AN ABSTRACT OF THE THESIS OF

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Moisture intrusion in residential structures can lead to substantial fungal decay and this damage costs billions in repair/replacement costs. The extent of damage and the rate at which it occurs are primarily dependent on the wood moisture content and temperature in the structure. Determining the risk of decay for various building materials would help designers identify the most suitable materials and schedule maintenance/replacement; however, attempts to model decay have been constrained by the lack of data on decay rates under varying environmental conditions. In this project, the rates of decay, as measured by loss in flexural and strength properties, were assessed on three wood species under varying temperature and moisture conditions for three fungi that commonly attack building components. The results were used to develop nine models to predict fungal decomposition rates in wood at moisture contents above fiber saturation point. The models incorporate relationships between temperature, and fungal species for three species of wood (Douglas-

fir, western hemlock and southern pine) at various moisture content regimes. The models rely on empirical data obtained from flexural and strength testing of four thousand beams and were validated against previously published data.

Fungal decomposition was found to cause considerable flexural losses (~50-60%) after only 6 weeks of fungal exposure in all wood species at 25 and 35^{o}C. MOE losses at 15^{o}C were not evident until week 12.
Decay was generally associated with strength losses in the range of 20-40% for wood incubated at 25 and 35^{o}C for 6 weeks, losses were lower at 15^{o}C. Flexural results obtained from non-inoculated control beams showed a progressive increase in loss, which could not be explained by chemical analyses of the wood.

Chemical analyses performed on decayed samples were consistent with the tendency for brown rot fungi to increase alkali solubility with time, as well as with the tendency for white rot fungi to consume nearly all breakdown materials as they are produced.

The results provided the basis for continued study to further refine the model. Eventually the model could be used to predict fungal effects based upon time of wetting, wood species and temperature.

Modeling Changes in Flexural Properties of Softwood Beams during Fungal Decomposition

by
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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request

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June M. Mitsuhashi Gonzalez, Author

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DEDICATION

This thesis is dedicated to my Mother, Gloria Gonzalez Aguila.

Esta tesis te la dedico a ti, Mami, por haberme dado todo tu amor y apoyo incondicional. No tengo palabras para expresarte mi agradecimiento por todo lo que has hecho y sacrificado por mí. Todo lo que he llegado a ser te lo debo a ti. Un simple gracias no es suficiente, pero es sólo el comienzo.

Chapter 1 – Introduction

Wood has been successfully used as building material for thousands of years due to its availability, ease of use, and superior insulating and strength properties. Wood also has some negative aspects. Most notable is its susceptibility to microbial degradation. A variety of organisms can reduce wood properties, making the wood unsafe for use.

Billions of dollars are spent each year on maintenance and repair of wood based structures due to decay. These costs are likely to increase due to social and economic trends towards more energy efficient homes that tend to trap moisture, creating ideal conditions for fungal and insect attack. One of the major issues with regards to decay is safety. Buildings that have been decayed and do not comply with safety standards are more likely to fail and kill people, especially during natural disasters like earthquakes and hurricanes.

Brown rot and white rot fungi are among the major contributors to biodeterioration in wooden structures out of soil contact. Fungal attack can sharply reduce wood properties with little to no visible evidence of decay. The most important factors for decay development in non-treated wooden structures are temperature and wood moisture content. Temperature directly affects metabolic activities that are mediated by enzymes like digestion,

assimilation and synthesis. Water is a reactant in enzymatic hydrolysis, a diffusion medium and solvent, is required in metabolic processes and acts as a swelling agent that facilitates penetration of fungal decomposition compounds into the cell wall matrix.

Moisture can be difficult to control in buildings because changes in building design that incorporate vapor and water barriers in walls and heavy insulation reduce the airflow and ventilation. These changes have markedly increased the amount of moisture in structures, providing a more suitable environment for fungal growth.

Moisture intrusion and subsequent decay development can reduce the structural capacity of a building, creating conditions that may cause it to catastrophically collapse under stress. Engineers generally determine if a wooden member should be replaced solely by visual assessment or they may use probes to test the integrity of the wood surface; however, these techniques are imprecise and often lead to removal of more wood than might be necessary. Often, the decision is based upon prior evidence of wetting, under the assumption that wet wood has been subjected to some fungal attack.

On a larger scale, estimated service lives for various building materials have become increasingly important as architects and specifiers examine the

greenness of building materials, based, in part, on service life. There are a number of approaches for assessing durability. On a small scale, durability of individual wood species can be assessed using various laboratory tests (ASTM D-2017, EN113, EN 335), but these do little to predict performance in structures. Scheffer's climate index (1971) was among the first quantitative attempts to use temperature and rainfall as predictors of decay risk. These data were used to develop a decay risk map for wood exposed above the ground in the United States. Leicester expanded this performance model (2005) to predict wood performance in Australia, but the utility of this model is limited because much of the data used to develop the model was based on visual decay assessments, providing little information for a structural engineer seeking more definitive data on wood condition.

Although the effects of fungal attack on strength properties have been widely studied, there is a surprising lack of comparative data that can be used to predict the effects of decay in buildings based upon time of wetting and temperature. Often, studies concentrated on one fungus or one wood species exposed under a limited set of environmental conditions. The other factor complicating this work is the tendency of most studies to use mass loss as a primary measure of fungal attack. While mass loss is easily measured, there is ample evidence showing that fungi cause dramatic losses in the mechanical and flexural properties of wood at very early stages of attack when there is

minimal mass loss. Thus, models using mass loss data may seriously underestimate the impacts of decay. In addition, data on mass losses provides little useful information on the degree of damage or residual service life of a structure that has been subjected to decay.

Visually estimating decay to predict condition produces similar under-estimates of damage, leading to a higher risk of determining that a weak structure is sound. This makes it difficult to provide accurate data for engineers and designers to determine whether the degree of damage in a given structure requires retrofitting or replacement. Developing effective data on the effects of fungal attack on wood properties under a range of environmental conditions would allow the development of models to predict the effects of decay in various wood assemblies.

The objectives of the current study were to determine and document strength losses and chemical changes in wood during fungal attack under various temperature and moisture conditions, to use the data to build mathematical models to predict flexural losses in wood and to compare the models to previously developed data. Our hypothesis is that strength losses of wood would be greater on western hemlock and southern pine wood at warmer temperatures. We also hypothesized that fungal attack would be optimal at specific moisture regimes that were dependent on the fungal species and that

the wood properties most affected would be modulus of rupture > modulus of elasticity > mass loss.

Chapter 2 – Literature Review

Biodeterioration of Wood

Biodeterioration alters the properties of wood due to the activities of organisms (Hueck, 1968; Allsopp et al., 2004). In the US, it is estimated that 10% of timber cut each year is used to replace wood that has deteriorated in service (Zabel and Morrell, 1992). Deterioration includes diminished aesthetic appeal and, most importantly, reduction of structural properties. Recent estimates quantify these losses to be over $5 billion annually (Schultz and Nicholas, 2008). Deterioration of wood can be caused by a number of organisms, but decay fungi are considered to be the major contributors (Cartwright and Findlay, 1946; Zabel and Morrell, 1992).

Decay fungi. Not all fungi can degrade wood, but those that do are broadly divided into functional groups based upon their ability to degrade the primary wood polymers. Some degrade the carbohydrate polymers, while others degrade all three wood polymers. In forests, biodegradation of woody material by decay fungi recycles sequestered CO_2 to the atmosphere and contributes to the improvement of forest soils by incorporating humic material (Bagley and Richter, 2002).

Biodegradation in wood structures has serious implications for life, safety, performance and service life. Wood decay fungi can degrade one or more of the various wood polymers and cause changes in physical and chemical properties of wood. The most important wood destroying organisms are classified into three types: soft-rot, brown-rot and white-rot fungi (Morris, 1998;Zabel and Morrell, 1992).

a) Soft-rot fungi. Soft-rot fungi are ascomycetes that can grow throughout the wood, but their damage occurs in the secondary walls of tracheids and fibers, resulting in cell wall erosion or cavity formation. Soft-rot damage tends to occur in very wet wood near the wood surface. Although soft-rot fungi severely damage the wood they attack, the damage is often shallow and the softened surfaces can be scraped away, leaving sound wood underneath. Soft-rot fungi are commonly found in wood used in farm soils and cooling towers where environmental conditions limit growth by other wood decay fungi (Hunt and Garratt, 1967; Morrell, 1981).

b) Brown-rot fungi. In the northern hemisphere, brown-rot fungi are the most commonly found and destructive type of decay fungi in structural wood (Goodell, 2003). Ten percent of all wood-decay fungi cause brown-rot and 80% of them occur on coniferous wood (Goodell, 2003). Brown-rot fungi are basidiomycetes and their decay is characterized by the attack of

carbohydrates (cellulose and hemicelluloses) in cell walls, leaving behind a lignin-rich brownish residue.

Brown-rot fungi initially attack wood by extensive depolymerization of carbohydrate components at a distance from the hyphae. This results in rapid loss of strength with little mass loss. It has been proposed that initial depolymerization of wood is caused by diffusible low molecular weight agents since hydrolytic enzymes are too large to enter the cell wall matrix. (Cowling and Brown, 1969; Koenigs, 1974; Schmidt et al., 1981). These non-enzymatic hydroxyl radicals dissociate carbohydrate chains, opening up pore structures in the cell wall to allow access by large enzymes (Stone and Scallan, 1965, 1968a,b; Kerr and Goring, 1975; Cowling, 1961; Cowling and Brown, 1969; Cowling and Kirk, 1976). Hydroxyl radicals are believed to be produced by extracellular Fenton chemistry (Goodell et al., 1997; Arantes and Milagres, 2006a,b, 2009). As a result, the non-crystalline cellulose component is often heavily degraded prior to enzymatic penetration into the cell wall (Arantes et al., 2010).

Although lignin was thought to be slightly modified by brown rot fungi, recent studies suggest that lignin is extensively attacked, modified and repolymerized without cleavage of the phenolic ring. Hydroxyl radicals, generated through the action of Fenton chemistry are believed to catalyze

removal/modification of propyl side chains and methoxyl groups, followed by repolymerization. This mechanism allows brown rot fungi to attack cellulose and hemicellulose components without using metabolic energy to produce a large array of lignin-specific degrading enzymes (Arantes et al., 2010; Arantes and Milagres 2006a; Jin et al., 1990; Gierer et al. 1992; Gierer 1997; Lanzalunga and Bietti 2000; Machado et al. 2000). Lignin has also been found to undergo some side chain oxidation promoted by Fenton-based reactions (Arantes et al., 2009).

c) White-rot fungi. White-rot basidiomycetes are the largest group of wood decay fungi and decompose all wood polymers. Some species degrade all three polymers at the same rate, while others preferentially attack lignin at the early stages of decay. White rot fungi leave the wood white and fibrous. The attack of white-rot fungi is divided into two mechanisms: selective and simultaneous lignin degradation.

In selective lignin degradation, the fungus preferentially degrades lignin and hemicellulose components of the cell wall. It has been suggested that the mode of attack must occur though low molecular weight metabolites (i.e. phenolates), similar to the mechanism described for brown-rot fungi (Blanchette et al., 1997; Goodell et al., 2006; Arantes et al., 2010) since lignocellulolytic enzymes are also too large to penetrate the intact structure of

cell walls. This supports the hypothesis that low molecular non-enzymatic compounds are the first fungal chemicals to affect the wood. Free radical generation results in the diffusion of lignin fragments (Arantes and Milagres, 2006a, Arantes et al., 2010).

In simultaneous degradation, the fungus progressively degrades all wood cell wall polymers. Enzymatic action is responsible for the attack and gradual erosion of wood cell walls (Arantes et al., 2010). Ligninolytic enzymes cleave oxidative aromatic rings in the lignin structure. The extracellular ligninolytic system consists of phenoloxidases (laccases), manganese peroxidases, lignin peroxidases, and H_2O_2 (Gold and Alic, 1993; Scheel et al., 2000). The role of a specific enzyme in lignin degradation depends on the fungus. Generally, the most important enzymes are laccases and manganese peroxidases (Scheel et al., 2000).

Fungi associated with decay in buildings in the US

Fungi most commonly associated with decay in buildings in the US include *Meruliporia incrassata*, *Coniophora puteana*, *Gloeophyllum trabeum*, *Postia placenta*, *Serpula lacrymans*, *Paxillus panuoides*, *Antrodia serialis* and *Antrodia vaillantii* (Duncan and Lombard, 1965). The most common fungi found in freshly felled Douglas-fir trees and poles are *Antrodia carbonica* and

Postia placenta (Morrell et al., 1988, 1987; Przybylowicz et al., 1987). All of these fungi cause brown-rot. One of the most common white-rot fungi found in the US is *Trametes versicolor* (Cowling, 1957; Wilcox and Dietz,1997). Three of the most common fungi, *Postia placenta* (Fr.) M. Larsen and Lombard)(Madison 698), *Gloeophyllum trabeum* (Pers.:Fr.) Murr. (Madison 617), and *Trametes versicolor* (L:Fr.) Pilat (Madison R-105), were studied in this research project.

Factors Affecting Growth and Survival of Wood Decay Fungi

The major factors for successful growth and survival of wood rotting fungi are a food source, free water, oxygen, and moderate temperatures (USDA, 2010; Zabel and Morrell, 1992). If any of these requirements are removed, the fungus may be killed or forced into a dormant stage. Chemicals can be used to treat wood to limit fungal attack, but most wood used in wood framed construction is untreated (Zabel and Morrell, 1992).

Oxygen is seldom a limiting factor in wood buildings. Oxygen levels in sound wood can be as high as 17% and less then 1% in decaying wood (Thacker and Good, 1952; Hintikka and Korhonen, 1970). Most fungi can grow at much lower regimes. The minimum concentration for fungal growth is

between 0.4 and 1.3% (Scheffer and Livingston, 1937; Snell, 1929; Jensen, 1967).

Since non-treated wood is generally utilized for structural building purposes under aerobic conditions, the only factors that can be controlled/modified are free water and temperature. Temperature can be controlled in a structure, but it is difficult to create temperature conditions that limit fungal attack while allowing the structure to be inhabited. Most buildings are designed to shed or exclude water, limiting conditions that are suitable for decay.

Water

Water is essential for fungal growth in wood. It is a reactant in hydrolytic breakdown of complex carbohydrates into simple sugars for fungal assimilation. Free water acts as a diffusion medium and solvent in order to release digestive enzymes and subsequently absorb solubilized substrate decomposition products. It is necessary for various fungal metabolic processes such as respiration, synthesis and growth. In addition, water facilitates the penetration of degradative compounds into the cell wall by swelling and enlarging small capillaries in the wood (Zabel and Morrell, 1992).

