et al,* 1988; Carr 1955; MacLean 1962). Heat can be used to increase chemical penetration, but it increases the costs (He et al, 1997). In addition amine oxides have recently been found to promote deeper penetration of active ingredients including a variety of carbon-based fungicides and insecticides, particularly if the surface application is followed by a period of heating (Ross 2010)

Boron solutions tend to be less active against mold fungi, however, this problem can be solved by combining boron with other fungicides (MacLean, 1962). Additional advantages of boron compounds are that the presence of the chemical can be detected using indicators, making it easy to verify the treatment and very low mammalian/fish toxicity.

Material treated by dip diffusion has two major advantages over the currently approved methods, it is verifiable, especially if a dye indicator is used in the treating solution, and it provides protection over an extended period of time. However, this method also has some drawbacks including lack of data showing that the treatment prevents emergence of established insects and fungi from the material. The use of chemicals also requires special care during disposal. For example, low temperature cooking fires may not completely combust insecticides and fungicides, thus making them available for human consumption (Morrell, 2001a). However, this problem can be overcome by choosing chemicals with low mammalian toxicity such as boron. The risk of damaging the treated layer of wood is also a concern since loss of the protective barrier may allow renewed attack, while leaching may reduce the amount of protection. Despite these drawbacks, dip diffusion probably merits further testing as a SWPM mitigation tool.

Pressure treatment: Pressure treatment overcomes some of the problems associated with dip diffusion by forcing the treating chemical deeper into the wood. Pressure treatment has been in use since 1838 when the Bethel or full-cell process was patented (Nicholas, 1973). Since that time, numerous oil- and water-based chemicals have been employed to protect wood against decay using this process. Indeed, the pressure treatment process is well understood in regards to its ability to prevent decay in sound timbers (Hunt and Garratt, 1938).

There are a variety of national and regional wood treatment standards and quality assurance programs related to treated wood exist around the world e.g. American Wood Protection Association (AWPA), Canadian Standard Association (CSA), the European Committee for Standardization (CEN), Nordic countries standard (NWPC), New Zealand Standard (NZS), Korean Standards (KSF), Japanese Industry Standards (JIS), and emerging Chinese standards. These standards all specify required retention and penetration levels for different wood use categories, preservatives and wood species (Wang and Morris, 2009). Treatment categories are generally separated based on targeted service conditions (i.e. the decay hazard), product size, and the level of structural importance. Wood treated to the standard of one country may not meet the requirements of the importing country in terms of decay risk classification, penetration and retention requirements or the allowance of specific biocides. For example, pentachlorophenol is widely used for utility poles in the U.S. but is banned in many countries. Standards may also have different requirements for preservative penetration. For example, the penetration requirements in AWPA standards are based on the assumption that the sapwood is perishable and easily degraded. As a result, the AWPA Standards require almost complete sapwood penetration, while only 10 mm of penetration is required in heartwood. The Europeans (CEN) have a variety of approved preservatives with different retention levels for different use categories that specify different penetration requirements from 0 to 6 mm in heartwood. The Nordic countries (NWPC) specifications only reference Scots pine and other permeable species, so they require full penetration of the sapwood of Scots pine and no heartwood penetration requirement. Some countries have strong national certification programs for preservative treatment, inspection and application of certification marks, while standards in other countries are less stringently enforced.

There have been attempts to develop a global wood protection standard, but this has proven to be a difficult task because of different national philosophies as well as the wide variety of treatment chemicals and wood species. However, limited progress has been made to complete an international (ISO) standard. Further progress on an international standard would greatly facilitate a better understanding of the potential pest risk differences posed by global trade of treated wood and non-treated wood in the international trade.

Pressure processes are used to treat nearly 360 million cubic meters of wood annually in North America, prolonging the service life of this material from a few years to decades (Morrell 2001b; Nicholas, 1973). The treating capacity of this industry is large, allowing it to rapidly treat packaging material used in international trade at a relatively low cost. As with dip diffusion treated material, the treatment would be verifiable by the importing country and the treatment would give the SWPM prolonged protection, reducing the risk of re-infestation following treatment. Pressure treatment has added benefits over dip diffusion treatment including uniformity and quality of treatment. The barrier created using the pressure method is generally much thicker, reducing the risk that the protective layer will be damaged to expose untreated wood. The thicker barrier also decreases the likelihood that an existing pest will exit the material in a viable state. In addition, pressure may force pesticides into the insect galleries eradicating them in situ (Morrell, 2001b). The treating process is also relatively rapid, reducing the amounts of inventory a SWPM producer would need to have on hand (Nicholas, 1973).

