Wood Discolourations & Their Prevention
With an Emphasis on Bluestain
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Summary

It is common to encounter wood products that diverge from wood’s natural colour. These discolourations occur throughout the whole processing chain, may affect value, and raise questions from users and producers. Discolourations are generally classed as either microbial or non-microbial in origin but some are complex and involve both biotic and abiotic factors. The terminology, as well as possible methods for control and remediation, are discussed. In some cases preventative measures remain unknown, while for other discolouration types some methods may be more feasible than others, and for some an integrated approach is needed. Microbial discolourations are more commonly encountered and among these the discolouration caused by bluestain fungi are the most prevalent, especially on softwoods. Since it has also been the focus of more studies, this brochure covers bluestain control in significant depth.

Diagnostic Key for Wood Discolourations

We planned to develop a simple diagnostic key to identify types of discolouration by using a hand lens, simple chemical reagents and reference pictures from this book. Such a key proved to be too complex and impractical for popular use but the guidelines in this brief section may assist diagnosis. Because the industry is familiar with them the most common discolourations such as bluestain, sticker stain and hemlock brown stain are usually easy to diagnose, especially if the wood species and some of the history of the wood are known. Other types such as surface bluestain, mold, bacterial, black yeast stain, inorganic deposits, metallic or enzymatic discolourations need an experienced eye and sometimes access to compound microscopy or other tools to identify them.

Fungal discolourations may be accompanied by fluffy or powdery surface growth of the fungus especially if the wood is moist or in a humid environment – white (usually decay), black (often bluestain) or variably coloured (usually molds). While decay often occurs in heartwood it is often not evident until the wood is deteriorated. Bluestain always occurs on sapwood and most often in softwoods, especially pines. Mold also predominantly occurs on sapwood of both softwoods and hardwoods and while it develops in a range of colours, it includes dark tones similar to bluestain. Unfortunately surface dirts are variable and can look like dark mold or bluestain fungi. Although bluestain fungi, mold or dirt may look similar to the naked eye a hand lens can often be used to differentiate among them, however diagnosis often cannot be confirmed without higher magnification.

Sawing wood sometimes exposes deeper discolourations within the wood, and these are more difficult to diagnose. They could be fungal, bacterial or non-microbial in origin. Hardwoods are more prone to non-microbial discolourations which are sometimes specific to the wood type. For those unfamiliar with them, non-microbial discolourations are hard to identify, and until better keys are devised they are best diagnosed by matching the discolouration with pictures and text in this or other publications. Iron stain is perhaps easiest to detect and confirmable, by the bleaching action of phosphoric acid (see page 11) if the stain is not too intense.
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Definition & Types of Wood Discolouration

Terminology on discolourations of wood may be ambiguous. We define *discolouration* or *wood discolouration* as a **deep or shallow change in colour that diverges from the natural wood colour**. Discolouration often, but not always affects wood value. *Stain* is often used interchangeably with *discolouration*, however *stain* or *wood stain* is also used to describe a finishing product that is deliberately intended to change the wood colour. Some discolourations have been studied in depth, and in some cases can be prevented; for other discolourations knowledge of the cause(s) and prevention remain elusive (Scheffer and Lindgren 1940). Discolourations can occur in both sapwood and heartwood. They can also occur at any stage in the wood processing chain, including standing trees, green logs, green or kiln-dried lumber and on wood products in service. Some may be initiated (but remain inconspicuous) in one stage but show up in later stages of wood processing, while others develop fully in one stage. Based on their causal factors and nature, wood discolourations can be put into two major groups, *microbial* and *non-microbial discolourations*, terms that are preferred over *biological* and *non-biological* which are less precise. As suggested by the name, microbial discolourations, which are also the most economically significant discolourations, are caused by micro-organisms, in particular bluestain fungi, mold, decay or bacteria. Among these, discolourations caused by bluestain fungi are the most common and they have been studied extensively. Though common on softwoods they may affect hardwoods as well.

Non-microbial discolourations commonly occur under specific conditions and while more often associated with hardwoods, they also affect softwoods. Non-microbial discolourations can be mechanical (e.g., burn marks, dirt), chemical, biochemical or photochemical but may also, for example in the case of hemlock brown stain, have both chemical and microbial involvement (Kreber 1995).

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1 In this book we will continue to use the word stain to mean discolouration in those cases where the term is entrenched, for example bluestain.
Non-Microbial Discolourations

Non-microbial discolourations are often referred to as chemical or enzymatic discolourations. Kitchens and Amburgey (2007) separate non-microbial discolouration into enzymatic and non-enzymatic categories. The main difference is that enzymatic discolourations only occur in sapwood as they are associated with live cells; non-enzymatic discolourations have various causes that do not involve enzymes. Non-microbial discolourations are more likely to occur in manufactured products than in logs; however the stain precursors often appear to develop in living tissue in the tree or living/dying tissue in the log. Some non-microbial discolourations that develop in the standing tree or in logs become visible when the logs are sawn into lumber. The main control option is to reduce log storage times. Some of these discolourations develop in lumber, for example during kiln drying, and show when the lumber is surfaced. Except for appearance, wood affected by non-microbial discolourations normally has the same properties as non-discoloured wood. Non-microbial discolourations are not as well understood as microbial ones despite their common occurrence. Some, like those that develop during kiln drying, are relatively well documented and solutions have been proposed (Kreber et al. 1999; Kreber et al. 1998). Other discolourations can be controlled under certain conditions through such practices as fumigation or wood stressing that kill the living tissue involved in producing precursors to the discolouration process (Kitchens and Amburgey 2007). Drying techniques that avoid initial slow drying are recommended for whiter woods where surface blemishes are more pronounced, however planing is commonly done after kiln drying and this tends to remove surface discolourations.

Typically non-microbial discolourations occur when natural chemicals in the wood react with air, usually through oxidation which forms polymers that are darker in colour. They are usually initiated in wood that is above 40% moisture content (oven dry weight basis). Non-microbial discolourations that are not enzymatic include colour change associated with depositions or reactions with metals or minerals. They can occur in both sapwood and heartwood. Chemical discolourations can exhibit light to dark brown deposits in ray and parenchyma cells and occasionally in vessel elements. These deposits range from small, globose, brown bodies to amorphous, brown deposits that may extend completely across the vessel elements (Campbell 1959). They can sometimes be differentiated from biological discolourations by reaction with a saturated oxalic acid solution, which selectively bleaches some non-biological discolourations, especially iron stain.
Surface Brown Stains

*Kiln Burn, Machine Burn, Scorch, Coffee Stain*

Light charring of wood due to excessive kiln temperature or friction through contact with machinery such as the planer, is commonly called kiln burn or machine burn, respectively. These stains have very dark browning or actual charring (black colour) caused by excessively high temperatures. The wood appears to be scorched. They can be found in both sapwood and heartwood and on varying wood species. Kiln burn is also used as a synonym for brown (coffee) stains that are most common in pines (Hulme and Thomas 1975) and are probably initiated in the log or green lumber stages. Pine brown stain becomes visible during or after air or kiln drying. The discolouration is probably caused by the movement of extractives and the free liquid water towards the surface, followed by their concentration and polymerization. This discolouration has yellow to dark brown or chocolate tones. The colour also can go deeper into sapwood and may appear in patches or streaks or in a more uniform pattern.

**PREVENTION/REMEDITION**

Adjusting equipment (e.g., a planer) to prevent machine burn and modifying the kiln drying process, frequently by trial and error, are commonly used to reduce surface brown stains. Stacking lumber with dry stickers soon after sawing to optimize air drying, minimizing storage time during the warmer months and prompt kiln drying have been suggested. For example stacking procedures were shown to be very important for green wood since close piling or inappropriate stickering reduce air flow and promote brown stain (Cech and Pfaff 1980). Drying lumber at an initial kiln dry-bulb temperature of 130°F (until 30% MC or fibre saturation point) and later not above 212°F for green pines while using low humidities, have shown some success (Moore et al. 1990). Chemical methods for prevention of brown kiln stain in pine have been attempted (Hulme and Thomas 1975) but do not appear to be used commercially.
Hemlock Brown Stain
Oxidation or Tannin Stain

A thorough review of the mechanisms of various discolourations in western hemlock (*Tsuga heterophylla*) was done by Kreber and Byrne (1994). The characteristic hemlock brown stain is visible in different forms: surface brown stain that occurs in drying logs and lumber, particularly on the end grain; subsurface brown zebra stain that occurs during kiln drying in sapwood, predominating in the earlywood and therefore giving a striped appearance; and smaller amounts of grey stain that can occur deep within the log (Kreber 1995). The ends of susceptible green hemlock lumber pieces can be almost black after some air drying has occurred, with iron and/or manganese sometimes darkening the browning. Now that kiln drying of western hemlock has become more common, the subsurface zebra stain is particularly economically damaging as it can prevent the generally clear-grained hemlock sapwood being sold as an appearance grade product, unless planer allowances are made excessively thick. Although appearing macroscopically in different forms, the appearance of brown stain under the microscope is similar – globular brown deposits – mainly in the longitudinal tracheids (Ellis and Avramidis 1993).