Water is generally the key limiting factor for decay in structural wood. Wood is a hygroscopic material due to the presence of hydrophilic groups within the lignocellulosic matrix (Skaar, 1972; Griffin, 1977; Schniewind, 1988). In wood, water exists as free liquid or vapor in the lumens or as bound water in the cell walls. Below the fiber saturation point (~30% for most softwoods) free water is not available, limiting the growth of decay fungi. The ideal moisture content for most fungi is between 40 and 80% (Scheffer and Verrall,1973; Zabel and Morrell,1992). Increasing moisture content eventually limits oxygen availability, decreasing the rate of decay (Eaton and Hale, 1993). Moisture absorption is a function of the size and proportion of wood pores and the chemical composition of the wood structure (Siau, 1971; Hartley el. al., 1992; Wadso, 1993; Viitanen and Ritschkoff, 1991). The upper moisture content limit for optimum growth in Douglas-fir is 70%, while inhibition of decay occurs at moisture contents greater than 110% (Snell, 1929). The upper limit of fungal growth in a given wood species is inversely related to specific gravity, which is related to void volume. Woods with lower void volumes will tend to reach lower maximum moisture levels than wood with larger void volumes (Snell, 1925).

Temperature

Temperature affects the rate of growth and the predominant species of fungi that will attack the wood (Cartwright and Findlay, 1934). Temperature is considered the second most important limiting factor that influences fungal

activity. Metabolic activities that are mediated by enzymes such as digestion, assimilation and synthesis are directly affected by temperature. The optimum temperatures for wood decay generally range between 20 and 35 ^{o}C (Zabel and Morrell, 1992; Morris, 1998; Brischke et al.,2006). Each 10 ^{o}C drop in temperature reduces fungal growth by half. Fungi become dormant at temperatures below 5 ^{o}C. The upper growth limit is 46 ^{o}C, but many fungi are not killed until they reach 67^{o}C (Morris, 1998). Elevated temperatures cause irreversible denaturization of proteins. Cold temperatures result in cessation of growth, but are generally not lethal unless the organism depletes storage reserves during dormancy.

There have been attempts to determine the relationship between temperature and the rate of wood decay, but the relationship is poor and inconsistent because few experiments evaluated a sufficient range of environmental conditions (Snell, 1922; Fritz, 1924; Lindgren, 1933).

Minimum, optimum and maximum temperatures for wood decay vary according to fungal species. *Gloeophyllum trabeum* has the ability to grow at relatively high temperatures, with an optimum of about 35 ^{o}C and some growth at 40^{o}C (Lindgren, 1933; Cartwright and Findlay,1934). *Trametes versicolor* grows rapidly in culture and has a wide temperature range. The optimum temperature for this fungus is between 28-30^{o}C. The appearance of the

mycelial mat varies according to the temperature at which it grows (Lindgren, 1933; Cartwright and Findlay, 1934). *Postia placenta* produces chlamydospores at elevated temperatures, which facilitates survival during prolonged exposure to elevated temperatures and other adverse conditions (Powell, 2002). This fungus is also tolerant of many copper compounds.

Decay in Buildings

Although wood has been used as a building material for thousands of years due to its availability, ease of use, strength and great insulating properties, its susceptibility to degradation has led consumers and building designers to view wood as inherently less durable than steel or reinforced concrete.

One of the most important considerations when wood is used in construction is service life. Events such as the earthquakes in Northridge, California (1994) and Kobe, Japan (1995), or hurricanes such as Katrina, in Louisiana (2005) have increased the awareness of the effects of decay on structural performance of wood in intense events. Countries like Australia and Canada are even considering explicitly including durability requirements in building codes (Foliente et al., 2002a).

Currently, the methods for design and service life planning are very simple and most do not consider any fundamental mechanisms of biodegradation or the factors that affect these mechanisms (Bennett et al., 2001; Foliente et al., 2002b). There is a need for durability-related information and knowledge to help wood users understand how structures will perform over time.

Decay problems in buildings are caused mainly by moisture intrusion due to poor design or failure of the building envelope. The causes can include water leakage, convection of damp air and subsequent moisture condensation and moisture accumulation in structures due to insufficient ventilation. Decay problems tend to be concentrated in parts of the structure that accumulate water. These parts include joints, end-grain and lower parts of panes in wooden windows, sub-floors and attics with poor ventilation, lower parts of floors and walls and locations affected by water leakage (Cartwright and Findlay, 1946; Viitanen, 1986; Singh, 1994).

Decay problems in buildings can be very complicated. The microclimate is affected by moisture migration and accumulation, composition, texture and surface quality of the material, temperature, humidity, water condensation and air circulation (Handegord, 1983; Grant et al., 1989). Water is the main driving force supporting germination, hyphal growth and sporulation of fungi. Humidity

is critical for the formation, release and survival of spores. Zabel and Morrell (1992) have estimated that 90% of damage in houses is due to temperature and moisture effects.

Although it is difficult to find data, there is a general perception that the incidence of decay in houses is increasing. The increase may be due to social and economic trends towards energy efficient homes and to changes in home design. These new building techniques tend to increase moisture trapping, compromising the service life of the home (Viitanen, 1986, 1994; Grant et al., 1989).

Changes in building design incorporate vapor and water barriers and insulation, reducing airflow and ventilation, increasing moisture retention within the structure and providing a suitable environment for fungi to develop (Viitanen, 1986, 1994; Grant et al., 1989). Many building design concepts for energy efficient homes directly conflict with those for durability. For example, homes designed for durability have steep roof slopes (30-40^{o}) and encourage cross ventilation to prevent moisture accumulation, while energy efficient homes need shallow slopes to reflect light and reduce the outside temperature of exterior walls (Lewis, 2007).

Aesthetic and economic factors also affect durability. Most homes are now built with short overhangs to reduce material costs whereas homes designed for durability incorporated longer roof overhangs to channel rainwater runoff away from the foundation, protecting the siding and windows and controlling solar heating inside homes (MHRA, 2000).

Moisture Movement in Buildings

Water movement in buildings follows multiple pathways, but it will eventually reach equilibrium with its surroundings. Water moves through wood by liquid flow, capillary action, and air movement.

Liquid flow is driven by gravity, causing water to move downhill. For example, water condensation on a window pane will flow onto the sash and move down the wall. Movement of moisture in wood is a function of several factors including negative/positive pressure inside a building, the stack effect (rising of less dense hot air) and external wind speed. Capillary suction occurs when wood acts like a sponge, moving water upward against gravity. In the case of vapor diffusion, water molecules diffuse to areas of greater concentration through permeable materials (MHRA, 2000). Liquids and vapors can move through wood capillary structures by means of pressure, permeability, and diffusion. Cell wall passage is restricted to diffusion. Water,

as vapor or bound water, can move into wood through cell walls or through capillary structures. Fiber cavities, cell walls, and the pit system (pit chambers, pit membrane openings, pit membrane substance) are all involved in moisture diffusion through wood (Stamm and Raleigh, 1967a,b)

The development of decay is invariably connected to moisture related problems in a structure. In all cases, there must be a moisture source, a mode of moisture transport, and a site where moisture accumulates. Water tends to dissipate when in contact with a surface, resulting in evaporation. Most building materials tolerate occasional wetting and can accumulate moisture until a tolerance level is reached (MHRA, 2000). Fungi may grow and cause degradation above this level. Moisture intrusion influences the physical, mechanical, and chemical properties of wood. The process of degradation can be inhibited by keeping wood at low moisture contents (<28%) (Zabel and Morrell, 1992; Carll and Highley,1999). It is important to remember that wood absorbs moisture more rapidly than it can release it and needs more time to dry than to wet (MHRA, 2000).

Decay and Strength Properties

The effects of decay on wood strength and the rate at which it occurs are major concerns for wood scientists, structural designers and engineers.

Some mechanical properties decrease dramatically at the early stages of decay without noticeable changes in wood appearance (Wilcox, 1978). This early stage poses structural dangers due to sudden failure of otherwise sound appearing material. Extensive studies have focused on evaluating the effects of early decay on changes in wood properties (Scheffer, 1936; Henningsson, 1967; Green et al., 1991).

In the late 1950's, mass loss was regarded as the principal measure of wood decay (Hartley, 1958). The early stage of decay, also called incipient decay, is the decay occurring at or below 10% mass loss (Wilcox, 1978). The property most sensitive to incipient decay is toughness or "the ability to withstand shock loading" (Bowyer et al., 2003). Several examples are described in Wilcox's review (1978) on the effects of early decay on strength. Richards (1954) tested brown rot and white rot fungi on a softwood and found a reduction of 50% in toughness with only 1% mass loss. Clearly, flexural properties are more sensitive to initial fungal attack.

The focus of the present study was on static bending, which is considered the second most sensitive property to incipient decay (Wilcox, 1978). Static bending measures wood strength and stiffness. The static bending properties addressed in this study were modulus of rupture and modulus of elasticity. Modulus of rupture (MOR) is the mechanical property

that describes the maximum load a beam can carry before it fails, commonly referred to as strength. Modulus of elasticity (MOE) is the elastic property that describes the resistance to bending, or stiffness (Bowyer et al., 2003).

Cartwright et al. (1931) found that MOE was reduced by 55% and MOR by 50% at 2% mass loss. At 6% mass loss, there was a reduction of 66% on MOE and 61% on MOR, and wood lost 70% of its original strength at 10 % mass loss. Mulholland (1954) did not find such extreme strength and stiffness losses, but MOR and MOE reductions were 13% and 4%, respectively, at 2% mass loss.

Winandy and Morrell (1993) found a linear relationship between 1-18% mass loss with 5-70% strength loss in small Douglas-fir beams exposed to decay. In this study, 35% MOR loss and 20% MOE loss were achieved after almost three months of exposure to a brown rot fungus. Exposure to a white rot fungus resulted in MOR losses of 27%.

Winandy et al. (2000) exposed wood under controlled moisture, temperature conditions and found that considerable bending strength losses occurred before detectible mass losses. MOR losses of up to 40% and MOE losses of 20% occured at only 7% mass loss after 12 weeks of fungal

exposure. Smith et al.(1992) found that MOR and MOE declined 28% and 12%, respectively, after 5 months of exposure of Douglas-fir to brown rot fungi.

A variety of previous studies indicate that substantial strength losses occur during the incipient decay stage when fungal attack is difficult to detect (Winandy and Morrell, 1993; Wilcox, 1978; Winandy et al., 2000; Cartwright et al., 1931). By the time decay is visible, wood failure is imminent. A system (or model) to predict strength losses caused by fungal attack could help prevent sudden failures of structural wood members in service.

Prediction of Service Life

Service life is the period of time after installation during which a building or its parts meets or exceeds the performance requirements specified during the design phase (ISO, 2000; Beall, 1998). There are several approaches for predicting durability of individual wood species using laboratory tests such as the European Standard Hazard Classes and the corresponding ASTM durability classes (ASTM D-2017, EN113, EN 335), but these do little to predict performance in structures. These standards only categorize wood into very resistant, resistant, moderately resistant and non-resistant wood according to use conditions and moisture regimes.

One of the best known models for estimating decay in wood structures above ground is the Scheffer Climate Index (Scheffer, 1971). This was one of the first attempts to use the mean monthly temperature and number of days per month with 0.01 mm or more of precipitation to produce an index that predicts decay risk for non-painted wood exposed above ground. The model is attractive because it is simple and uses widely available weather data, but is limited to exposed untreated wood.

Leicester (2005) used the Climate Index as the basis for a prediction model that evaluated structural collapse, unserviceability and aesthetic deterioration. The drawback of this model is the lack of background information and data on decay rates. The durability inputs for this model were primarily derived from field stake and above ground trials that relied on visual estimates of decay, not estimates of wood properties as a result of that damage.

In 2000, the International Organization for Standaridzation (ISO) published standards 15686-1 and ISO 15686-2 (ISO 2000b,c) to address service life in buildings. These standards introduced a simple method (“factor method”) that estimated the service life of buildings and their components. This approach was a multiplicative model based on seven modifying factors (quality of components, design level, work execution level, indoor environment,

outdoor environment, in-use conditions and maintenance level) that affect service life. The model adjusts a reference service life, or estimated value based on data gathered from manufacturers, experience, expert opinion, publications or building codes, to an estimated service life. The disadvantage of this model, like all previous models described, is that it estimates service life based on judgement, not quantifiable, scientific data (Hovde, 2002).

The first factor to consider when developing a service life prediction model is durability hazard (Foliente et al., 2002a,b). Durability hazards for wood include fungal and insect attack, marine borer attack, fastener corrosion, chemical and mechanical damage, wind load and seismic loads. A pathology of degradation (causes, processes, development, and consequences) needs to be established for each durability hazard. Finally, the performance of wood under each durability hazard must be quantified for different environments and exposure levels (Frohnsdorff and Martin, 1996). The main focus of the present study was to document strength losses caused by decay fungi. These data can be used to help establish durability hazards for fungal attack.

Even though decay has been studied for more than a century, there is little comparative data on deterioration caused by decay fungi at various temperatures and moisture contents. The purpose of this work was to build a set of reliable comparative data and model the effect of exposure time on the

growth of decay fungi (*P. placenta*, *G. trabeum* and *T. versicolor*) in Douglas-fir, western hemlock and pine wood subjected to different humidity and temperature conditions. This research incorporates the areas of wood science, engineering and mycology to assess the effects of fungal attack on strength properties (modulus of elasticity and modulus of rupture) of microbeams of three of the most common wood species used for structural applications in the United States. This information was used to develop predictive models using time of wetting and temperature as tools to evaluate losses in strength.

Chapter 3 – Materials and Methods

Specimen Preparation

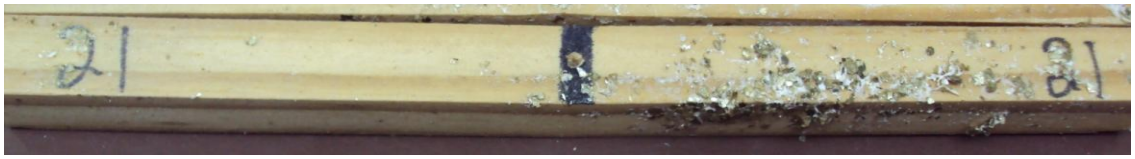
Douglas-fir heartwood (*Pseudotsuga menziensii*)(Mirb.) Franco, western hemlock (*Tsuga heterophylla*) (Raf.) Sarg sapwood/heartwood and southern pine (*Pinus spp.)* sapwood were kiln-dried prior to use. Douglas-fir and western hemlock lumber was locally obtained from the Coast Range of Western Oregon. In order to ensure that western hemlock was not a mixture of hem-fir, wood was hand-picked from the green chain of a mill that almost exclusively cut western hemlock. Southern pine wood was obtained from the southeastern United States (North Carolina), but was not identified to species.

Lumber was cut into 10 x 10 x 160 mm long specimens free of knots and juvenile wood. The 10 x 10 mm dimensions were oriented as close as possible to true tangential or radial orientation. Juvenile wood was discarded due its variable strength properties (Bendtsen et al. 1988). One thousand four hundred and fifty-eight (1,458) beams were cut from each wood species. Because of the variable recovery of beams from each parent board, no attempt was made to end-match samples. Forty-eight beams were randomly allocated to each of the treatments where they were inoculated with one of three decay fungi (*Postia placenta* (Fr.) M. Larsen and Lombard) (Madison 698),

Gloeophyllum trabeum (Pers.:Fr.) Murr. (Madison 617), and *Trametes versicolor* (L:Fr.) Pilat (Madison R-105). The inoculated beams were incubated in vermiculite at a moisture level which preliminary trials had shown would produce one of three wood moisture content ranges (30-40, 60-80, and 100-130%) at one of three temperatures (15, 25, and 35 ^{o}C). The experimental design was a complete randomized block with equal replication.