The pressure treatment process has considerable potential for mitigating pest risks on SWPM, but there are some knowledge gaps and disadvantages. There is little knowledge concerning the emergence of established insects or fungi from treated material. Members of the Buprestidae are known to continue development in pressure treated Douglas-fir poles and emerge through the treated shell. There is currently no evidence supporting the ability of this method to penetrate insect galleries, especially those that are tightly packed with frass. Pressure treatment tends to provide protection by placing high chemical retentions near the surface to provide decades of performance. This is unnecessary for SWPM since it does not come into ground contact, it is not exposed to highly decay prone environments and its service life is relatively short. As a result it may be possible to use less toxic chemicals at lower chemical retentions to reduce both costs and the potential environmental impacts of treated SWPM (Morrell, 2004).

Pressure treatment also has some drawbacks. It introduces potentially dangerous chemicals into the fuel wood supply chain. This problem can be addressed by using combustible chemicals with low mammalian toxicity. However, many of these chemicals have not been completely investigated for this application. In addition, the treatment envelope can still be damaged on pressure treated wood during pallet or dunnage production. The current solution to this problem is the application of diffusible preservatives to drilled and cut areas but this would be difficult in a production operation. Another major disadvantage of the pressure treatment process is that differences in permeability between species will result in different depths of treatment. This can be reduced by incising refractory species, however, incising reduces the strength of the material. Thus, incising may not be feasible for all SWPM applications. Inadequate protection in some species could allow for the continued movement of insects and fungi.

Pressure treatment of SWPM is an alternative to heat treatment and fumigation with some distinct benefits; by virtue of deeper and longer lasting protection compared to the other proposed methods. Pressure treatments are largely designed to keep organisms out rather than affecting organisms already established within. The ability to eliminate established pests is among the knowledge gaps that must also be filled before this method can be applied to SWPM. These include determining chemical levels necessary to give adequate protection and assessing the ability of treatments to eradicate established insects and fungi.

In order to assess pressure treatment, ponderosa pine boards infested with the new house borer (*Arhopolus productus*) were pressure treated with alkaline copper quaternary compound (ACQ), borates or an experimental system containing tebuconazole and imidacloprid . Penetration was excellent in all treatments (Figures 1, 2); however, none of the treatments was capable of killing larvae established in the wood. Larvae in the wood continued to tunnel to the surface of treated boards and larval galleries were completely penetrated with preservative. Subsequent tests indicated that larvae were able to bore through treated veneer but did not ingest the wood, thereby avoiding any toxicants. While the larvae were able to bore through the treated wood shell, no adult beetles emerged from any of the treated wood samples, while numerous new house borer beetles emerged from the untreated control boards (Figure 3). The inability of the pressure treatment to affect larval survival would generally not be a problem as long as the boards were isolated; however, it might become a problem if the larvae were able to bore through the treated board into an adjacent untreated board where it might complete its life cycle.

Pressure treatment might be useful for pallets and other reusable SWPM, although the chemical would have to be chosen carefully since many pallets are used to transport food or medicines. In addition, disposal at the end of the useful life of the wood product must be considered. Some treatments, such as copper based systems should not be burned; however, pallets represent a low cost fuel source in many countries. Treated pallets would either have to be treated with chemicals capable of being burned or the pallets would have to be carefully controlled to ensure that they were disposed of properly.

Modified Wood: Although they are more of a subset of conventional pressure treatment processes, treatments that alter wood characteristics, notably its hygroscopicity may have application in specialized higher value packing materials.

Wood modification processes change the properties of wood through the application of heat, chemicals, or enzymes (Jones, 2003). Currently there are three major processes that have been commercialized: thermal modification, acetylation, and furfurylation. Modified wood has a small but growing market share, especially in jurisdictions (e.g. Europe) where regulations increasingly restrict the use of wood treated with pesticides.