In addition to the alternate names given above, hemlock brown stain is sometimes called enzymatic stain, though there is less evidence of a role for enzymes in its formation than that described in the next section for other species. Although mainly evident on lumber products, the stain appears to result from unknown precursors that are present in the sapwood of the tree or log. The staining is believed to be a complex process with oxidative chemical and microbial-induced staining both mentioned as causes (Kreber 1993; Kreber 1994; Kreber and Byrne 1994). Specific compounds in the sap such as catechin have been suggested as precursors to the stain (Barton and Gardner 1966) but the amounts of catechin present in sapwood are very small (Kreber 1995). Hemlock brown stain periodically causes significant economic losses in the US Pacific Northwest and in Canada.
Non-Microbial Discolourations

PREVENTION/REMEDIATION
Prevention measures remain largely unknown for hemlock brown stain, especially the subsurface brown stain that occurs during kiln drying. Planing the dried lumber can remove the brown discoloration but sometimes as much as 3mm of wood has to be removed from each face and this is beyond modern planer allowance targets for rough lumber. Avramidis et al. (1993) reported that pre-steaming lumber prior to kiln drying could alleviate the discoloration but this has not been demonstrated on an industrial scale. Chemical treatment with a high loading of quaternary ammonium salt solutions can prevent the superficial type of hemlock brown stain on green lumber ends (unpublished Forintek data). Efforts to determine whether prolonged log storage or dry-land storage vs river storage (Kreber and Byrne 1996; Byrne and Minchin 2003) have not shown success in preventing hemlock brown stain in susceptible pieces.

Pacific Silver Fir Brown Stain
Western hemlock is often sold as part of the hem-fir species group and the Pacific silver fir (Abies amabilis) component is much less susceptible to discolorations. Pacific silver fir sometimes shows an intense black-brown discoloration that occurs during kiln drying of some susceptible pieces of this wood. Because Pacific silver fir is sold in the hem-fir species group, this discoloration is sometimes mistaken for hemlock brown stain. This discoloration has been suggested as being produced from a stilbene (3,3’-dimethoxy-4,4’dihydroxystilbene) associated with log storage and possible bacterial breakdown of lignin (Barton and Smith 1971). This discoloration is therefore possibly microbial and is, unusually for wood discolorations, associated with wood breakdown.

PREVENTION/REMEDIATION
This is not a common stain and prevention methods are unknown. Prompt log processing may reduce the problem if the precursor development takes place during log storage, but this has not been confirmed.
Log End Stain

This type of stain develops in logs during storage when temperature and moisture conditions of the air are favourable (long storage in warm weather). This type of stain is commonly seen on hardwood logs in Eastern Canada and Eastern US.

Log end stain can also occur on softwoods such as western hemlock where brown stain sometimes develops.

PREVENTION/REMEDICATION

The only sure and effective method to prevent this discolouration is to process logs as soon as possible. Some studies suggest that killing of the live tissue in logs, by heat or fumigation for example, is a potential control mechanism (Forsyth and Amburgey 1992; and an internal Forintek study).
Enzymatic Discolourations

These are a type of biological non-microbial discolouration occurring mainly in hardwood species. Red alder (*Alnus rubra*) is a North American hardwood that is susceptible to an enzymatic discolouration both in the log and green lumber stages. The reaction of the enzyme phenoloxidase with wood extractives has been implicated as the cause of the red surface discolouration of alders (Hrutiord and Luthi 1981; Terezawa *et al.* 1984). Some non-microbial discolourations, such as surface reddening in red alder, are caused by enzymes secreted by the living tissue (Kreber *et al.* 1994). For this to occur, tissue needs to still be living and the precursors exposed to air.

Similar discolourations due to the production of polyphenolic compounds in living cells occur in oak, beech and maple. A greyish to brownish discolouration of the sapwood of several hardwood species is quite common. The exact origin of grey stain is unknown but it is believed to result from enzyme-mediated reactions within the parenchyma cells. The discolouration frequently originates at the heartwood-sapwood interface and spreads throughout the sapwood. Usually the stain is not noticeable until rough-sawn lumber has been air-seasoned and planed (Forsyth and Amburgey 1992).

**PREVENTION/REMEDICATION**

Killing of the live tissue in logs or lumber, by heat or fumigation for example, is a potential control mechanism (Kreber *et al.* 1994; Kitchens and Amburgey 2007). Red alder is mainly used for appearance purposes and the surface dressing during manufacture generally removes this shallow stain.

Dip treatment of fresh lumber in 5% sodium bisulphite followed by diffusion storage is also suggested (Forsyth and Amburgey 1992). Enzymatic discolourations cannot be prevented by commercially available anti-sapstain formulations. Rapid utilization of logs and rapid drying of lumber minimizes the enzymatic discolourations.

Mechanically stressing the lumber is also reported to help, however, this has not been commercially implemented (Kitchens and Amburgey 2007).
Interior Grey, Pink or Brown Discolourations

These stains initiate in the sapwood of most hardwood logs near the heartwood/sapwood boundary and are revealed when the logs are cut into lumber. They are common in logs that have been stored and appear to be caused by the oxidation of wood extractives during seasoning. They can also develop in logs stored under sprinklers. Oxalic acid is reported to remove most of the stain, thus separating it from bluestain which it sometimes resembles. Poor drying conditions during warm, humid weather may promote interior grey staining in green lumber (Moore et al. 1990). This stain develops in lumber when the outer surface of the green board has dried to below the fibre saturation point (~30% MC) before oxidative chemical reactions can be completed, while the major inner portion of the board is still green. This can happen in stacked lumber that begins to air dry before kiln drying. Brown seasoning stain in western and eastern white pines can be found as narrow margins of bright wood on the board surface or at the heartwood/sapwood boundary (Cartwright and Findlay 1946).

PREVENTION/REMEDICATION

There is no sure and effective method to prevent these discolourations. The best way to prevent these discolourations is to use appropriate kiln drying schedules. More prompt processing of logs and drying of lumber may also reduce some of these discolourations.
Iron stain is by far the most common form of metal stain and it is caused by elemental iron reacting with phenolic chemicals in the wood to form black iron tannates (common black ink pigment). It is commonly seen around mild steel wire and nails in wood which has become wet; galvanized or stainless nails will not cause iron stain. The discolouration is sometimes found on commercial lumber where sources of iron can be particles from steel wool, filings, lubricants containing metal fines, steel rollers or chains, or airborne particles (e.g., from the brakes or the wheel-on-rail friction of railway cars, causing so-called travel stain). It is largely a surface discolouration but can penetrate a few millimetres if the particles of iron are large enough to provide soluble iron.

Diagnosing iron stain involves spotting a dilute (~3%) phosphoric (or oxalic) acid on the stained part. The acid breaks down the iron tannate into colourless ferrous salts and the iron stain is thus decolourized. Oxalic acid does not always work. It is best to use a method such as energy dispersive x-ray fluorimetry to confirm the presence of iron and/or other metals (e.g., manganese). Some trees or logs are capable of absorbing metals that do not stain the log until they migrate in aqueous form to the surface and are exposed to drying conditions. In western hemlock a black chemical stain resulting from iron and manganese complexes can occur, particularly on the ends of logs or green lumber that are allowed to surface dry.