The remaining beams served as non-inoculated controls. Three bags with 6 control beams each were allocated randomly to one of the 27 groups consisting of one of three levels of temperature (15, 25 or 35 ^{o}C), one of three levels of moisture content (30-40, 60-80 or 100-130%), and one of three wood species (Douglas-fir, western hemlock or southern pine). Each treatment consisted of eight bags containing six microbeams. The bags were considered the experimental unit and the microbeams were the sampling units.

Once allocated in their groups, all beams in that group were numbered from one to forty-eight and then were oven dried (105 ^{o}C) and weighed (nearest 0.001g). Oven-dried mass was recorded to enable us to determine the subsequent moisture content and mass loss of beams gravimetrically for each harvest. A single 2 mm diameter hole was drilled 5 mm into one tangential face of each beam 80 mm from one end of the beam for later fungal inoculation (Fig.1).



1a

1b

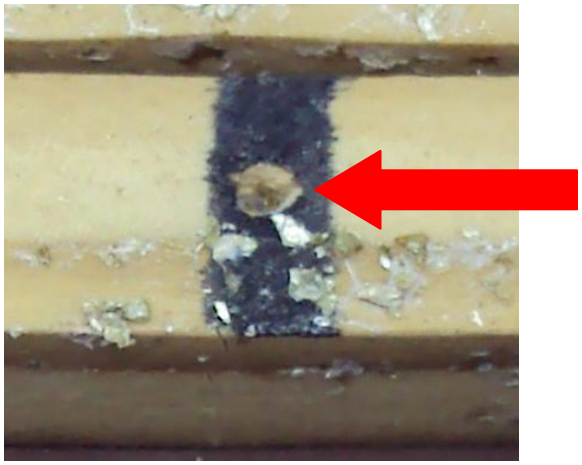


Figure 1. Visual representation of a) microbeam (160 x 10 x 10 mm) with an b) inoculation hole (2 mm in diameter)

Preparation of Media

A modification of a method described by Curling et al. (2000) was used where 100 g of vermiculite were placed in a transparent, autoclavable incubation bag (535 x 210 x 120 mm) that was fitted with a microporous filter patch that allowed for gaseous exchange, but excluded contaminating fungi and bacteria.

Prior to beginning sample preparation, several preliminary tests were performed in order to determine the water holding capacity of the vermiculite

that would allow the microbeams to reach the target moisture content, the minimum for the samples to reach target moisture content and the quality of the sealing process.

The moisture holding capacity (WHC) of vermiculite was determined following the method described in ASTM Standard D2017-05 (ASTM, 2005). Water was added to the vermiculite in the autoclavable bag to bring the moisture content of vermiculite up to 24, 60, and 73% of the predetermined WHC so that the beams would reach the target moisture content (30-40, 60-80, and 100-130% respectively). Once WHC of vermiculite was determined, six beams from a given wood/fungal species and temperature/moisture content combination were introduced in a bag which was then autoclaved for 60 minutes at 121^{o}C. Two bags per wood species were prepared for each of the three moisture content regimes. Every three days, three microbeams were extracted from the bags and weighed to determine moisture content. All microbeams reached a minimum of 40% moisture content by day six. Beams could be mechanically tested once they had been conditioned in the vermiculite for a minimum of five days because the wood was over the fiber saturation point (Bowyer et. al., 2003; USDA, 2010).

In preliminary trials, bags were inoculated by unsealing, inoculating, and then heat sealing the inoculated wood in thermal sealed autoclavable bags.

Three bags each containing six microbeams and 100g of vermiculite at 60% WHC were autoclaved and end sealed with a thermal impulse sealer. Another three bags were prepared, but sealed by tightly twisting the end of the autoclavable bags, folding the end and using a rubber band to keep it in that position (Fig. 2). The bags were incubated at 28^{o}C for 15 days. The rubber band method proved to be more efficient than a thermal impulse sealer at excluding contaminants out. None of the bags sealed with the rubber band experienced contamination, while two of the bags that were thermally sealed had microorganisms growing on the microbeam surfaces. Once WHC, time to reach target moisture content and the sealing technique were determined, we proceeded with sample preparation.

Six wood specimens of the same species were placed in each bag containing 100 g of vermiculite at one of the three levels of WHC. The bags were autoclaved for 45 minutes at 121^{o}C. Bags were stored for two weeks prior to inoculation to allow the beams to condition to the target moisture content before introducing the test fungus.

Figure 2. Autoclavable bag end-sealed with a rubber band.

Fungi

The brown-rot fungi used to inoculate beams were *Postia placenta* (Fr.) M. Larsen and Lombard)(Madison 698) and *Gloeophyllum trabeum* (Pers.:Fr.) Murr. (Madison 617). These two fungi are commonly isolated from coniferous wood exposed out of ground contact (Duncan and Lombard, 1965). The white-rot fungus utilized was *Trametes versicolor* (L:Fr.) Pilat (Madison R-105). This fungus is the most commonly isolated white rot fungus in North American buildings (Cowling, 1957; Wilcox and Dietz, 1997).

Fungal inoculum was prepared by adding several 4 mm diameter disks cut from the actively growing edge of a culture of the test fungus into a flask

containing 125 mL of 1.5 percent malt extract solution. The flasks were incubated in stationary culture at 28^{o}C for ten days. The resulting mycelium was collected by filtration and rinsed with 300 ml of sterile distilled water in order to remove any residual nutrients. The resulting mycelium was placed in 250 ml of sterile distilled water and then macerated in a blender to break up individual hyphae. The blender container was sterilized (30 minutes at 121^{o}C) between batches. The hyphal suspension was placed in an autoclaved jar and stored at 5^{o}C until use.

The hyphal suspension from each jar was tested to determine viability of the inoculum. One mL of fungal suspension was distributed on growth media in a petri dish. A glass spreader was used to homogeneously distribute the hyphal suspension in the plate. The plate was incubated for 10 days at 28^{o}C and the number of colonies was monitored. The inoculum was considered to be viable if at least ten colonies where detected.

Biological Exposure

Each bag containing six beams was inoculated with one of the three hyphal suspensions. In order to prevent contamination, inoculation was done in a laminar flow hood. A pipetter was used to deliver 100 µL of blended inoculum into each inoculation hole. The middle section of the specimen,

where the hole was located, was covered with a 20 mm deep vermiculite ridge. Bags were end-folded and sealed immediately with a rubber band to prevent contamination (Fig.2). The bags were placed into one of three temperature controlled conditioning chambers maintained at 15, 25, or 35^{o}C. Incubation periods for both brown and white rot fungi were 0, 6, 12, 18, 24, 30, and 36 weeks. Bags were periodically opened under a laminated flow hood to allow for air exchange and maintain aerobic conditions for the test period.

Destructive Evaluation

One bag per treatment was extracted from each temperature controlled chamber at a given time point to determine the effects of fungal exposure on flexural and physical properties of the microbeams. The six microbeams were tested to failure in three point bending following the procedures described in ASTM Standard D 143 (2009) over a 130 mm span at a speed of 2 mm/min at a single point in the center on a Karl Frank Universal Testing Machine (1981) with a maximum load of 50,000 N. Tests were performed at the Cellulose and Paper Department of the University of Guadalajara. All tests were carried out inside the bags to prevent the microbeams from drying or being contaminated by other fungi.

In three-point bending tests, microbeams rested on two supports and the force was applied from a single point in the center perpendicular to the fungal inoculation hole. In this system, the maximum bending moment (force) was directly under the load head, coinciding with inoculation hole in the beam. The inoculation hole was located in the neutral axis. This approach ensured that the test load was applied directly above the site where the fungus was originally introduced. Six beams were tested to failure per treatment group and these data were then used to determine the proportional limit. This value was used to determine the loading used for the remaining beams in each treatment that were tested non-destructively.

The microbeams tested to failure were removed from the bags, weighed and oven-dried to determine moisture content and mass loss. These beams were later used for chemical analysis.

The stress-strain curves obtained from the tests were used to calculate the modulus of rupture of each beam and identify the linear segment, or proportional limit, of the stress-strain curve. The formula used to calculate MOR is shown below.

$$\text{MOR} = \frac{3PL}{2bd^2}$$

MOR was measured in N mm^{-2} (MPa), where P was the load (N), L was the span (mm), b was the width (mm), and d was the depth (mm).

The load at 30% of the proportional limit was calculated and later used as a load limit for the non-destructive test. This calculation was done to ensure that the limit of recoverable strength was not exceeded so that beams regained their original dimensions and form.

Nondestructive Evaluation

All beams in a given treatment were non-destructively evaluated using a three point bending test at each time point (0, 6, 12, 18, 24, 30, and 36 weeks). The maximum load applied to the microbeams was equal to 30% of the load under the proportional limit, as previously described.

The resulting stress-strain curves from the non-destructive tests were used to calculate modulus of elasticity (MOE) for each beam using the formula below.

$$E = \frac{P' L^3}{4\Delta' bd^3}$$

Where E is the MOE in bending (N mm^{-2}), P' is the load (N) at the limit of proportionality, L is the span (mm), Δ' is the deflection (mm) at the limit of proportionality, b is the width (mm), and d is the depth (mm).

Testing was performed inside the sealed bag to maintain sterility and prevent contamination. Every harvest contained one less autoclavable bag containing six microbeams than the previous sampling period due to destructive tests performed at each time point (Fig. 3). MOE and MOR at each time point were expressed as a percentage of the original value determined for each species.

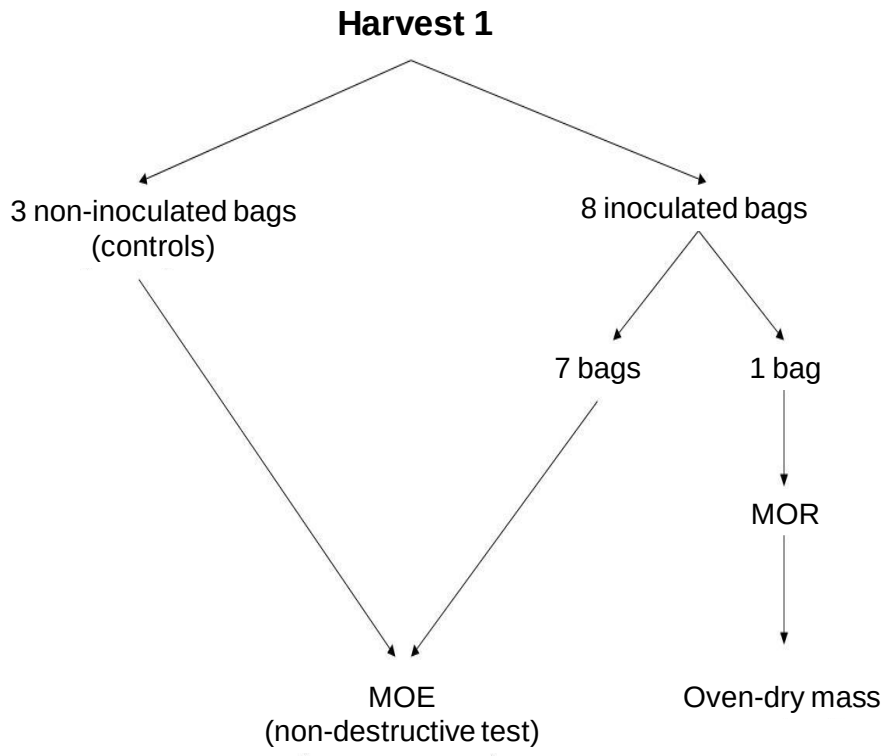


Figure 3. Number of samples and tests performed on the beams for the first harvest (after 6 weeks of inoculation) of a treatment.

Chemical Analyses

The potential effects of fungal exposure on chemical composition of the wood were determined using alkali solubility and acid-insoluble lignin tests. The alkali solubility test has been used to assess the effects of fungal attack on the carbohydrate portion of the wood, while the acid insoluble lignin test estimates the total lignin content in wood. Beams decayed by *P. placenta*, *G. trabeum* or *T. versicolor* at 25^{o}C were selected at random and tested for lignin

content and alkali solubility. Sample beams from all non-inoculated treatment combinations after 36 weeks of exposure to one of three temperatures and moisture content regimes were also tested for alkali solubility and lignin content to determine if they had undergone any chemical changes during the experiment.

The middle 60 mm section of each of the microbeams that were previously tested for MOR was cut and ground to pass a 40 mesh screen. Due to the severe mass losses at the advanced stages of decay a decision was made to combine ground material from the six microbeams from a given autoclavable bag for each fungal-exposure combination.

For alkali solubility (ASTM Standard D 1109-84, 2007), one gram of wood ground to pass a 20 mesh screen was introduced in a beaker containing 200 mL NaOH (1%) and placed in a boiling water bath for 1hr with periodic stirring. The contents were then filtered by suction on a tared crucible and washed with 100 mL hot water, then with 50 mL of acetic acid (10%) and finally with hot water. The crucible with the ground material was dried to constant mass at 103^{o}C and alkali solubility was calculated using the following formula:

$$\text{Matter soluble in caustic soda, \%} = [(W1 - W2)/W1] * 100$$

where:

W1 = weight of moisture-free wood prior to test

W2 = weight of dried specimen after treatment with NaOH solution

Higher alkali solubility signifies more decay or degradation of the carbohydrate fraction of the wood.

Acid-insoluble lignin was assessed on a 1g wood sample following procedures described in TAPPI Standard T-222 OM-02 (TAPPI 2006) to estimate total lignin content. Fifteen mL of 72% sulfuric acid was added to the ground wood while macerating the material. The material was dispersed and heated in a water bath at 20 ± 1oC for 2 hours with frequent stirring. The material was transferred to a flask with 300 to 400 mL of water and diluted to 3% sulfuric acid content in a total volume of 575 mL. The solution was then boiled for 4 hours while maintaining constant volume by periodic addition of water. Insoluble material was allowed to settle and the solution was filtered through a fritted glass filter and washed with hot water. The crucible with the lignin was oven dried (105 ± 3 ^{o}C) to constant weight. Weight was recorded and lignin content was calculated using the formula:

Lignin, % = A 100 / W

where:

A = Final oven dry weight (g)

W = Initial oven-dry weight of wood (g)

In addition to these tests, seven randomly selected western hemlock samples at various stages of decay (*G. trabeum* at week 0, 6, 12 or 18, and *T. versicolor* at week 0, 12 or 18) were sent to IPS Testing Experts (Appleton, Wisconsin) for cellulose and hemicellulose determination. The results obtained from these tests were compared with changes in flexural properties in relation to losses of the various hemicelluloses and cellulose components.

IPS Testing Experts followed TAPPI Test Method T 249 cm-00 (TAPPI, 2000) for carbohydrate composition of extractive-free wood and wood pulp by gas-liquid chromatography. The analysis was performed on approximately 300 mg of sample, milled to a 40 mesh. The samples underwent hydrolysis, neutralization, reduction, and acetylation prior to analysis on a Flame Ionization Detector-Gas Chromatograh (FID-GC). The acid soluble portion of the samples was used to determine the carbohydrate content. The percent of the five constituent sugars (arabinan, xylan, mannan, galactan, glucan, and cellulose) as determined by carbohydrate analysis were reported.