Thermal modification (also referred to as heat treatment) involves heating wood to high temperatures (160-260°C) in an anoxic environment (Militz, 2002). Treatment times vary from 15 minutes to 24 hours depending on the process (Kamdem et al., 1999). Various methods have been used to reduce oxygen in the system including nitrogen, oil and steam (Homan and Jorissen, 2004). Thermally modified wood has reduced strength and increased durability (Militz, 2002). Though it has enhanced resistance to decay (Tjeerdsma et al., 1998), this may not be sufficient for applications such as ground contact use (Welzbacher and Rapp, 2005) or window applications (Vidrine et al., 2007). Thermal modification alone has not been found to improve termite resistance (Smith et al., 2003). Most thermal modification processes, however, should meet the heat treatment requirements as specified in ISPM No 15.

Acetylation is a wood modification process that reacts acetic anhydride with accessible hydroxyl groups on the wood cell wall (Rowell, 2007). This results in the formation of acetyl groups bound to the wood and free acetic acid, which is then removed (Rowell, 2007). Acetylated wood has been shown to have increased resistance to decay fungi (Takahashi et al., 1989; Beckers et al., 1994; Brelid et al., 1997), but is less effective against mould and stain fungi (Wakeling et al., 1992) and termites (Militz et al., 2009).

The depth of acetylation depends on wood species and moisture level. It is likely that the centers of larger boards might not be fully treated; however, acetic acid from the treatment reaction is likely to move into some of these areas and the heat coupled with vacuum used to remove excess acetate acid might contribute to reduced pest survival.

Furfurylation is a wood modification process that impregnates wood with furfuryl alcohol and then cures the impregnated wood forming a polymeric furfuryl resin grafted to the wood (Lande et al., 2004). Furfurylation improves dimension stability, hardness, resistance to decay fungi and resistance to termites (Westin et al., 2004; Venås and Wong, 2008). Furfurylated wood has also shown some resistance to mold (Gobakken et al., 2010). The depth of furfurylation will likely by limited by wood characteristics. Thus, treatment will vary among boards and organisms may not be directly affected by the chemical although they may be affected by the subsequent curing process.

The wood modification processes merit further study for their potential to eliminate pests and prevent renewed infestations, although their high costs will likely limit applications.

Figure 1. Example of copper penetration (green areas) in cross sections cut from unseasoned ponderosa pine containing active beetle infestations and pressure treated with ACQ.

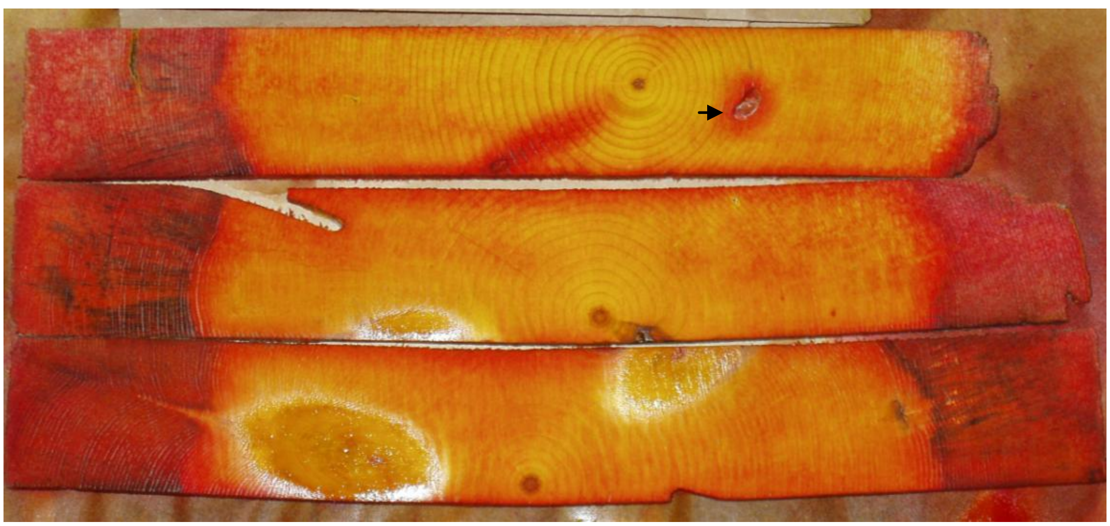

Figure 2. Example of boron penetration (red areas) in cross sections cut from unseasoned ponderosa pine containing active beetle infestations and treated with disodium octaborate tetrahydrate. Note the treated insect gallery, surrounded by untreated heartwood, in the first cross section (arrow).