As mentioned previously, this dark stain is often mistaken for hemlock brown stain which can darken to an intense black colour if there are large amounts of iron or manganese. The source of the metals is speculative as they could already be in the tree when it is felled or they may be absorbed during river storage, which is commonly done on the west coast of North America with western hemlock logs. Anaerobic mud on river bottoms contains a lot of free iron and manganese. Western hemlock trees can take up solubilized iron and manganese from the soil, but with considerable within and between tree variability (Warren et al. 1952). In some species iron may form different kinds of complexes with the extractives. In western red cedar, iron will complex with thujaplicins to form a water-insoluble red stain that can only be removed by certain organic solvents (Barton and MacDonald 1971).
Iron stain requires the presence of iron, wood and water and will not occur if one of these is absent. Some ways to avoid it are: preventing deposits or minimizing contact time with iron particles on wood; covering wood during transport or storage to prevent rain contacting iron strapping and staples; using non-iron materials to strap and protect corners of green lumber; minimizing log exposure to anaerobic mud during river storage. When aqueous chemical treatments are used to protect wood, for example from sapstain, contamination from mild steel or iron should be avoided. In dip or spray application systems a metal ion sequestering agent or iron stain inhibitor such as phosphoric acid can be added (Moore et al. 1990). Iron stain can usually be removed by planing.

Mineral Discolouration

Mineral stain is a deep streaky stain that can develop in standing or fallen trees in mineral rich soils. It may show in the form of dark lines or streaks in oak, green to brown zones in sugar maple, or purple to black areas in yellow poplar (Cassens 2006). Discolouration can sometimes be traced to a wound in the tree close to the ground or in broken roots still in contact with the soil. Calcium oxalate is one mineral thought to be associated with such stain. It tends to dull machining knives (Knaebe 2002).

One possible method of prevention seems to be to dry wood rapidly, either using fans or kilns. The drying schedule should not be too aggressive in order to avoid surface checking (mineral stain tends to produce surface checking when dried). However, kiln schedules don’t really have an impact on reducing mineral discoloration in sugar maple. No other effective control is known.
Sticker Stain

Sticker stain or sticker shadow is a subsurface grey to brown discoloured area that usually runs across the width of a piece of lumber exactly where a sticker was located during drying. Typically the stain is barely, if at all, seen in rough lumber, but is only evident after planing (Wengert 1998). It may be especially visible in whiter woods and extra caution is needed in drying these. Moore et al. (1990) distinguished two different forms: faint to moderate greyish to brown, mainly in sapwood where there was close contact of a sticker with lumber; and the lighter coloured wood directly underneath the sticker that stands out compared to adjacent darker wood. During kiln drying, the higher the initial kiln temperature the more pronounced the discolouration becomes. The stain has been associated with old logs, probably with secretions from cells as they are dying. The basic cause appears to be slow drying under the stickers when the lumber is still above about 40% MC. The final oxidation and discolouration may actually occur below 15% MC and is accentuated by higher temperatures during the final steps of the kiln schedule (Wengert 1998). Fungal discolouration may sometimes also be associated with stickers where trapped water causes prolonged moisture retention and subsequent colonization by microorganisms.

PREVENTION/REMEDICATION

This stain can go deeper in the wood than the shaving removed by the planer and may be even more visible after planing. Avoiding prolonged wood storage in warm weather is one method of prevention that may be effective, but it is not always practical. Sticker stain may be associated with slow drying (e.g., drying during warm, humid weather conditions). Methods for faster drying or avoiding high humidities in the kilns might be effective (Cane 1990). Lower initial dry-bulb temperatures are recommended to minimize the colour contrast between the light coloured sticker stain and adjacent wood. Avoiding wet stickers, avoiding high kiln temperatures, and using good schedules and controls will help prevent sticker stain. A Forintek study (Tremblay 2000), showed that material used to manufacture stickers (wood, wood/plastic or plastic) has no effect on this process. However, profiled stickers (vs square-section stickers) have proved significantly beneficial for reduction of sticker staining by improving drying rate under stickers.
Reaction Wood

*Rotholz*

Compression wood in softwoods or tension wood in hardwoods are abnormal wood growths that often occur when trees are growing in windy conditions or the tree is leaning. This pressure on xylem cells on one side results in denser and darker wood with a reddish hue due to a change in morphology of wood fibres. They become shorter and develop thicker cell walls so there is less demarcation between the earlywood and latewood and the affected rings are often wider. Typically, water can still pass between the fibres but minerals may get caught, causing a discolouration. Also, there is more cellulose and lignin in compression wood than in normal wood (Kramer and Kozlowski 1979). This wood shrinks and warps extensively and is more brittle.

**PREVENTION/REMEDICATION**

This occurs as a physiological reaction in the growing tree and there are no known prevention measures.

Compression Marks

Several other types of stains can develop on hardwoods, such as compression marks. This type of stain is often associated with logs and green lumber manipulation and appears on localized strong pressure areas i.e., created by harvester and debarker rollers. (Chauret and Giroux 1999; Clément et al. 2006).

**PREVENTION/REMEDICATION**

Compression marks can be minimized by preventing strong pressure on logs and green lumber during processing (i.e., adjusting/lowering cylinder pressure; using different roller designs).
Water Stain

Water stain is an irregular surface discolouration caused by water that drips onto or runs over the wood and subsequently dries. Water stain shows up more on lighter woods. This stain normally has yellow to brown or black tones due to extractives or foreign material that are left behind after evaporation. The affected area is usually surrounded by a denser, darker ring. Some species with high extractive contents, such as western red cedar heartwood are particularly susceptible to water stains that often darken as the soluble extractives dry and polymerize into brown water marks, often called tea or coffee stain (see Surface Brown Stains).

PREVENTION/REMEDIATION
Water movement of soluble extractives can be prevented by minimizing water-wood contact in service or during drying. It is shallow and can be removed by planing or refinishing. Wood in service outdoors can be sealed by applying a sealant.

Weathering Stain

Outdoor exposure to sun and rain causes untreated or insufficiently protected wood to change colour, usually first darkening or yellowing due to sunlight, then eventually weathering to grey.

PREVENTION/REMEDIATION
Weathering can be minimized by protecting the wood from long periods of exposure to sunlight and precipitation. UV light inhibitors can reduce the propensity for weathering stain to occur. There is ongoing research to develop clear finishes that will keep the natural wood appearance for years and prevent such weathering discolouration.
Logs and moist lumber are susceptible to biological staining if stored under specific conditions conducive for microbial growth, not processed in a timely manner or otherwise not protected. The causal organisms are much more likely to attack sapwood than heartwood as the sapwood is relatively rich in available nutrients and usually does not contain phenolics or wood extractives that inhibit microbial growth. Although discoloured wood can host several types of organisms, it is important to identify the predominant cause of any discolouration. For example in order to remediate the problem or prevent reoccurrence it is important to distinguish bluestain from bacterial stain or mold. The terminology is sometimes confusing, for example ‘sapstain’ is often used to indicate any microbial discolouration of sapwood including those caused by bluestain fungi and molds. To reduce confusion in terminology we have settled on the terms presented here based on the nature and biology of causative organisms and on practical experience.
Bluestain

Deep and Surface Bluestain

Bluestain is the most common biological stain. Deep bluestain discoloration of sapwood in temperate zones is caused by growth of bluestain fungi in the sapwood portion of logs. These fungi are typically from the genera Ceratocystis, Ophiostoma, Grosmannia, Leptographium and Sphaeropsis—all which have wet slimy spores that easily attach to arthropods such as insects. The fungi are carried and dispersed by insects to new hosts, where they are able to colonize wood with high moisture and ineffective host defense chemicals. These fungi are pioneer colonizing species with little competition from other organisms. While healthy standing trees or logs with intact bark sustain no bluestain, logs with damaged bark can develop stain spreading in from the damaged area. Bluestain fungi are most efficiently transmitted via bark beetles that bring their associated bluestain fungi tunnelling directly through the bark. The staining fungi can grow up to two cm per day longitudinally along the tracheids and parenchyma of softwoods (Uzunovic and Webber 1998). Mechanical equipment, especially harvesters, appears to play a significant role in bluestain dissemination (Uzunovic et al. 2004). Dissemination of spores via water films was also reported by Dowding (1969).

On the log cross-section bluestain usually appears as permanent wedge-shaped blue or grey streaks, though in some circumstances the whole of the sapwood can be colonized. It is revealed in lumber when the log is sawn and cannot be removed by planing. In softwoods the colour is caused by darkly pigmented fungal threads (hyphae), growing particularly in the ray cells and to a lesser extent within the tracheids. Bluestain is found in some hardwoods where the dark-pigmented hyphae grow primarily in longitudinal vessels (Campbell 1959). Bluestain hyphae contain deposits of the dark polymer melanin within their cell walls but there is no diffusion of pigment outside the hyphae. As well as logs, green piled lumber may be vulnerable in warm weather to growth of deep-penetrating bluestain fungi. These fungi can originate from prior log infection and/or from post-sawing colonization. However, further bluestain development in lumber declines rapidly as wood is dried by ambient air. If the fungus has died off during log aging/drying there will be no further development during lumber storage.
Surface bluestain is caused by some members of the genus *Ophiostoma* often with *Sporothrix* or *Pesotum* anamorphs. These fungi are saprotrophic (i.e., not pathogenic to live trees) in nature and are competitive on drier wood that is still above the fibre saturation point. They do not penetrate deeply and occur commonly on sapwood of partially dried green lumber or on fully dried lumber that has become re-wetted. The discolouration develops after sawing and can be spread by insects, water films or contaminated equipment. The stain is due to darkly (black-dark brown) pigmented sporing structures that develop on the surface and it can be removed by planing. It is often confused with mold and an expert eye is required to distinguish between the two.