Vermiculite pH was determined using a pH meter by mixing 1 g of dry vermiculite with 9 g of water. In order to assess the effect of vermiculite on alkali solubility of wood, a laboratory test was designed. Three 60 by 10 by 10 mm sections of Douglas-fir microbeam were introduced in a flask containing 200 mL of vermiculite leachate. The flask was agitated for 24 h at 150 RPM at room temperature. Another flask with the same number of beam sections and same amount of vermiculite leachate was left at room temperature without agitation. Leachate pH was measured before and after the 24 h. The Douglas-fir sections were then ovendried, ground and tested for alkali solubility as described earlier.

Statistical Analyses

Experimental Design

The experiment was organized as a full factorial design with main effects of temperature at three levels, inoculation at three levels, moisture content at three levels and incubation at seven levels (Table 1). Samples were inoculated with either *P. placenta, G. trabeum* or *T. versicolor*. Seven incubation times were considered for the examination of flexural properties at various levels of decay. The set alpha level for test significance in this study was 0.05. Flexural values of 3 bags (experimental unit) containing 6 microbeams (sampling units)

were collected at each treatment combination. The average value of the 6 microbeams was reported as the bag MOE value. The total number of data points was 2268.

Data were analyzed using PROC MIXED (SAS, 2008) where bag was the random variable. Since convergence criteria, or the maximum-likehood algorithm, was not met, the data were partitioned depending on wood species. Within wood species, further partitioning of the data was based on trends. The most determinant factor was temperature. Thus, the analysis was partitioned by the temperature factor.

Due to unconstant variances at each time point, all MOE values were log transformed and a TYPE=UN(2) was used to specify for an unstructured covariance of the R matrix where time intervals were correlated with different variances in each time period. Since variances for the last two harvests were low compared to the initial harvest due to high decay rates, the decision was taken to omit week 30 and 36 from the statistical analysis, allowing for two more bags to be included in the design. Furthermore, the inclusion of controls did not allow the models to converge due to constant variances throughout time. Therefore, controls were also omitted from the models. Nine models resulted with the factor levels shown in Table 2. Results were back transformed into ratios following the quotient property of logarithms:

$$\log MOE_t - \log MOE_0 = \log (MOE_t/MOE_0)$$

where:

MOE_t is the estimated MOE effect at week t and MOE_0 is the estimated effect at week 0.

Ratios represented the median residual flexural values per harvest and were expressed in percent. Confidence limits and standard errors were adjusted with Dunnet multiple comparisons where all differences were compared with a control level, which was harvest at week 0 for all combinations of moisture content and temperature.

This study did not have enough replicates to be able to partition the data and validate the model. Furthermore, given that data were analyzed using mixed models, we were not able to obtain a R^2 value, or measure that reflected the proportion of variation in the response that was explained by the model (measure of goodness of fit). A mixed model with more than one source of variation does not provide a R^2 because R^2 values do not take into account the random components of the model, except the residual variation. The variation in the response comes from several sources making it difficult to determine what proportion of the data is explained by the model.

A MOR model could not be created since only one bag was collected at every time point for each of the treatment combinations.

Factor	Level
Wood	Douglas-fir southern pine western hemlock
Temperature	15, 25, 35°C
Moisture content	1, 2, 3
Fungi	*P. placenta* *G. trabeum* *T. versicolor* *X (control)*
Time (weeks)	0, 6, 12, 18, 24, 30, 36
Bags (Random effect)	3

Table 1. Factor levels for the initial factorial design

Factor	Level
Moisture content	1, 2, 3
Fungi	*P. placenta* *G. trabeum* *T. versicolor*
Time (weeks)	0, 6, 12, 18, 24
Bags (Random effect)	5

Table 2. Factor levels for each wood species at a given temperature

Chapter 4 – Results and Discussion

The technique used to grow *P. placenta*, *G. trabeum* and *T. versicolor* on microbeams over vermiculite beds was successful, resulting in every inoculated sample beyond week 0 showing signs of growth by the target fungus. No contamination was observed. Mycelium uniformly covered the surfaces of microbeams incubated at 25 and 35^{o}C after approximately 6 weeks of incubation and after 12 weeks of incubation at 15^{o}C. The control samples had no sign of contamination after 36 weeks.

Wood Properties

MOE Losses

Based on all wood property assessments, *P. placenta* and *G. trabeum* had greater effects on flexural properties than *T. versicolor*. Fungal growth progressed very rapidly in the early stages at 25 and 35^{o}C. Hyphae of brown-rot fungi were detected growing throughout the vermiculite media after only six weeks of inoculation, while hyphae of *T. versicolor* only became visible at 25 and 35^{o}C after 12 weeks.

Beams experienced distinct color changes after only six weeks of fungal exposure (Fig. 4). Visual appearance and detection of hyphae were consistent

with detected MOE losses, although these losses were much higher than expected for all three fungal species (40 - 60%) (Fig. 5-7).

In general, all wood species incubated at 25 and 35^{o}C experienced 40-60% MOE losses at week 6 and reached 100% MOE loss by week 30 to 36 (Fig. 5-7). One possible explanation for the high initial MOE losses was that the load was applied at the inoculation point, where fungal decay was likely to be greatest. Thus, while the degree of damage across the entire beam might be slight, the damage at the inoculation point could be substantial.

Overall, initial stages of decay (week 6-18) showed significant differences in progression of MOE loss at each harvest for each of the treatment combinations (Table 5-13) except between weeks 30 and 36. Most of the experimental units (bags) had reached almost 100% MOE loss by week 30 precluding further losses.

All southern pine beams inoculated with the two brown-rot fungi exposed at the three moisture contents had similar losses at the six week point (~50-60%). *T. versicolor* colonized microbeams experienced a 30-45% MOE loss after 6 weeks. Results 12 weeks after inoculation varied for the two brown rot fungi depending on incubation temperature. The beams incubated at 25^{o}C had lower MOE losses than those at 35^{o}C. For example, southern pine beams

incubated at 25^{o}C had MOE losses ranging from 65-75%, while MOE losses for beams incubated at 35^{o}C were between 58-95%. Beams inoculated with *T. versicolor* showed a similar trend, but MOE losses were lower. MOE losses for beams exposed to *T. versicolor* at 25^{o}C ranged from 60-62%, while losses for those exposed at 35^{o}C were between 80-92%. In general, MOE losses caused by *T. versicolor* were around 20% lower than those caused by the brown rot fungi at all time points for beams incubated at 25 or 35^{o}C (Fig. 5-7).

MOE losses obtained 18 weeks after inoculation were also higher for samples incubated at the highest temperature, although the differences were small. MOE losses for beams incubated at 25^{o}C ranged from 84-92%, while beams incubated at 35^{o}C experienced losses between 93 to 98%. MOE losses for beams inoculated with *T. versicolor* were slightly lower than those obtained with the brown rots (81-87%).

Douglas-fir beams inoculated with *P. placenta*, *G. trabeum* or *T. versicolor* and incubated at the two higher temperatures (25 and 35^{o}C) experienced similar MOE losses of 52 to 57% after 6 weeks. As with southern pine beams, MOE losses were greater at the higher temperature, 12 weeks after inoculation. There were differences depending on the fungus. Beams exposed to *P.placenta* at 25^{o}C had the lowest MOE losses (58-65%), followed

by *G. trabeum* with 56-78% loss. MOE losses at 35^{o}C were similar for both fungi (80-88%).

MOE losses in Douglas-fir beams after 18 weeks of incubation were lower than those obtained for southern pine beams at 25^{o}C (77 - 90%). Beams exposed to *P. placenta* seemed to experience a decrease in MOE losses with increasing moisture content, but these differences were not significant. Beams incubated at 35^{o}C experienced MOE losses of 90-99% for both brown rot fungi. Microbeams inoculated with *T. versicolor* had MOE losses in the range of 78-89% after 18 weeks.

MOE losses in western hemlock at the initial harvest were similar to those for the other two woods for both brown rots and the white rot (45-68 and 36-50% respectively). As with the previous species, MOE losses in the second harvest were lower at 25^{o}C than at 35^{o}C, while MOE losses for the third and fourth harvest were very similar.

Metabolic activities of most organisms decrease at lower temperatures and this was evident when the test fungi were incubated at 15^{o}C (Fig. 5). MOE losses for beams incubated at 15^{o}C were lower than those observed at 25 or 35^{o}C. For the first harvest, random bags from each fungal type were monitored to determine if fungal activity was sufficient to proceed with flexural testing of all

microbeams. No detectable changes in MOE were found 6 weeks after inoculation at 15^{o}C, thus the decision was taken not to test microbeams for the first harvest (6 weeks after inoculation). MOE losses were considered to be zero for all microbeams at 15^{o}C. Fungi began to cause losses with prolonged incubation at 15^{o}C.

MOE losses in southern pine wood inoculated with brown rot fungi ranged between 43 to 64% after 12 weeks of incubation. Douglas-fir beams showed a similar range of MOE losses regardless of the fungus (37-45%) for the second (week 12) and third harvests (53-62%) (week 18). Western hemlock wood experienced the lowest MOE losses for both the second and third harvests (42-51% and 47-63% respectively). Fungal type did not appear to affect MOE losses.

Modulus of elasticity (MOE) is generally among the most sensitive measures of degradation because subtle changes in the polymer matrix can have a dramatic effect on this property (Wilcox, 1978). MOE results were comparable to those of Machek et al. (1998) who exposed non-durable (beech, elm and poplar) wood in unsterile soil tests at 26-28^{o}C and found 50-60% MOE losses after six weeks and 77-86% after 12 weeks. On the other hand, Li, et al. (2007) obtained 40% losses on pine stakes after 12 weeks under the same conditions. Losses increased to 60, 70, and 85% after 14, 20 and 24 weeks of

exposure, respectively. Curling et al. (2002) obtained MOE losses in pine wood of 50-90% 8 to 10 weeks after inoculation of wood with a method similar to the one used in the present study. Winandy and Morrell (1993) used vermiculite as a substrate and inoculated the center section of Douglas-fir beams. The results from their study showed much lower MOE losses than those obtained from Douglas-fir microbeams in the present study. While their MOE losses were 5, 15, 15, and 50% after 6, 12, 18, and 24 weeks, respectively, the losses from the current study were 50, 60, 80, and 90%, respectively, at comparable temperatures.

The unexpectedly vigorous mycelial growth in the initial stages of the study could be attributed to the substrate. Although the effect of vermiculite has not been addressed in studies of wood microbiodiversity, Borrero et al. (2004) found vermiculite to be a very conducive growth medium and superior to many types of compost with higher nutrient availability, for several *Fusarium* wilt species on tomato. None of the studies using vermiculite as a substrate (Curling, et al., 2000, 2002; Winandy and Morrell, 1993) have reported any adverse effects due to the interaction of wood with vermiculite.

Non-inoculated Microbeams

The controls were prepared and exposed using the same procedures as all other samples except that they were not inoculated with fungi. The original

MOE (time 0) measurements were taken after autoclaving to reduce possible differences due to heat exposure. MOE after autoclaving was slightly lower than those published by Bowyer, et al. (2003) (Table 3) but this might be due to the autoclaving prior to testing or the natural variability of wood. MOE progressively decreased with incubation period in controls (Fig. 13, Tables 14-16), reaching 20% loss after 36 weeks for beams exposed at 15 or 25^{o}C. The reduced MOE may be attributed to repeated flexing of beams. Li et al. (2007) found 10% losses of stiffness after testing a beam ten times for modulus of elasticity.

MOE losses in controls over time incubated at 35^{o}C (Fig. 13) were even higher than those found at 15 or 25^{o}C, especially after 18 weeks. One possible explanation for this increase would be a heat induced pH change. Wood is generally acidic, while the vermiculite tends to be basic. The pH of the environment has been found to substantially affect wood strength properties (Wangaard, 1950; Stamm, 1964; USDA, 2010; Winandy and Rowell, 2005). These effects can be aggravated by time, elevated moisture and high temperatures. Alkaline solutions tend to be more destructive to wood fibers because they are more readily absorbed (Winandy and Rowell, 2005). The vermiculite used for this project had a pH of 8 and one possible hypothesis to explain MOE losses in the controls incubated at 35^{o}C could be related to the effects of prolonged exposure to the mild alkaline environment to which the

microbeams were subjected. Although a 10^{o}C change in temperature alone should not affect wood properties, increases in temperature did significantly increase MOE losses at each harvest time (Table 4). Temperature alone does not account for the loss of MOE in non-inoculated beams, but it could have affected the kinetic reactions between the mild alkaline environment and the microbeams.

In general, cellulose is more resistant to alkaline environments and lignin is more resistant to acid ones. Hemicelluloses are susceptible to both acidic and alkali degradation (Sjostrom, 1993). Wood is known to have a buffering capacity under an acidic or alkaline conditions and should be able to partially neutralize acidic and alkaline media by the dissociation of weak acid groups. Wang et al.(2010) found that weak acid groups from hemicellulose modified the alkaline adhesive near the glue line at a pH of 8 and higher. They suggested that diffusion of reactants into and out of wood might have caused the hydrolysis of hemicelluloses and oxidation of sugars.

Hemicellulose integrity has been found to be highly correlated with wood by distributing the load across the wood matrix (Winandy and Morrell, 1993; Sweet and Winandy, 1999). Disrupting the hemicelluloses network leads to marked losses in flexural properties with very small mass change. This effect has been noted with both biological degradation and with exposure to acidic

fire retardants. The increased incubation temperature might have accelerated this effect, resulting in higher MOE losses. Unfortunately samples of vermiculite from the 36 week incubation period with non-inoculated microbeams were no longer available for analyses to determine if pH was lowered by wood. The role of vermiculite pH will be further addressed in the chemical analysis section.

The models developed to predict the effect of temperature, moisture content and wood species should not be affected by MOE effects on the non-inoculated microbeams because the increased MOE losses occur until week 18, where inoculated microbeams were already too decayed to make a noticeable difference. In future research, the interaction between vermiculite and wood must be addressed if temperatures higher than 35^{o}C are studied. It is important to note that wood in most structures is rarely continuously exposed to temperatures this high.

An attempt to “normalize” data by subtracting the non-inoculated microbeam MOE values from those of inoculated beams to determine the effect of MOE loss attributed to fungal growth alone did not provide an explanation for the decreasing MOE values for the controls with time.

Property (Green)	Present Study	Bowyer, et al. (2003)
Modulus of Elasticity (MPa)		
Douglas-fir	10,424	11,100
Western hemclock	9,028	10,200
Southern pine	9,858	
longleaf		11,000
loblolly		9,700
slash		10,500
Modulus of Rupture (kPa)		
Douglas-fir	53,000	52,000
Western hemclock	46,000	48,000
Southern pine	46,000	
longleaf		59,000
loblolly		50,000
slash		60,000

Table 3. Comparisons of MOE and MOR values at time 0 and previously published data.

MOR Losses

Since all microbeams belonging to a treatment combination were in the same experimental unit (ie bag), there was insufficient replication to estimate significant differences between time points. Error bars in the figures represent the variability within each bag (Fig. 8-10).