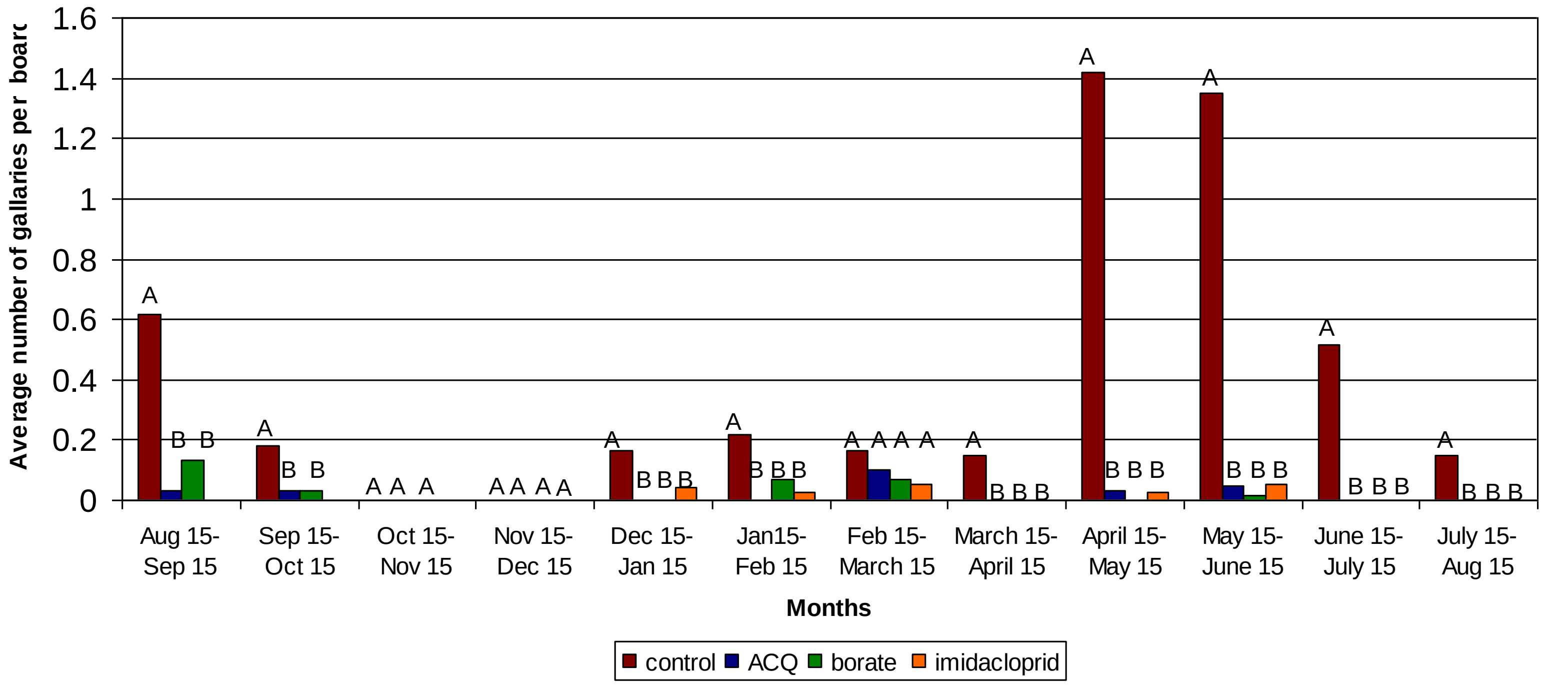

Figure 3. Average number of new larvae or adult holes detected per month on the surfaces of beetle infested pine samples treated with ACQ, borates, or imidacloprid. Imidacloprid treated materials were not included during the first three time periods. Bars with the same letters do not differ statistically significantly from one another (α =0.05)(Schauwecker and Morrell, 2008b).

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