Typically bluestain fungi (deep and surface colonizing) do not cause significant changes in wood’s mechanical properties as the causal fungi utilize easily digestable nutrients like sugars, starch and triglycerides and cannot digest components of the wood cell wall (Fleet *et al.* 2001). However, bluestain fungi increase the permeability of sapwood and this facilitates preservative treatment (Lindren and Scheffer 1939). A few bluestain species such as *Botryosphaeria theobromae*, which causes bluestain in tropical hardwoods, have enzymes that can attack the wood cell wall and cause measurable strength loss (Encinas and Daniel 1995).

**PREVENTION/REMEDICATION**

Bluestain development in clean logs can often be prevented as it takes time for the infection, growth and staining processes to occur. The practical options for bluestain control are based on historical knowledge as well as an understanding of the pest organisms and their biology. The options include prompt processing, chemical control, freezing and snow storage, log drying, oxygen-less storage (water storage and storage under an elevated carbon dioxide (CO₂) atmosphere, reduction of mechanical damage, control of insect vectors, and fungal food reduction through ‘sour-felling’ or biological protection. These options are discussed on the following pages. End coating of logs may also prevent bluestain, providing there is no bark damage on logs or bark beetle attack.
Unpreventable Bluestain

Sometimes bluestain cannot be prevented because it is associated with insect attack of standing trees. In areas affected by aggressive bark beetles, such as in the current mountain pine beetle infestation in British Columbia and Alberta, bluestain has already developed in the trees prior to felling. The mountain pine beetle carries several aggressive bluestain species that can completely stain the sapwood within a month. A similar situation exists with southern pine which is commonly attacked by the southern pine (bark) beetle. These discolourations are not preventable unless the beetle vector is controlled; difficult to do on a tree stand scale when the beetle population is high and suitable host trees are available. Theoretically felling and processing trees immediately after attack (green stage) can be done before bluestain develops. However, it is hard to detect attacked stands from the air until the foliage shows signs of reddening, by which time the sapwood is bluestained and the adult beetles have hatched. This is not a practical method of controlling bluestain over large areas of insect outbreak. Early detection of new beetle attack by ground surveys and subsequent felling and burning of the trees containing the live insects is being used to slow the spread of the mountain pine beetle in Alberta. The bluestain in the logs from bark beetle-attacked trees poses a marketing issue, and the dryness and checking of logs creates a manufacturing challenge.
Chemical Control of Bluestain in Logs

Lindane (benzene hexachloride) and methyl trithion were used for a short time in the 1950s and 1960s for control of ambrosia beetles in stored logs (Richmond 1986). Canada, unlike some other countries, has not traditionally used chemical pesticides for the treatment of fresh logs to prevent bluestain. Currently there are no available registered pesticides for use on fresh logs in either Canada or the USA. Due to environmental concerns and stringent registration processes for pesticides applied in the field, it is unlikely that new chemicals will be registered in North America for this purpose. Other jurisdictions such as New Zealand permit chemical treatment. Although radiata pine logs are highly susceptible to staining, the road infrastructure in New Zealand allows just-in-time tree harvesting prior to domestic sawmilling. Logs that are bound for export are often chemically treated within a few days of harvest—at the shipping terminal prior to being loaded onto ships.

Chemical Prevention of Fungal Growth in Lumber

Chemical prevention of sapstain and mold on lumber is done with envelope chemical treatments that prevent fungi from accessing the nutrients in the wood. Chemicals can be applied to lumber by spraying, brushing or dipping (in-line dip or bulk dip). A review of chemical sapstain control was undertaken by Byrne in 1998. In Canada the earliest chemicals used for sapstain control of west coast softwoods were inorganic salts such as sodium carbonate or bicarbonate salts which came into use in the 1920s (Eades 1956). These chemicals were not fully effective especially after the practice of close piling green lumber started. Based on tests done in the 1930s sodium tetrachlorophenate was introduced and was used until the late 1980s. The Canadian industry pioneered a code of good practice for application of chlorophenates (Konasewich and St. Quintin 1994) especially in mill spray application. In 1988 other chemical formulations with narrower spectrum toxicity replaced the chlorophenates and improved formulations have followed. At the current time sapstain control
Microbial Discolourations

Microbial discolourations are mainly based on a small number of active ingredients – triazoles, quaternary ammonium salts and an iodocarbamate. These are mixed in formulations, and also often in tank mixes at the site of application, with various ‘non-active’ compounds to improve efficacy and cost effectiveness.

Sapstain control products are used in coastal BC and the Pacific Northwest of the USA for green lumber, but an increasing amount of production is now kiln dried. Control products are mainly applied with in-line spray systems or by dipping in the sawmills. In Eastern Canada, chemical sapstain control products are applied in the summer to a small proportion of green lumber produced, mainly that bound for export to Europe or lumber that is highly susceptible to discolouration such as eastern white pine. Chemicals are also used in the Southeastern USA, particularly for southern pine which is highly susceptible to staining. Products used for sapstain control have to be registered as pesticides by the Pest Management Regulatory Agency in Canada or the Environmental Protection Agency in the USA. Their respective websites contain lists of registered products.

To be effective, chemical protection should be applied to green lumber immediately after manufacture. Properly applied, these products are effective. Occasional failure of the products is usually attributable to inadequate or uneven application or to extensive pre-existing fungal infection.

Best Lumber Storage Practices

Both superficial sapstain and mold may develop quickly on freshly sawn green lumber. Green lumber is defined as lumber where MC is above 28% oven dry weight. When surface drying is impeded and conditions are warm and humid bluestain/mold growth may be visible to the naked eye within a few days, but normally takes one or more weeks to be apparent. Control options for fungal growth on lumber are limited to drying or chemical treatment. For green lumber waiting to go into a dry kiln, promoting air drying is the best strategy (McMillen and Wengert 1978). For successful air drying, optimum stickering with sticks of dry wood about 1/2-inch thick by 1/2-inch wide and storage of the piles

Bulk dip treatment of lumber. This is a common delivery system for chemical surface treatments. Tanks must be kept clean and free of debris and wood to be treated should also be clean and free of soil and sawdust. The tank should be covered to protect it from weather and prevent dilution by rain. Mild steel metal tanks may be corroded by some acid formulations, thus contributing to iron stain on the wood. For corrosive liquids the tank should be constructed of stainless steel or protected by a corrosion resistant coating. Chemical concentration rate in the tank should be monitored regularly and maintained at the correct concentration. The level of liquid should always fully cover the entire dipped lumber pack.
in a ventilated place should provide sufficient air-flow between the layers of boards. Best practice requires placing stickers between each layer of boards across the pile, with no more than two-foot spacing, and aligning them vertically with the row below so that the weight is transferred properly, thus reducing the tendency for warping. To prevent checking in the lumber, first and last stickers in all rows should be as close to the end of the pile as possible. An air drying yard has to be laid out for good air flow. Strong winds and warm dry weather promote drying while still, moist air—fog, rain and high humidity—will encourage fungal growth. Considerations such as solar aspect may also be important; the tops and sides of the loads should be protected from sun and rain. If there is a shortage of kiln capacity and air drying conditions are suitable, a successful strategy is to use the kilns to lower the initial moisture content under controlled conditions and then to air dry in the mill yard. If the target moisture content is not achieved by air drying, the drying can be completed in the kilns. Such a strategy maximizes kiln capacity but increases inventory and handling costs.

Lumber storage sites should be clean, flat, dry, well drained and well ventilated. Storing bundles of wood on vegetated or moist soil areas, in puddles or near standing water invites mold, stain and soiling problems. A gravel or concrete pad is preferred. Packages of lumber should be kept 6 to 8 inches off the ground as dry wood in contact with the ground will absorb water. Ensure the area is clear of obstacles, debris and vegetation that can harbour insects that transfer bluestain, prevent good ventilation and keep the air moist.