MOR losses caused by *P. placenta* incubated at 35^{o}C ranged from 13-38% (Fig. 10). MOR losses 12 weeks after inoculation were 18-73% and increased to 90% after 18 weeks. Strength losses resulting from attack by *G.*

trabeum were comparable to those from *P. placenta*, while *T. versicolor* was associated with much lower MOR losses. Beams exposed to *T. versicolor* lost 9-11% of their MOR after 6 weeks except for western hemlock beams at the highest moisture content regime (100-130%) which lost up to 23% in MOR. MOR losses after 12 weeks ranged from 12-20% and reached 100% by the time wood was exposed to fungi for 30-36 weeks. The highest degree of decay at 35^{o}C was found when wood was maintained at 40-60% moisture content. Western hemlock beams experienced greater strength losses in wood at 30-60% moisture content. The lowest MOR losses for the two brown rot fungi were found in beams maintained at the highest moisture regimes in beams incubated at 25^{o}C (Fig. 9).

In general, MOR losses were lower at the highest moisture content regime for all three fungi incubated at 35^{o}C. Although the incubating bags were opened periodically help maintain oxygen levels, the reduced fungal effects could be attributed to insufficient oxygen in the wood lumen. Boddy (1983a,b) found that increasing either temperature (5-25^{o}C) or moisture content in wood caused an increase in CO_2 evolution. In this study, CO_2 evolution was used to assess the respiration rate of wood decay organisms to quantify effects of abiotic variables. She found that increasing temperature at constant moisture content caused increases in respiration rate, CO_2 production and O_2 uptake. On the other hand, evolution rate decreased at high temperatures

accompanied by high moisture contents. Flanagan and Veum (1974) found that the higher the temperature the lower the moisture content at which respiration rates attenuate because high moisture contents slow the rate of oxygen diffusion, limiting respiration. This effect occurs sooner at higher temperatures because the demand for oxygen is greater.

Higher strength losses were found in beams maintained at higher moisture contents and exposed to *T. versicolor* at 25^{o}C, agreeing with the tendency for this and many other white rot fungi to be more active in wetter environments. MOR losses were similar for both brown rots incubated at 25^{o}C with losses of 12-40%, 20-75% or 30-90% after 2, 12 or 18 weeks respectively. Strength losses for *T. versicolor* incubated at 25^{o}C were higher than those at 35^{o}C ranging from 0-25%, 9-30% or 4-50% after 6, 12 or 18 weeks, respectively.

As expected for lower temperatures, MOR losses in beams incubated at 15^{o}C were much lower than those obtained at 25 or 35^{o}C (Fig. 8). The highest losses were produced by *P. placenta* which caused greater losses in beams at moisture contents closer to the fiber saturation point. MOR losses were only around 19% for beams exposed to *P. placenta* at the highest moisture content. MOR losses in beams exposed to the other two fungi at 15^{o}C were negligible, except for *G. trabeum* on southern pine at 40-60% or 80-100% moisture

content (~30 and 60% MOR losses, respectively). Negative values were detected in some individual treatments. This likely reflected the natural variation in the strength properties of wood and these results indicate that the fungal/environmental combination had no effect on wood properties.

Flexural properties are among the most sensitive measures of incipient decay (Wilcox, 1978). Compression strength losses of up to 60% were reported on sapwood exposed to wood rotting basidiomycetes under ideal conditions for one week (Morris and Winandy, 2002). Moderately durable heartwood losses were around 25% under the same conditions.

MOR losses during the initial stages of exposure (6-18 weeks) in our tests were not as sensitive to incipient decay as MOE (Fig. 16). Modulus of elasticity is generally affected earlier and to a greater extent by fungal attack than the modulus of rupture (Cartwright et al., 1931).

Curling et al. (2000) found considerable strength losses after only 6 weeks of exposure of southern pine to *G. trabeum* (50-80% MOR loss) or *P. placenta* (38-75% MOR loss), while *T. versicolor* caused lower strength losses of 5-10% in the same time (Fig. 8-10). MOR losses after 12 weeks ranged from 85-95% for both brown rot fungi and around 10-35% for the white rot fungus. Curling used feeder strips that had been pre-inoculated with 5 ml of

liquid mycelial suspension. This produced much higher amounts of initial inoculum per wood sample and likely accelerated colonization and decay. Both Curling's study and the current study found higher degrees of strength loss compared to other published data. These differences may reflect the inoculation method. Concentrating inoculum at the point where the beam was eventually loaded to failure likely further contributed to this effect.

Non-inoculated Microbeams

MOR values in non-fungal exposed beams at the start of the test were slightly lower than those previously reported (Bowyer, et al.,2003) (Table 3), but this might be due to the autoclaving prior to MOR testing or to the natural variability of wood. Winandy and Morrell (1993) found a 12% loss in MOR attributed to autoclaving samples.

Non-inoculated microbeams had maximum MOR losses of ~10% (Fig. 14, Tables 14-16) after 36 weeks of inoculation. MOR losses after 36 weeks of incubation progressively increased with temperature (Fig. 14, Tables 14-16), reaching -2 to -1% at 15^{o}C, 4-7% at 25^{o}C and 8-10% at 35^{o}C. MOR differences between temperatures could not be analyzed statistically because the six beams per treatment combination per time were sub-samples, not replicates.

Mass Losses

Mass losses were determined for every microbeam inside each bag for every treatment combination at every harvest (Fig. 11-13). Due to the lack of integrity of microbeams in advanced stages of decay, all microbeam fragments in a bag sometimes had to be pooled and weighed together.

Mass losses generally followed the trend found with MOR losses rather than that of MOE losses. As in the case of MOR, losses were lower at the highest temperature (35^{o}C) at the highest moisture regime (100-130%).

Mass losses caused by the white rot fungus, *T. versicolor*, were low, generally under 5% except for southern pine samples incubated at 25 or 35^{o}C where losses reached 18% after 36 weeks and Douglas-fir at 35^{o}C and 100-130% MC which experienced mass losses of 40%. Microbeams exposed to the lowest temperature (15^{o}C) had the lowest mass losses, supporting previous MOE and MOR results and indicating that temperature control can slow the natural rate of decay in a structure.

Cartwright et al.(1931) found that there was a reduction of 50% in MOR and 55% reduction in MOE at 2% mass loss. The present work found reductions of 25-38% in MOR and 55-60% reductions in MOE at 2% mass loss

(Tables 1-9). As previously reported (Curling et al., 2000, 2002; Imamura, 1993; Kim et al., 1996; Ruddick, 1986; Schmidt et al., 1978; Wilcox, 1978; Winandy and Morrell, 1993), considerable strength losses occur before significant mass losses become apparent (Green et al., 1991; Scheffer, 1936; Wilcox, 1978; Winandy et al., 2000).

Non-inoculated controls had mass losses ranging from 0.5 to 2% which would be considered normal background losses for laboratory tests due to wetting and drying and/or extractive losses (Freitag, 2010). Non-inoculated beams had 0-10% MOR losses at these mass losses.

MOR losses of microbeams at comparable mass losses were extremely high in the presence of fungi. This is partially explained by the fact that inoculated beam mass loss includes the mass of hyphae within the wood. The initial phase of fungal growth includes a short exponential phase when hyphal branches are initiated. New hyphae then extend at a linear rate to uncolonized regions within a substrate (Tortora et al., 2009). Fungal biomass replaces the biomass formerly represented by wood components.

Mass loss has long been considered the simplest method to measure decay rates in wood (Hartley, 1958), but it has been broadly reported that considerable strength losses occurring below 10% mass losses can be

detected confirming that mechanical property changes provide a better measure of fungal decay (Scheffer, 1936, Green et al., 1991; Winandy et al., 2000). This can be confirmed by the data obtained in the present study (Fig.16) where property losses followed the pattern of MOE loss > MOR loss > mass loss. In general, there was a slow increase in mass loss compared to MOE or MOR losses in all fungal and wood species combinations over time.

Figure 4. Douglas-fir beams 0, 6, 12, and 18 weeks after inoculation with *P. placenta* at 35°C

Harvest (weeks)	15°C	25°C	35°C
6	A	B	C
12	A	B	C
18	A	B	C
24	A	B	C
30	A	B	C
36	A	B	C

Table 4. Tukey-Kramer comparisons of mass losses in beams exposed for 6 to 36 weeks by temperature (15, 25 and 35°C) of all wood species. Values followed by a different capital letter within a category (row) are significantly different (α = 0.05).

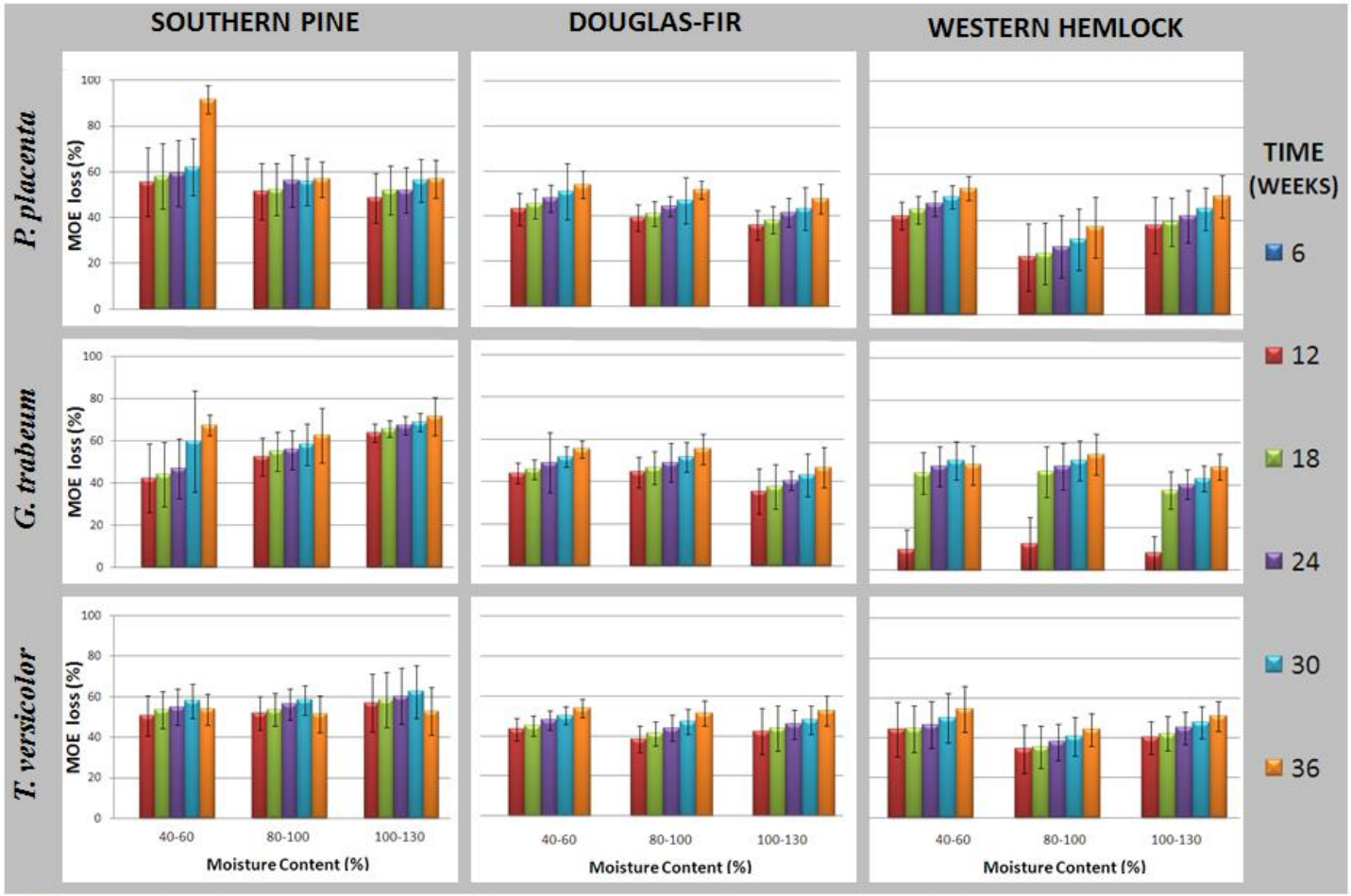


Figure 5. MOE losses of southern pine, Douglas-fir and western hemlock beams maintained at 3 moisture contents for 6, 12, 18, 24, 30, and 36 weeks after inoculation with *P. placenta*, *G. trabeum*, or *T. versicolor* and incubated at 15°C. Bars represent one standard deviation from the mean.

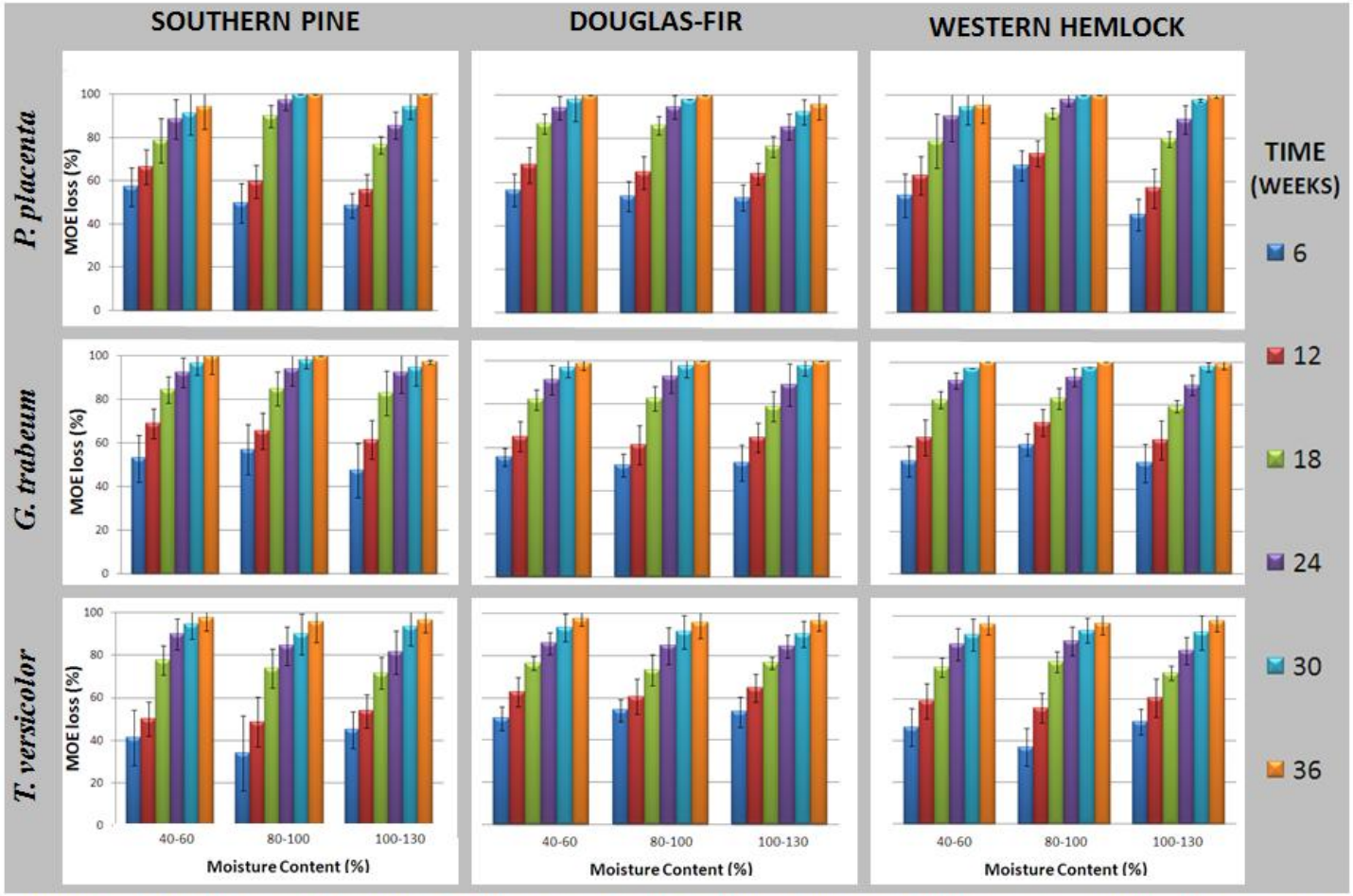


Figure 6. MOE losses of southern pine, Douglas-fir and western hemlock beams maintained at 3 moisture contents for 6, 12, 18, 24, 30, and 36 weeks after inoculation with *P. placenta*, *G. trabeum*, or *T. versicolor* and incubated at 25°C. Bars represent one standard deviation from the mean.