Wrapping dried lumber prevents it from getting re-wetted. Wrappers are made of polyethylene or paper/polyethylene composite materials often fibre-reinforced to give tear strength. Intact polyethylene wraps are efficient at protecting wood from moisture but they may trap moisture inside the package if the wood is not dried properly or if the wrap has been damaged and allowed ingress of moisture. Packages of lumber should be wrapped with staples on the side of the package not the top. When a wrap is damaged, for example by forklift trucks, it should be replaced or the lumber tarped to prevent water infiltration during outdoor storage.
Tarps are temporary and easily develop holes on package corners or other points of stress. Tarps should not be tucked under the pile or wrapped tightly with the cover extending beyond the bundles. Unwrapped lumber piles (both green and kiln dried) should not be stored outside for significant time where they are subject to moisture pickup from rain, snow or ground surface water. To limit unwanted fungal growth, outdoor storage on the building site should be minimized. This can often be achieved by careful inventory management and delivery planning. Production dates should be used to ensure proper inventory rotation (‘first in-first out’) in all channels of wood products’ distribution.

As is done with logs, water storage or sprinkling of green lumber will prevent drying and keep it green and free of fungal infection by depriving oxygen to the organisms. This is theoretically feasible but is rarely done. Apart from the difficulty in wetting the large surface area, drying of wetted wood extends drying time and increases energy costs.

**Prompt Log Processing**

The most effective and historically proven option for bluestain control is processing of logs without delay, especially during the warm months when they are most vulnerable. This means processing within 2 to 4 weeks of felling when conditions are conducive to fast staining. The following strategies have worked for some operations but require good woodlands and manufacturing coordination:

- In vulnerable periods, lower yard and woodlands’ inventories, thus reducing the average storage time before processing.
- Where possible recognize bluestained and beetle-attacked logs right after attack, and harvest and process them before the stain becomes significant.
- Process high-quality logs first.
- Control log storage inventory to ensure implementation of ‘first in-first out’.
Standard industry practices often do not always allow for fast log processing, and log storage is usually required. Harvesting and log transport in Canada is closely associated with weather and is often concentrated in periods when the ground is frozen. When the soil is thawing or wet, harvesting and transport is not possible as harvest sites and roads have insufficient bearing capacity. Governments seasonally regulate transport in order to protect public roads as well as offering incentives to encourage winter transport. Harvesting may also be interrupted to protect migratory animals such as woodland caribou or birds. Such constraints force mills to increase their yard or log deck stock during the winter to ensure there are sufficient logs to allow uninterrupted mill operation. Thus some mills can have up to 100,000 m³ in yard stock going into in the spring-summer-fall, the period most vulnerable to staining. In this case, methods other than fast log processing need to be considered. Log yard layout should be designed to facilitate ‘first in-first out’ processing.

Log storage yards should be kept clean and free of debris which can harbour insects and be sources of inoculum to infect clean logs. Some mills have insect control programs, such as pheromone traps and trap logs, in their yards to reduce the infestation of logs by beetles (discussed on page 30).

A study on best storage practices has been conducted by Forintek in Eastern Canada to investigate the influence of seasons, log types and storage time on the sapstain development in jack pine logs (Yang and Beauregard 2001). In spring-felled trees sapstain did not develop significantly until after four weeks of storage with the severity of stain increasing proportionally with storage time thereafter. Full-length logs were more stained than cut-to-length logs, with all logs seriously stained after three months of summer storage. September-felled logs were stored over winter without significant stain, but stain development was rapid after April of the following year. Growth of stain was more rapid on debarked logs than on logs with the bark intact.
Freezing and Snow Storage

In countries with a continental climate and periods of the year with temperatures below freezing, logs can be safely cold-stored as both insect and fungal activity cease and staining cannot initiate or progress when the temperature is low. In some areas, logs can remain frozen for several months. Sometimes the bottom logs in a large log pile can remain frozen into the summer even when ambient temperatures are above 10°C. Some forest industry companies have examined the feasibility of extending cold storage into summer months by piling snow on top of stored logs.

In a joint snow storage study by the Forest Engineering Research Institute of Canada (FERIC) and Forintek, piles were covered with up to one metre of compacted snow then topped with a 30 to 50 cm layer of sawdust to act as insulation (Nader 2003; Frigon 2006). The method proved successful as temperatures within the piles in February were -10°C while in August they were still -1°C. The temperature in control piles followed the ambient temperature. After seven months of storage under snow, logs were well protected, with fungal infection affecting less than 1% of the total wood. This method also protected against moisture loss and prevented development of decay and checks in the logs. The cost was estimated to be about $0.85/m³ for a 20,000 m³ pile, consisting of eight rows of logs 4.5 m high. The study monitored stain development by storage method. For the air-stored control deck of white birch, 177 fbm were stained per 1,000 fbm, compared to 29 fbm if water-stored and 2 fbm if stored under snow. The stain affected up to 75% of the lumber area if logs were previously stored without protection, while if water- or snow-stored, the maximum surface area affected was only 5% (Forintek unpublished data).

Based on our knowledge, if applied correctly (i.e., total cover of snow for the whole storage period) the method would effectively control bluestain as long as temperatures within the piles remained below 5°C. Once thawed the logs need to be processed quickly to avoid rapid deterioration in the warm summer months. During cold periods when snow is not available there is a possibility of using snowmaking machines. We are not aware of studies that examined artificial snow generation
for stain control but some studies have investigated this option for keeping roads and bridges frozen longer. Portable machines, varying in cost from $8,000 to $50,000, are available. The biggest drawback of this method is a requirement for large amounts of water to be available from local lakes or streams, an estimated 550 L of water being required for one cubic metre of uncompacted snow (Mountain View Technologies, Inc. 2008).

Log Drying

Neither mold nor staining fungi spores will germinate and thrive on wood that is below 19% moisture content unless the relative humidity is very high (above 90%) and sustained for days or weeks. It is common in a few countries to debark logs as this eliminates bark beetle attack as well as increasing the drying rate. Debarking and rapid log drying can prevent stain; however it is difficult to do practically and may result in significant checking. If logs are dried too slowly, especially in warm temperatures with high humidity or rainfall, ideal conditions for development of staining decay fungi may exist.

Oxygen-less Storage

Bluestain fungi are aerobic organisms and while staining fungi can survive 1 to 6 months without oxygen, they need oxygen to grow. Reduction of oxygen needs to be substantial (less then 0.3% in laboratory experiments) in order to stop their growth (Scheffer 1986). There are two practically feasible ways to reduce oxygen: one is wet storage where water replaces oxygen inside the wood and the other is storage in a CO₂ enriched environment. Both reduce levels of available oxygen though factors such as nutrient leaching, competition and antibiosis from other microorganisms during water storage. Toxicity of CO₂ may contribute to stain reduction in CO₂ storage.
Water Storage

Water storage can take the form of submerging logs in bodies of water (ponding) or by constant sprinkling. River or estuarine storage is often used in British Columbia as a convenient means to prevent wood degradation by fungi and insects, but it is only effective when all the logs are completely wetted. Logs on top of booms or bundles that remain partly immersed can suffer significant degradation. Ponded logs must be turned periodically to prevent drying of above-water portions. Logs stored on large lakes or estuaries are often wetted by wave action alone. Log booms moored near forests can develop severe ambrosia beetle attack (McLean 1985). Ambrosia beetles also carry bluestain fungi but the development of the stain is usually limited to a ring around the beetle galleries and the fungi do not colonise the rest of the sapwood. During ponding, sinker logs may be lost due to saturation having caused the green density to be higher than the surrounding water. Fresh running water is more effective than stagnant water that tends to encourage bacterial growth. In most countries water storage is under regulatory scrutiny and is restricted due to environmental concerns such as leachable wood extractives and bark debris accumulation.

Constant sprinkling with water recycling is possible where ponding is not feasible. It is regularly used on summer hardwood log decks in Eastern Canada, and in the Western USA (for softwoods) as well as for windthrown timber following natural disasters (Webber and Gibbs 1996). Storage under sprinklers must be thorough over the critical seasons (when temperature is over 4°C), keeping all surfaces drenched, especially log ends, otherwise it is ineffective. It can require a large volume of water (at least 12 mm/hour). According to a Swedish study, the lowest sprinkling levels for maintaining moisture content of softwood timber have been reported to vary between 25 and 33 mm/per 24-hour period, while the higher sprinkling intensities vary between 40 to 100 mm/24-hour period (Liukko 1997).
Storage Under Elevated CO$_2$ – Controlled Atmosphere

Storage in a carbon dioxide (CO$_2$) atmosphere is also used and, while reputedly commercialized and patented in Germany, there is limited experience with it in North America (Mahler et al. 1997; McKee and Daniel 1966; Feist et al. 1971; Amburgey 1979). It involves wrapping and sealing logs immediately after harvesting in a double layer of polyethylene sheet so that CO$_2$ builds up to 20 to 40% by microbial respiration. Decomposition of hemicelluloses and sugars through fermentation also generates additional CO$_2$ reducing oxygen levels to less than 0.1% after 3 to 10 days. Studies mentioned in the patent showed little or no insect, stain, or decay after four years. The efficiency of this method in arresting stain development in pre-infected logs is unknown. The feasibility of this method for the North American wood products industry is also unknown.
Prevention & Reduction of Mechanical Damage

Trees felled and processed manually with a chain saw sustain little bluestain damage as long as the bark remains intact and the logs have not been attacked by beetles. Tree harvesters, however, have been shown to play a role in the inoculation of wood-degrading fungi into freshly felled conifer logs (Uzunovic et al. 2004). Machinery used in forest operations damages the exterior of freshly felled logs, loosening and removing bark, and producing punctures and indentations up to several centimetres deep. Some damage is visible while some may not be so obvious. There is clear association with bark damage caused by forest mechanization (especially harvesters) and bluestain (Lee and Gibbs 1996). Damaged logs are susceptible to infestation by a range of wood inhabiting fungi. As insects and water films are the major modes of bluestain transmission any breaks in bark integrity that expose phloem and sapwood may be sufficient to act as entries for bluestain fungi. To reduce bark or wood damage some companies have examined changing or adjusting mechanical equipment (e.g., using less damaging feed rollers or adjusting the pressure). However, even when gentler rubber feed rollers are used, up to 50% of total bark coverage can be damaged, especially in the early summer when the cambium layer is active and the bark is easily stripped. With very low amounts of bark damage (0 to 10%) insignificant amounts of stain could result but in practice, this low level of damage is difficult to achieve.
Control of Insect Vectors

Various insects visit, breed and feed on the same woody material in which bluestain and other microorganisms are commonly found. Ophiostomatoid fungi are well adapted to dispersal by arthropods (Malloch and Blackwell 1993). Both sexual and asexual spores are coated with an adhesive or slimy material that helps them adhere to insects. Ascospores have shapes that allow multiple contact points with the insect body and can easily disperse in resin, but not in water (Whitney and Blauel 1972). Spores of bluestain fungi may be carried both in the intestinal tract and on the exterior of insects. Many wood-infesting insects could play a role in bluestain dissemination.

There are also specific and often complex associations between insects and fungi. The most highly developed relationships exist between bark or ambrosia beetles, and bluestain fungi. During the evolution of insect-fungus mutualism some insects (especially plant-eating and fungus-eating beetles) have developed special spore carrying structures called mycangia (Batra 1963). The beetle-fungus associations are seldom limited to one fungus per beetle species and usually there are two or more fungal species per beetle. Often the beetles that attack trees carry the more pathogenic fungi, thus they have been more extensively studied than the fungal associates of the beetles that attack weakened trees. However, since the beetles involved in secondary attack would normally attack logs or dead trees they might be associated with significant staining fungal species.

Ongoing research in the area of semiochemicals (message-bearing chemicals that include pheromones, kairomones and allomones) promises a new dimension in stain control. Semiochemicals have been successfully used since 1981 in baited traps for mass-trapping ambrosia beetles (Borden 1995; Lindgren and Fraser 1994). Mass trapping of bark beetles still poses a challenge. Combinations of semiochemicals that attract several species of Ips or Dendroctonus beetles as well as large woodborers have been studied and are being developed into cost-effective trapping programs (Allison et al. 2004). In certain situations repellent semiochemicals may be used to protect stored timber. There is a large and increasing volume of literature...
examining insect-fungus relationships, as well as growing understanding of the staining potential of some fungi. With sufficient knowledge there is potential to tailor a trapping program to vectoring insects in order to control stain. While still experimental, implementation of semiochemical technology is likely to become an important part of integrated bluestain management.

Fungal Food Reduction through ‘Sour-Felling’

Sour-felling is a direct translation of a Nordic term (Faeste and Johansson 1982) used to describe the method where trees are felled and delimbing postponed. The method has been used in several countries to produce a drier log. It is also known as transpirational, biological or crown drying; leaf drying or leaf seasoning (translation of Japanese “hagarashi”); delayed bucking, processing or delimbing; physiological drying; and summer felling (McMinn 1986a and McMinn 1986b; Visser 1985; Ratajczak 1973; Hartwig and Visser 1981; Hakkila et al. 1970; Patterson and Post 1980; Garrett 1985; Sachsse and Oliver-Villanueva 1991). Normally, staining fungi efficiently and rapidly exploit wet, fresh, nutrient-rich sapwood utilizing both stored and mobile simple foods (Fleet et al. 2001). Scientists have postulated that modifying the substrate by reducing moisture content and/or nutrient levels may reduce bluestain (Forintek unpublished report). Nutrients and moisture might be reduced by delaying delimbing, leaving the foliage on after felling and allowing respiration and passive transpiration to continue. Delayed delimbing can result in weather-dependent reduction in moisture content compared with trees that are delimbed right after felling. Although reduced bluestain in sour-felled trees has been reported, drying is usually the reason for sour-felling.

Three trials were completed by Forintek Canada Corp. wherein sour-felled and delimbed control trees were destructively sampled to determine the amount of bluestain after 6 to 7 or 12 to 13 weeks of summer storage (Byrne et al. 2001; Uzunovic et al. 2002). They indicated that sour-felling could reduce or prevent stain in pine by mechanisms not fully understood. Less surface
mold growth, reduced moisture content and depleted starch in sour-felled logs, compared to logs that were delimbed right after felling, were observed. Sour-felled trees also had less bark damage in the upper portions of the tree. Thus the stain reduction or prevention could be attributable to less bark damage, less moisture or less nutrients in the sour-felled trees.

Insects have long been known as vectors of bluestain fungi (Hartig 1884) but there was no evidence of beetle attack on the sour-felled trees. Kelsey and Joseph (1999) found that the branches on ‘crown logs’ (sour-felled) helped maintain low ethanol concentrations in the log tissue and thereby made them less attractive to ambrosia beetles. These authors also speculated that the effectiveness of leaving branches attached may vary with environmental conditions. Johnson (1961) and Johnson and Zingg (1969) also reported lower ambrosia beetle attack, and also less of the bluestain that lines their galleries, in felled trees when the limbs were left on.

Delayed delimming is a strategy for bluestain reduction which can be used by companies using separate felling and delimming equipment at the harvest site. Sour-felling is feasible when a feller/buncher is used for the initial cutting and delimers are used to remove the branches, practices widely used in the British Columbia interior and Alberta.
Microbial Discolourations

Biological Protection

The concept of biological control of one organism by another has a long track record in the agricultural sector, but is more novel in forestry and the forest products industry. The success of *Bacillus thuringensis* in combating various forest insect pests is one of the few working examples of biocontrol in forestry. Another is the use of the harmless decay fungus *Phlebiopsis gigantea* in Europe to control severe butt-rot caused by *Heterobasidion annosum*. In the field of wood products several researchers have published on the biological control of wood-staining fungi by bacteria or other fungi, usually molds (Uzunovic et al. 2002).

Many people have researched biological control of fungi in wood products and a few publications have reviewed this area (Morrell and Dawson-Andoh 1997; Mai et al. 2004; Uzunovic et al. 2002 and Young 2003). To our knowledge biocontrol on wood products has not been commercialized, but one product has a temporary registration in Canada and could be used commercially. A brief review of Canadian research is given here.