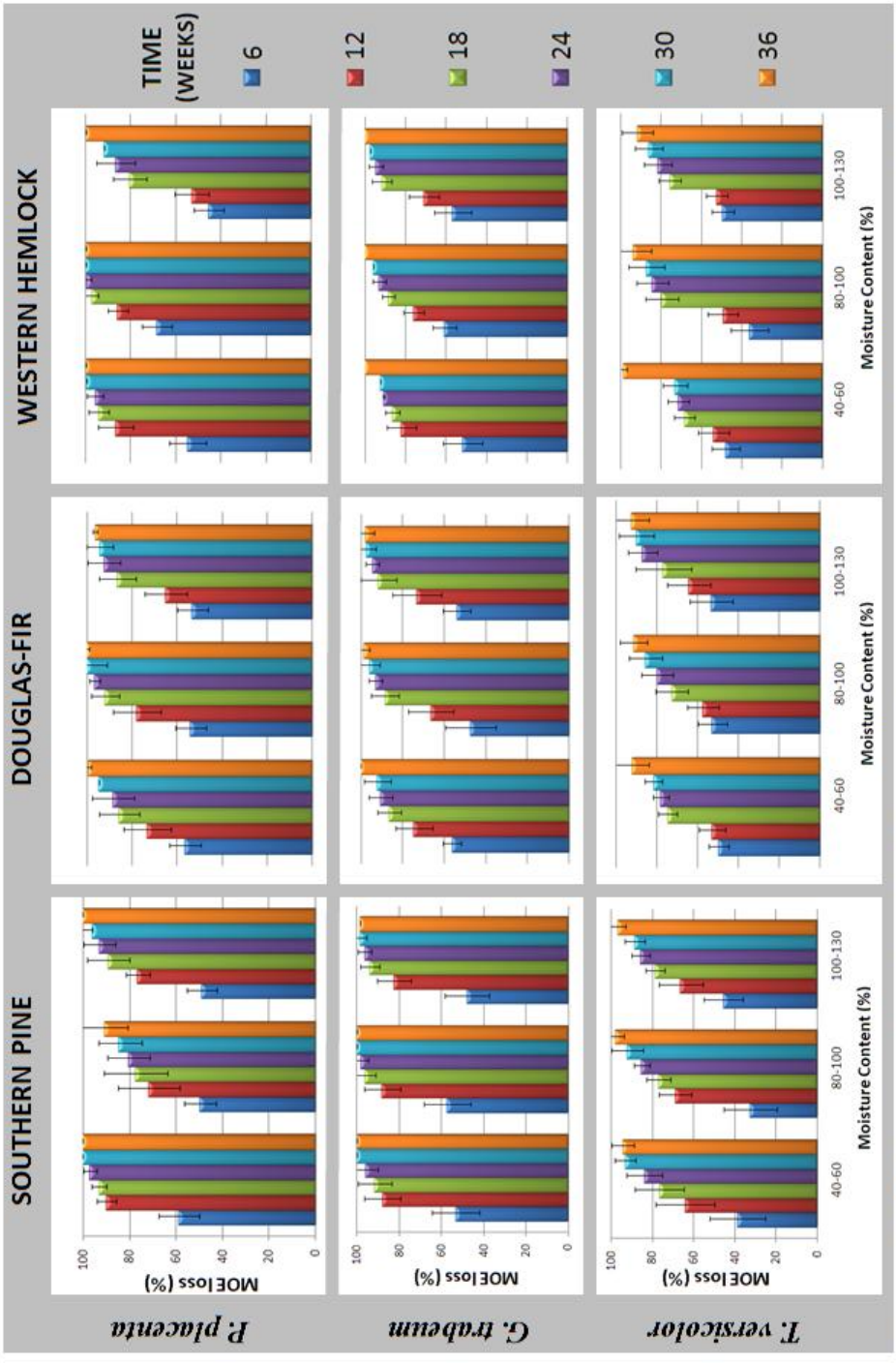


Figure 7. MOE losses of southern pine, Douglas-fir and western hemlock beams maintained at 3 moisture contents for 6, 12, 18, 24, 30, and 36 weeks after inoculation with *P. placenta*, *G. trabeum*, or *T. versicolor* and incubated at 35°C. Bars represent one standard deviation from the mean.

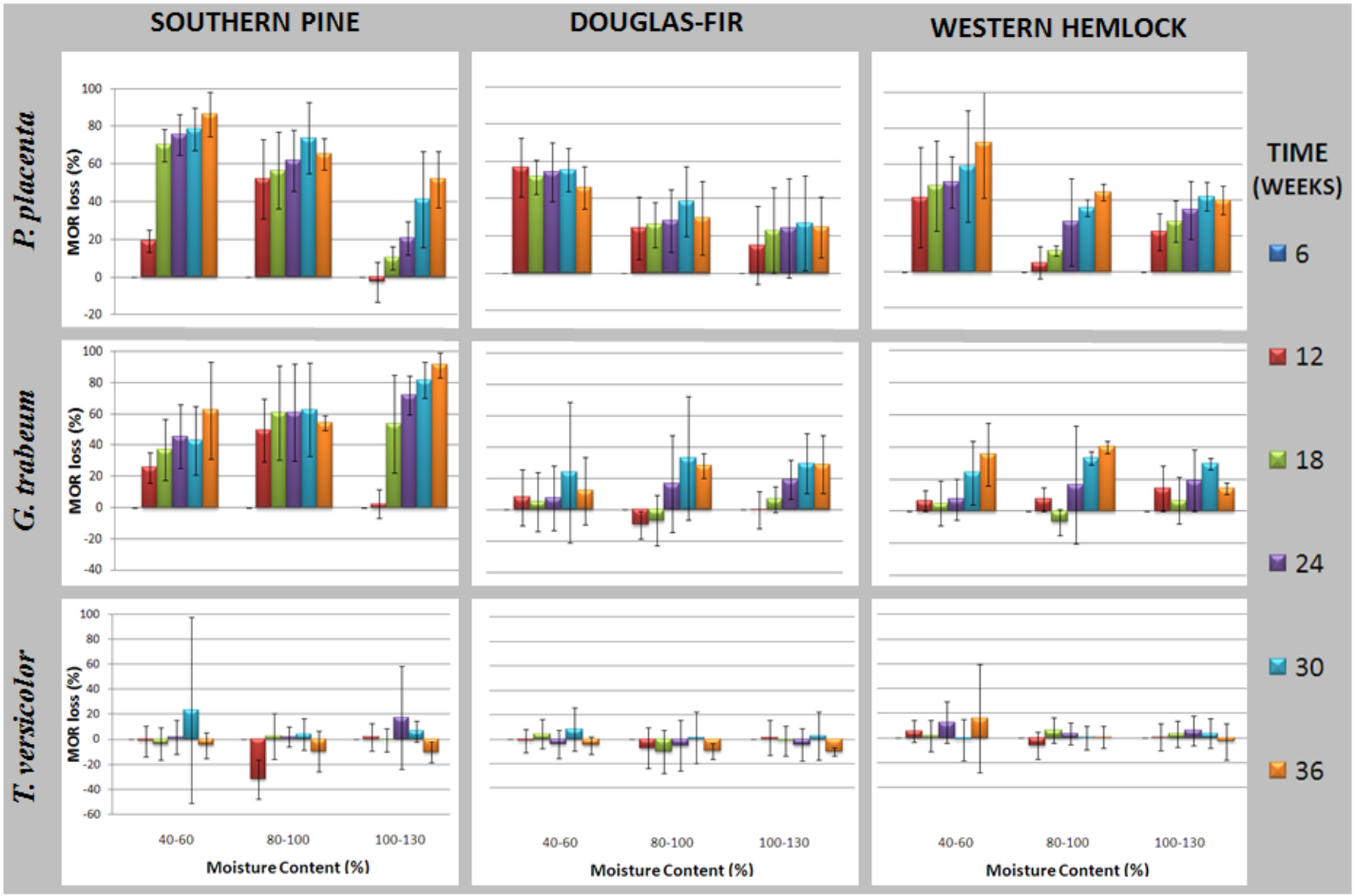


Figure 8. MOR losses of southern pine, Douglas-fir and western hemlock beams maintained at 3 moisture contents for 6, 12, 18, 24, 30, and 36 weeks after inoculation with *P. placenta*, *G. trabeum*, or *T. versicolor* and incubated at 15°C. Bars represent one standard deviation from the mean.

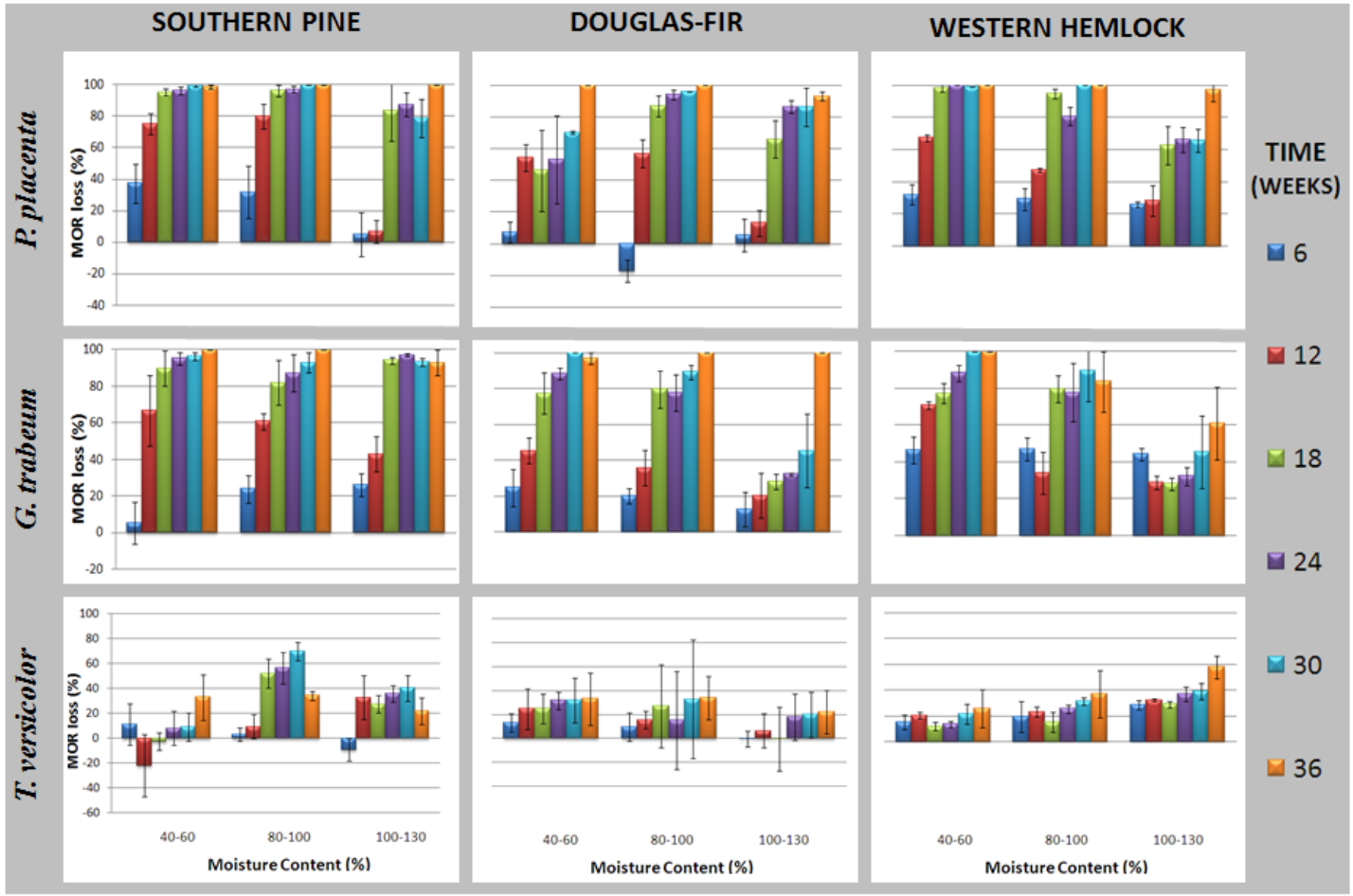


Figure 9. MOR losses of southern pine, Douglas-fir and western hemlock beams maintained at 3 moisture contents for 6, 12, 18, 24, 30, and 36 weeks after inoculation with *P. placenta*, *G. trabeum*, or *T. versicolor* and incubated at 25°C. Bars represent one standard deviation from the mean.