Forintek has pioneered biological control of sapstain in logs and lumber since 1986, and several hundred fungal species were screened for this purpose (Seifert et al. 1988). Among these micro-organisms, the mold *Gliocladium roseum* is one of the most studied antagonists (McAfee and Gignac 1997; Yang and Rossignol 1999). In 1988, Seifert et al. first reported that *G. roseum* strongly inhibited the growth of several sapstaining fungi under laboratory conditions. A simulated field test showed that *G. roseum* could protect steam pasteurized western hemlock and amabilis fir lumber against sapstain (McAfee and Gignac 1997). Work followed to improve the efficacy of *G. roseum* against sapstain on green lumber by co-applying an alkaline solution to change the pH of the wood surface. *G. roseum* is unaffected by a high pH, but sapstaining fungi are sensitive to alkaline. This integrated method for protecting softwood logs and green lumber from sapstain and mold was successful in field and sawmill tests (Yang et al. 2004). *G. roseum* was also found to protect hardwood logs against biodegradation prior to panel manufacturing (Yang et al. 2007). Results strongly demonstrated that *G. roseum* has potential as a commercial bio-pesticide.
Forintek has also tested biological protection of freshly felled logs using albino bluestain fungal strains (Uzunovic et al. 2002). Forintek showed that a commercially available albino strain of *Ophiostoma piliferum* (Sylvanex) can effectively control stain in lodgepole pine logs, colonizing fresh sapwood and displacing wild bluestain fungi. At the same time the wood remained stable in colour and stain free. Forintek’s field tests in Alberta, B.C. and Quebec clearly indicated that Sylvanex could control bluestain for the 13 weeks of the test duration, if applied to the total log exterior immediately after felling. Another example of successful biocontrol of bluestain was recently shown through recovery of an albino strain of *Ceratocystis resinifera*, a bluestain fungus that grows deeply in fresh conifer logs (Morin et al. 2006). This albino strain, Kasper, was tested for its ability to control bluestain in spruce logs caused by wild-type bluestain fungi. In laboratory and field trials Kasper reduced bluestain in test logs by 80 to 94%. Registration of this organism was under way at the time of writing.

Some biocontrol organisms may make wood more permeable. This will only be important where wood is finished and used for appearance purposes such as millwork.

Biological control involves the use of live microorganisms (such as antagonistic fungi or bacteria) or the use of derivatives of live organisms. Public awareness about microorganisms, and especially if their presence is obvious when treated products reach customers, may lead to questions on human safety or phytosanitary risk. As with chemical treatments, technology providers therefore have to address the human safety and environmental implications of bio-control agents through the registration process. Phytosanitary concerns about live organisms on wood products may need to be addressed under different regulations. Such guidelines should ensure that a particular bio-control technology does not pose undue hazards during its use.

Before any product is used industrially, performance and consistency need to be demonstrated. Researchers in New Zealand, Europe and USA have experienced inconsistencies in the performance of Sylvanex, which in some cases failed to control bluestain. There is
therefore a need for more fundamental research to understand the limits under which biological control can work. Sylvanex remains a good model biocontrol agent as it is the only one that has been temporarily registered in Canada for the control of bluestain in logs. An effective applicator system still needs to be developed to deliver the agent completely around the log perimeter on the harvesting site without disrupting the harvesting process and causing delays.

**Remediation of Bluestain by Bleaching**

There have been attempts to bleach bluestained wood. Forintek work (unpublished) indicated that the commercial wood bleaches based on oxalic acid, sodium hypochlorite or sodium hydroxide/hydrogen peroxide were insufficient to bleach bluestain. Severe bleaching using heated hydrogen peroxide was effective only on the surface and removed the wood colour completely. Hot hydrogen peroxide bleaching is also expensive and dangerous. Sodium hypochlorite has also shown promise and it significantly reduced the blue colour. However the bleached wood had undesirable green or yellow tones, still remained darker and lost its natural colour. Chemical bleaching also caused a yellowing of heartwood and unstained wood (Evans et al. 2007). In view of the large amount of bluestained lumber being produced in Western Canada from the mountain pine beetle-attacked lodgepole pine Forintek is re-examining treatments to remove bluestain (at the time of writing).
Brown Fungal Stain

Hubert (1929) mentions this stain found in sapwood of several pines that has exactly the same pattern as deep bluestain but the colour is distinctly dark to chocolate brown. It was attributed to an unnamed fungus that acts similarly to bluestain fungi. It is primarily a log stain and has not been found progressing or occurring in green lumber. Scientists have observed similar stain in the sapwood of lodgepole pine—the wood appears to be sound and it is not a first stage of decay. The sapwood of Norway spruce and Siberian larch is reported to be affected and the causal agent identified as *Discula brunneo-tingens* (Sphaeropsidales). The fungus is in the same group as *Sphaeropsis sapinea* which is a known agent of deep bluestain (Tjoelker *et al.* 2007). The fungus may enter the wood via the branch and stem wounds.

**PREVENTION/REMEDICATION**

Little is known about this type of stain and its prevention. The same methods used for deep bluestain control may be useful.
Stain In Service
Black Stain, Black Yeasts

This type of stain is caused by fungi capable of producing both highly melanised black yeast forms and hyphae. It is found on both the sapwood and heartwood of many wood species. Typical fungal genera are *Aureobasidium* and *Hormonema*, both of which are common in outdoor and indoor environments worldwide. They are often associated with elevated and prolonged moisture content alternating with dry periods. They occur on outdoor, finished or unfinished wood, often under surface finishes, on wet and decaying wood, as well as in indoor humid areas such as bathrooms and saunas. They appear as specks or streaks of black discoloration embedded in the substrate and do not have observable fuzzy growth. They utilize simple sugars and proteins on fresh wood and lignin breakdown products on weathered wood (Sharpe and Dickinson 1993).

**PREVENTION/REMEDICATION**

These fungi are difficult to control but avoiding exposure of wood to rain and moisture will prevent their development. For outdoor wood, research is addressing prevention or control using finishes with specific physical attributes, as well as fungicides.
Mold-related Discolouration

This type of discolouration is caused by the growth of fuzzy/woolly masses on the wood surface. Mold is usually associated with green lumber or various wood products that get wet in service. Mold is also often seen on logs that have been stored in a humid environment, particularly on the ends or where the bark has been damaged and the nutrient rich cambium or phloem is exposed. The fuzzy surface growth consists of a mycelial mat bearing spores and spore producing structures. The colour can range from white to very dark in almost any hue and with many fungal genera and species involved. Some molds can penetrate deeply into wood, but the usually colourless hyphae are not easily seen even under the microscope. Mold discolourations in hardwoods are often deeper and more difficult to remove. In large-vesseled hardwoods such as oak, fungi may sporulate inside the wood.

Some mold hyphae contain pigments that can diffuse outside the cells and penetrate slightly below the wood surface, staining the wood a range of colours (Eaton and Hale 1993). Examples are: yellow stain associated with Chlorociboria and Cytospora; brown stain with Thielaviopsis; red pith of pine by Cephalosporium; emerald green on oak and birch by Chlorosplenium; rose to violet on maples and poplars; purple and pink on pines by Fusarium; pink on softwoods by Geotrichum; green or pink by Gliocladium; yellow by Paecilomyces sp. and crimson orange by Penicillium sp. A distinct blotchy red/pink stain in hemlock and Douglas-fir is caused by Cephaloascus fragrans or C. albidus. Sometimes it is also found on green lumber.

Molds are predominantly found on sapwood but may also occur on the heartwood of some wood species. Compared to bluestain fungi that produce wet slimy spores, molds typically produce dry spores that are easily carried by air. Air dissemination is the major form of mold transmission. Mold is a surface discolouration problem (on logs, lumber, veneer and other wood products) and will not affect wood strength. If the wood is kept moist for a prolonged time under wet conditions, subsequent decay caused by different fungi, decay/soft rot may develop and this will affect wood strength.
PREVENTION/REMEDICATION

Drying of wood to reduce the moisture content below 25% is recommended (see section on Best Storage Practices for Lumber on page 21). However mold growth can still occur on dried wood under conditions of high humidity (above 80% RH) or where surface water may occur. Maintenance of ambient RH of less than 80% is recommended to prevent mold growth and condensation. There is ongoing research on moldicides to protect lumber and other wood products from mold, and formulations that are successful under specific conditions are emerging. Surface application of chemicals after sawing should prevent further mold growth, however they will not remove pre-existing discoloration. The best way to control mold growth is by proper moisture control: reducing exposure to high humidity; storing a product in open, airy places; air drying the product by stickering (stripping) or by kiln drying and preventing re-wetting.