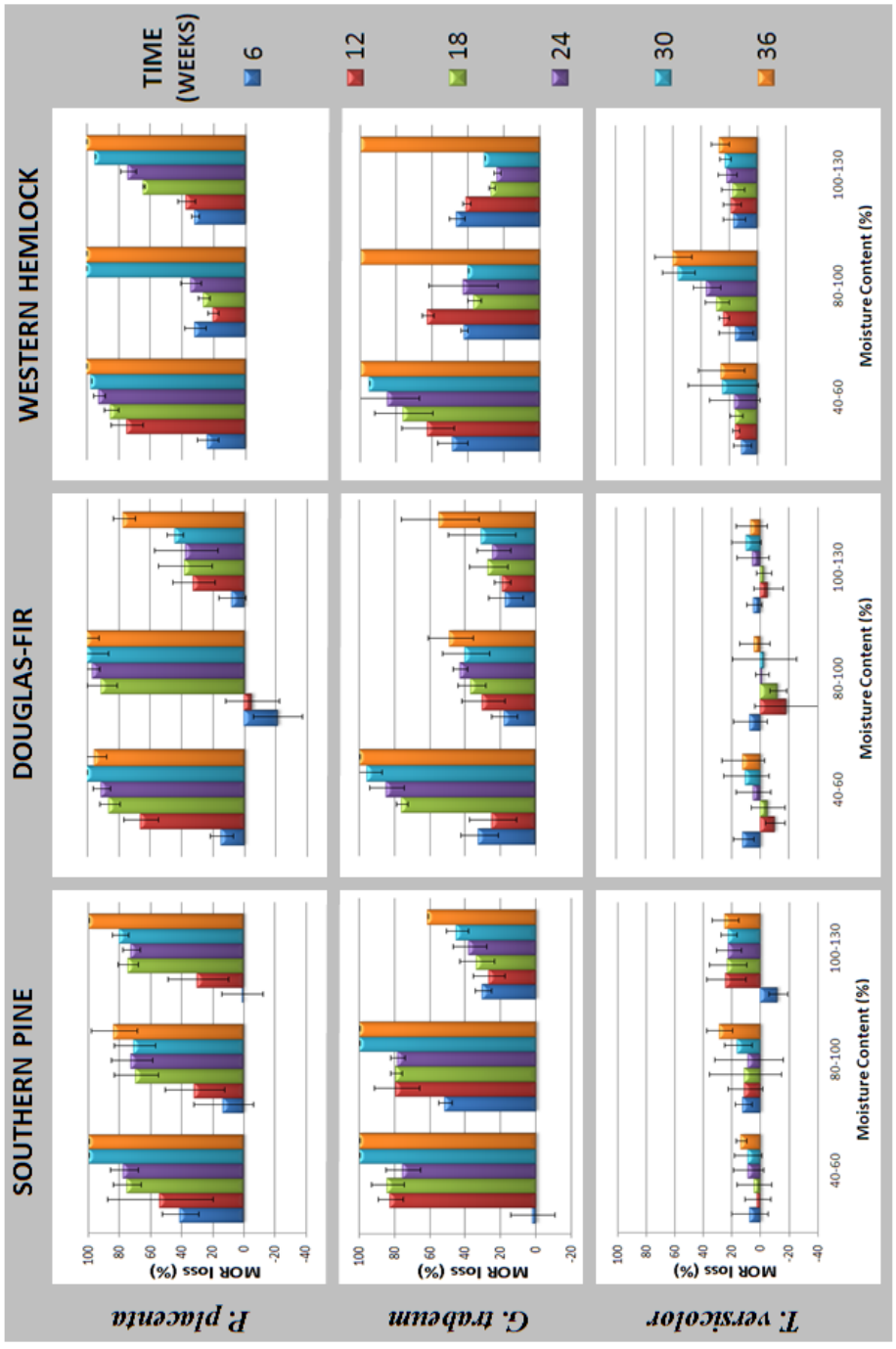


Figure 10. MOR losses of southern pine, Douglas-fir and western hemlock beams maintained at 3 moisture contents for 6, 12, 18, 24, 30, and 36 weeks after inoculation with *P. placenta*, *G. trabeum*, or *T. versicolor* and incubated at 35°C. Bars represent one standard deviation from the mean.

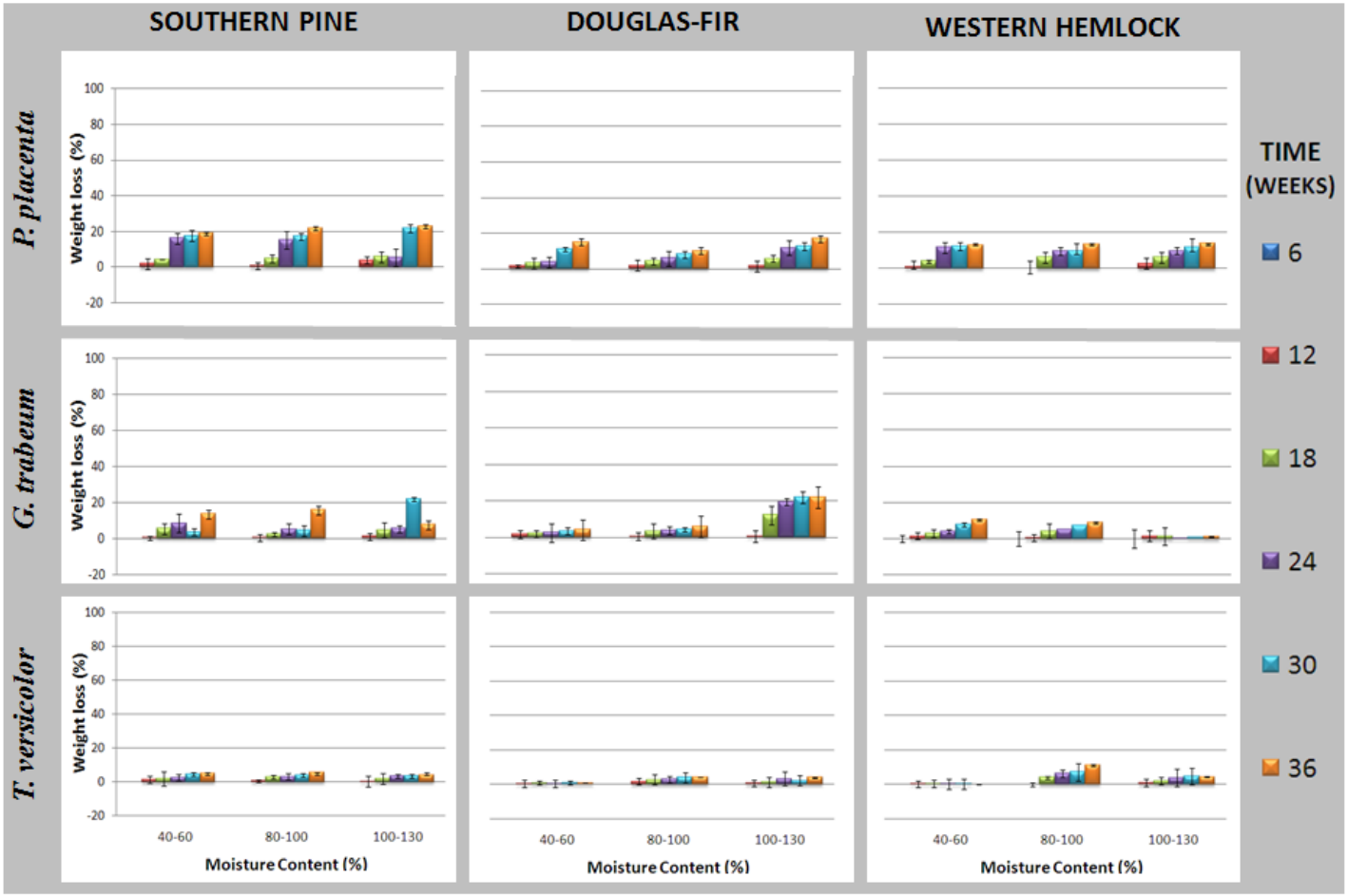


Figure 11. Mass losses of southern pine, Douglas-fir and western hemlock beams maintained at 3 moisture contents for 6, 12, 18, 24, 30, and 36 weeks after inoculation with *P. placenta*, *G. trabeum*, or *T. versicolor* and incubated at 15°C. Bars represent one standard deviation from the mean.

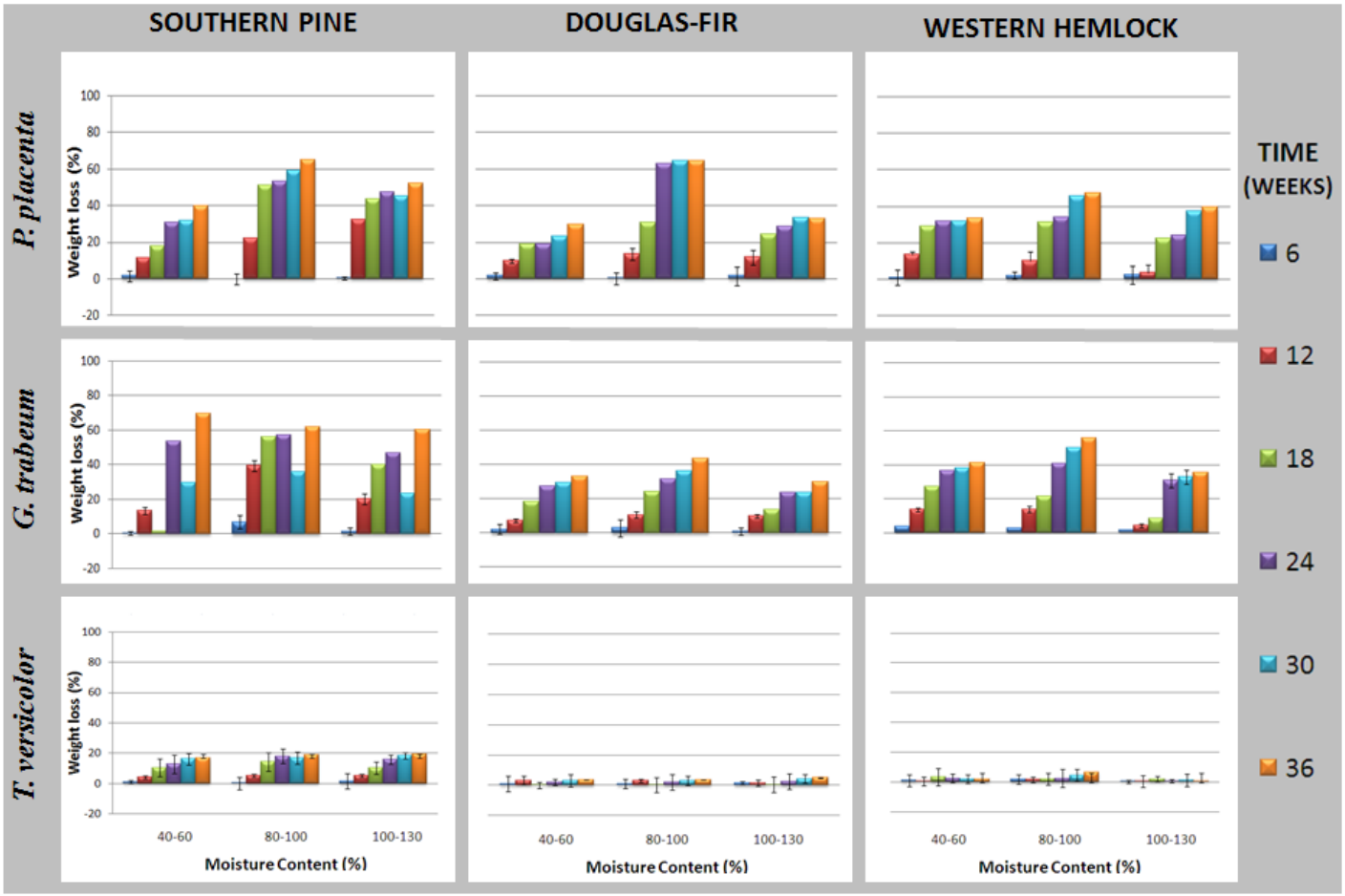


Figure 12. Mass losses of southern pine, Douglas-fir and western hemlock beams maintained at 3 moisture contents for 6, 12, 18, 24, 30, and 36 weeks after inoculation with *P. placenta*, *G. trabeum*, or *T. versicolor* and incubated at 25°C. Bars represent one standard deviation from the mean.

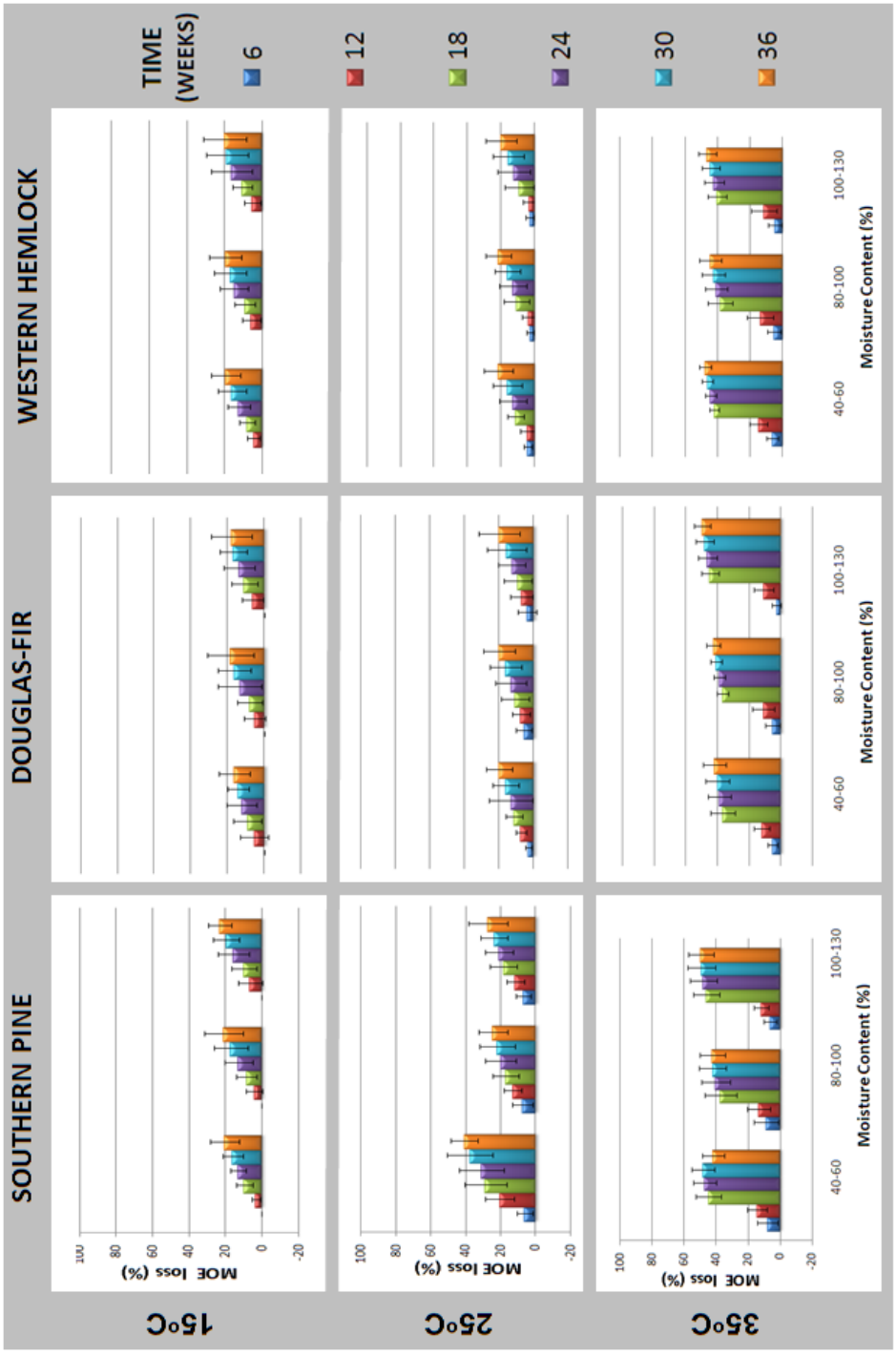


Figure 13. MOE losses of southern pine, Douglas-fir and western hemlock non-fungal inoculated beams beams maintained at 3 moisture contents for 6, 12, 18, 24, 30, and 36 weeks and incubated at 15, 25, or 35°C. Bars represent one standard deviation from the mean.