Nearly all mold discolourations can be removed during surface planing. Where needed, mold can usually be cleaned off wood with soapy water, scrubbing or power washing. Soapy water provides the surfactant needed to neutralize the hydrophobic properties that many molds have, enabling the molds to be carried in the water stream. Some detergents are more effective cleaners but may be slightly abrasive to wood; some have mild antimicrobial properties.
Decay-related Discolouration

Many basidiomycete, and some ascomycete fungi can, under specific conditions cause deterioration of the wood substance such that its chemical and physical properties are altered. Wood-decaying fungi may colonize standing trees, logs, or wet wood products in storage or service. They vary considerably in their growth rates and ability to cause decay and associated staining. Sapwood is most susceptible to decay, and heartwood of naturally durable species is least susceptible. Initial or later stages of decay can be associated with a change in wood colour that becomes more obvious as the decay process progresses. At first the fungi are not easily visible, even under the microscope, and gradually may show as white or pale yellow cottony mycelial growth, sometimes associated with discolouration of the wood underneath. Attack by white rot fungi usually shows as slightly bleached areas sometimes with visible black zone lines around these bleached areas. Brown rot fungi in the initial phases cause wood to slightly darken. In practice it is often difficult to diagnose incipient decay and associated staining. In the final stages of decay white rot fungi cause the wood to have a visibly bleached appearance. Given time, brown-rot fungi leave rotted wood that is soft, with a brown appearance and cubical cracking pattern. At this stage the presence of fruiting structures (conks, mushrooms) may occur, clearly indicating decay.

Decay requires time to develop. While fungal infection may have taken place, decay is typically not visible in logs between felling and processing unless the logs are stored inappropriately and/or for a long time. By then other organisms that cause biological stain will also have colonized the wood. Butt-rots in standing trees are also encountered, particularly in older trees. Some trees exhibit heart discolourations that may be the early (incipient) stage of heart rot. Red heart or redstain are terms used to describe a complex of basidiomycete fungi that commonly discolour lodgepole pine heartwood and were reviewed by Burdick et al. in 1996. The stain is a symptom of incipient decay that progresses slowly in the standing tree. At a more advanced stage the red heart becomes heart rot but this is not prevalent, being found in less than 7% of all trees that had redstain in an unpublished study at the Western Forest Products Laboratory.
PREVENTION/REMEDIATION

Decay normally needs moisture content to be above about 27% – based on oven dry weight – so if wood can be dried and kept below this MC the possibility of decay development is miniscule. Very wet wood, such as water-stored logs, is also less prone to decay. Chemical preservatives and some sapstain control products can slow and/or stop decay development in lumber. Preservative treatment is best done soon after sawing as preservatives generally cannot arrest development of already existing decay beneath the treated shell. Treatment with preservatives should be done according to the registration label directions. The use of heat or the use of diffusible chemicals such as borates will often arrest interior decay.

Bacterial Discolouration

Bacteria are commonly found in logs although the wood is only sometimes stained. Under conditions of prolonged moisture, bacteria may develop in excess and affect the wood. Bacterial counts can be up to 80 times greater in water-stored logs than in fresh green logs (Powell and Eaton 1993). Normally, activity of bacteria is most significant around bordered pits, and this increases the permeability of the wood. Bacterial stain might not be initially obvious but may become apparent later as streaking in products when finishes such as wood stains are used and the affected areas show increased uptake of the finish (Daniel et al. 1993). Permanent brown stains on the surface of water stored radiata pine logs were identified as tannin-like compounds derived from bacterial breakdown of flavonoid-glucosides that oxidize and concentrate on the surface during drying (Hedley and Meder 1992). Some conifers and hardwoods have wet pockets with abnormally high moisture content in the living tree and these pose a challenge during the drying process. Wetwood is associated with bacteria (Powell and Eaton 1993; Webber and Gibbs 1996) and often with water storage. Wetwood may appear as translucent, watery stains often associated with a sour or rancid odor.

PREVENTION/REMEDIATION

Reducing wood moisture content helps prevent microbial growth. Nothing much can be done for bacterial damage that occurred in the log stage and logs should be processed as rapidly as possible.
Uncommon Discolourations

This section covers a few examples of uncommon but characteristic discolourations. The causes of some are understood while some still remain unexplained.

Green Streaks in Douglas-fir

Distinct yellow or green streaks sometimes appear in BC Douglas-fir following the growth rings. Examination showed no signs of fungal growth, and analysis by X-ray fluorimetry showed no metal peaks. Under high magnification some tracheids from the discoloured rings appear to have distinct bright canary yellow granular deposits on their cell walls that are more prevalent in the latewood. The yellow substance is likely the flavonoid quercetin, a phenolic extractive found in Douglas-fir, especially in bark and heartwood. These streaks occur only in some parts of some wood samples, a distribution presumably related to the distribution of the extractive dihydroquercetin as hypothesized by Gardner (1960). The formation of the yellow quercetin is stimulated by heat and may be exacerbated by alkaline conditions such as those associated with some wood treatments. The discolouration is generally in the “enzymatic stain” category. A possibly related brown discolouration in the sapwood of Douglas-fir has been shown to be caused, at least in part, by enzymes in the sapwood (Laver and Musbah 1996). Troughton and Chow (1973) showed that extractives in Douglas-fir contributed significantly to the heat-induced colour-intensity change, as dihydroquercetin upon heating produced a distinct chromophore. This information is still preliminary and this distinct discolouration needs to be examined further.
Black Stain in Yellow Cedar Heartwood

This stain looks like thick pencil marks on the border between sapwood and heartwood in yellow cedar. Examination under 400x and 1000x magnification using a light microscope revealed characteristic dark pigmented fungal hyphae with roughened walls that pass across the tracheids in straight lines (Smith 1970). The hyphae penetrate the walls mechanically by producing small penetrating pegs, resuming their size on the other side of the wall, similar to the microscopic appearance of bluestain fungi. Some hyphae also follow tracheids longitudinally.

This stain has been reported by several authors (Smith 1970; Smith and Cserjesi 1970) but the fungus was not identified due to lack of sporulation in pure culture. More recently McDonald et al. 1997, Green et al. 2002 and Morales-Ramos et al. 2003 studied the effect of the fungus on the natural resistance and properties of yellow cedar, which is a durable softwood like western red cedar. The fungus establishes in standing trees where it enters via wounds or branch scars (Smith 1970). A woodwasp (Sirex) is also suggested as a possible vector (Morales-Ramos et al. 2003). The pattern of growth is similar to bluestain fungi although the fungus was reported as growing in the heartwood while bluestain fungi grow only in sapwood. Like common bluestain fungi this fungus does not destroy the wood substance and has negligible effect upon the structure of the wood. However, it has been shown that the fungus is able to chemically degrade certain of the tree’s natural extractives that are known to contribute to the high natural durability of yellow cedar. Thus, black stained regions of cedar might have lower resistance to wood decay and should not be used where high decay resistance is demanded (for example in ground contact).
Unusual Fungal Staining on Cedar Siding Showing in Stud Pattern

This stain is biological in nature and falls under the category “stain in service”. It is caused by black stain (yeast) fungi from genera *Aureobasidium* and *Hormonema* growing on exterior house paint. Typically rain is a source of inoculum and in the house shown at left the stain pattern follows the rain wetting pattern e.g., little immediately below overhangs. The fungus lives on UV breakdown products of lignin where there was also less sun exposure, while the stain is the most prevalent in portions of the house receiving the most direct sunlight. If the exterior finish (stain/preservative) contains oils, especially linseed oil, this could be additional fungal food. In this example the discoloration pattern reflects the pattern of studs or strapping and cavities behind the siding. Black stain fungi are probably growing beneath the coating in areas where moisture coming from inside the house is condensing within the wood siding. Hence it is not present where the studs block egress of humidity. On the other hand the studs may be thermally bridging, making areas of the siding warmer than between the studs, while insulation in the walls between studs prevents the warming of the exterior surface with heat from inside the house (Feist 1984). When moist air hits the siding it cools and can deposit moisture on the siding. Similar patterns can sometimes be found on garage doors when no vapor barrier has been installed in the wall between the house and the attached garage. Warm damp air enters the garage, cools, and water condenses on the coldest surface—usually the garage door.

Unusual Example of Weathered Wood

The yellow-jacket wasp has remove weathered, grey wood fibres from the surface to use in the ‘walls’ of their nests, exposing the raw wood underneath. This causes golden-brown streaks on the wood surface.
Resin Stain

These photographs show characteristic dark stain due to resin associated with wounds or other damage inside the living tree.
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Literature Cited


Terazawa, M., M. Miyake, and H. Okuyama. 1984. Phenolic compounds in living tissue of woods. V. Reddish orange staining in keyamahannoki (Alnus hirsuta) and hannoki (A. japonica) stabilized in vitro by the interaction of hirsutside and catechol oxidase after cutting the woods. Mokuzai Gakkaishi 30(7):601-607.