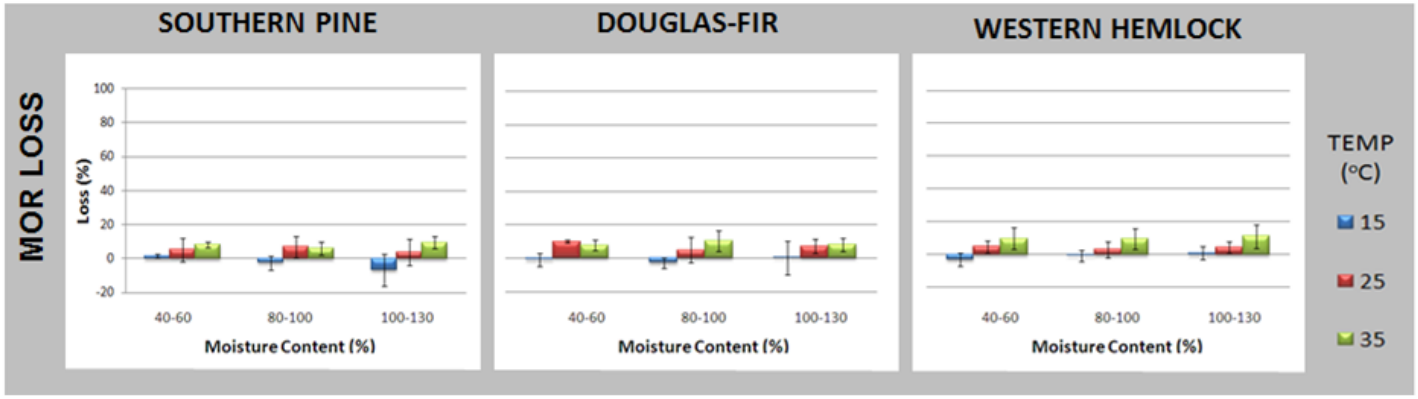


Figure 14. MOR losses of southern pine, Douglas-fir and western hemlock non-fungal inoculated beams beams maintained at 3 moisture contents for 36 weeks at 15, 25, or 35°C. Bars represent one standard deviation from the mean.

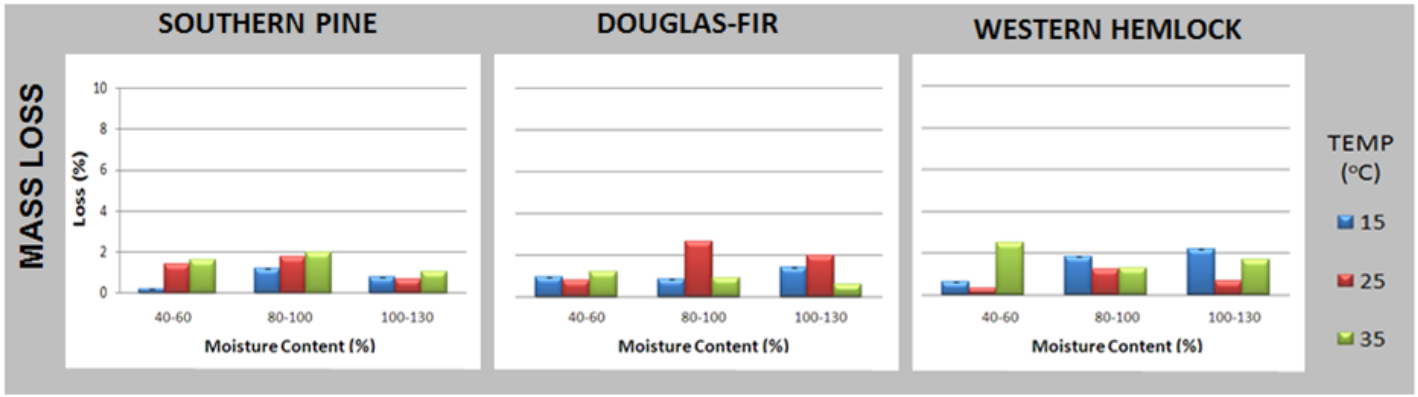


Figure 15. Mass losses of southern pine, Douglas-fir and western hemlock non-fungal inoculated beams beams maintained at 3 moisture contents for 36 weeks at 15, 25, or 35°C.

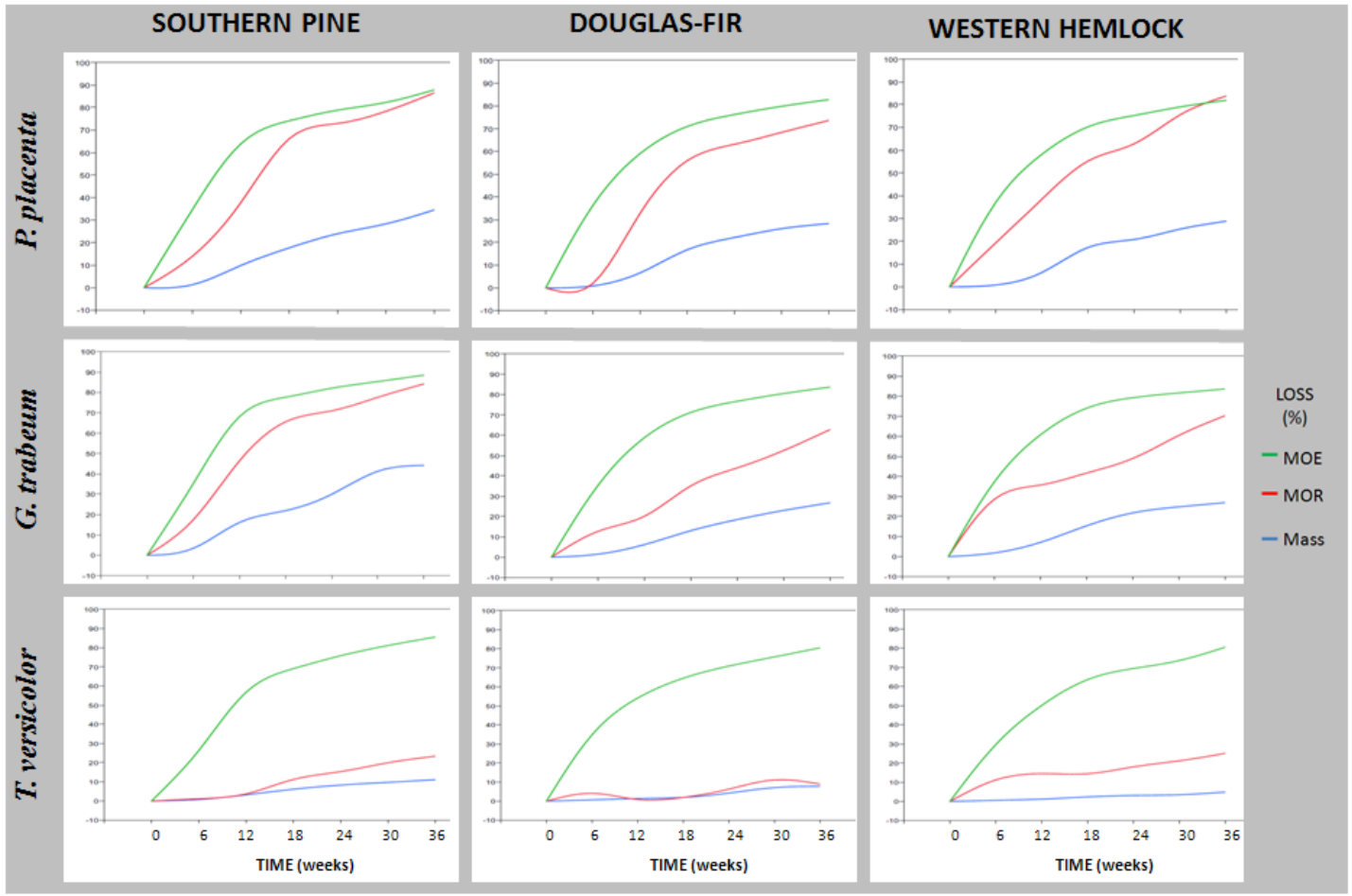


Figure 16. Losses in MOE, MOR and mass in southern pine, Douglas-fir and western hemlock beams for 6, 12, 18, 24, 30 and 36 weeks after inoculation with *P. placenta*, *G. trabeum*, or *T. versicolor*.

TARGET MOISTURE CONTENT	TEST FUNGUS	INCUBATION PERIOD (WEEKS)	MOR LOSS (%)	MOE LOSS (%)		MASS LOSS (%)
40-60%	*G. trabeum*	6	0.0	0.0	A	0.00
		12	7.9	43.9	B	1.88
		18	4.9	45.8	C	2.13
		24	7.4	48.9	D	2.64
		30	23.9	51.6	E	3.64
		36	12.1	55.2	F	4.19
	P. placenta	6	0.0	0.0	A	0.00
		12	56.8	43.1	B	1.53
		18	51.7	45.4	B	3.11
		24	54.3	47.9	C	B
		30	55.4	50.9	C	11.18
		36	45.7	53.9	D	15.13
	T. versicolor	6	0.0	0.0	A	0.00
		12	-1.4	43.2	B	0.27
		18	4.4	45.0	B	0.72
		24	-4.3	47.8	C	0.43
		30	8.2	50.1	C	0.94
		36	-4.8	53.8	D	0.75
80-100%	*G. trabeum*	6	0.0	0.0	A	0.00
		12	-9.8	44.4	B	0.62
		18	-6.8	46.4	BC	3.42
		24	16.4	49.0	CD	3.93
		30	32.9	51.6	DE	4.50
		36	28.1	55.3	E	6.10
	P. placenta	6	0.0	0.0	A	0.00
		12	24.1	39.3	B	1.98
		18	25.9	41.1	BC	4.29
		24	28.2	44.5	CD	6.01
		30	38.3	46.8	D	8.03
		36	29.6	51.6	E	10.12
	T. versicolor	6	0.0	0.0	A	0.00
		12	-7.1	38.4	B	1.63
		18	-10.2	41.1	BC	2.69
		24	-5.2	44.0	CD	2.84
		30	1.5	47.1	DF	3.90
		36	-9.6	51.5	E	4.12
100-130%	*G. trabeum*	6	0.0	0.0	A	0.00
		12	-0.2	35.4	B	0.76
		18	6.7	37.7	BC	12.37
		24	19.1	40.4	ABC	19.63
		30	29.5	43.1	BC	21.99
		36	29.0	46.5	D	22.03
	P. placenta	6	0.0	0.0	A	0.00
		12	14.9	36.0	B	1.63
		18	22.9	38.2	BC	5.73
		24	24.2	41.6	CD	11.71
		30	26.9	43.4	DE	12.74
		36	24.6	47.6	E	16.91
	T. versicolor	6	0.0	0.0	A	0.00
		12	1.5	42.2	B	0.73
		18	-1.3	43.9	B	1.26
		24	-4.4	45.7	BC	3.23
		30	2.7	47.9	BC	2.13
		36	-10.3	52.8	C	4.00

Table 5. Mean MOR, MOE, and mass loss values for Douglas-fir beams inoculated with one of three fungi (*G. trabeum*, *P. placenta* or *T. versicolor*) at three moisture content regimes (40-60, 80-100, and 100-130%) and incubated at 15°C for 6 to 36 weeks. Values followed by the same capital letter within a category are not significantly different (α = 0.05) by the Tukey-Kramer method.

TARGET MOISTURE CONTENT	TEST FUNGUS	INCUBATION PERIOD (WEEKS)	MOR LOSS (%)	MOE LOSS (%)		MASS LOSS (%)
40-60%	*G. trabeum*	6	0.0	0.0	A	0.00
		12	45.8	37.9	B	1.51
		18	3.7	40.3	B	3.10
		24	22.4	42.7	BC	4.18
		30	27.7	46.6	C	7.87
		36	35.5	49.5	C	10.49
	P. placenta	6	0.0	0.0	A	0.00
		12	41.8	42.3	B	1.02
		18	48.2	44.8	BC	3.98
		24	50.3	47.4	CD	11.65
		30	59.0	50.4	DE	12.26
		36	72.5	54.0	E	13.01
	T. versicolor	6	0.0	0.0	A	0.00
		12	5.3	44.4	B	0.24
		18	1.9	44.5	B	0.45
		24	12.5	46.7	BC	0.32
		30	-1.5	49.9	BC	0.24
		36	15.9	54.4	C	0.00
80-100%	*G. trabeum*	6	0.0	0.0	A	0.00
		12	-3.5	43.8	A	0.63
		18	4.0	46.1	A	4.31
		24	27.3	49.3	AB	5.09
		30	41.4	50.7	B	7.42
		36	39.8	54.6	B	8.81
	P. placenta	6	0.0	0.0	A	0.00
		12	5.3	24.5	AB	0.00
		18	11.9	26.1	ABC	6.16
		24	28.0	29.1	BCD	9.57
		30	35.9	32.2	CD	9.71
		36	44.6	37.4	C	13.17
	T. versicolor	6	0.0	0.0	A	0.00
		12	-6.2	34.4	B	0.00
		18	6.1	35.5	B	3.96
		24	3.5	37.9	BC	6.35
		30	0.4	40.8	BC	7.11
		36	0.7	44.1	C	11.12
100-130%	*G. trabeum*	6	0.0	0.0	A	0.00
		12	-1.7	37.1	B	1.56
		18	9.5	39.1	BC	1.43
		24	14.3	40.3	BC	0.40
		30	12.7	42.9	CD	1.00
		36	14.3	48.6	D	1.15
	P. placenta	6	0.0	0.0	A	0.00
		12	22.8	38.2	B	2.80
		18	28.4	39.5	BC	6.09
		24	34.6	42.0	BC	9.74
		30	42.2	45.3	CD	11.61
		36	40.1	50.5	D	13.71
	T. versicolor	6	0.0	0.0	A	0.00
		12	0.7	40.1	B	0.95
		18	3.2	42.2	B	1.95
		24	5.9	45.0	BC	3.77
		30	3.7	47.8	C	4.66
		36	-2.7	50.8	C	4.28

Table 6. Mean MOR, MOE, and mass loss values for western hemlock beams inoculated with one of three fungi (*G. trabeum*, *P. placenta* or *T. versicolor*) at three moisture content regimes (40-60, 80-100, and 100-130%) and incubated at 15°C for 6 to 36 weeks. Values followed by the same capital letter within a category are not significantly different (α = 0.05) by the Tukey-Kramer method.

TARGET MOISTURE CONTENT	TEST FUNGUS	INCUBATION PERIOD (WEEKS)	MOR LOSS (%)	MOE LOSS (%)		MASS LOSS (%)
40-60%	*G. trabeum*	6	0.0	0.0	A	0.00
		12	25.6	42.2	B	0.36
		18	37.1	44.0	B	5.55
		24	45.6	46.7	B	8.52
		30	43.0	59.6	C	8.42
		36	62.2	67.3	C	13.49
	P. placenta	6	0.0	0.0	A	0.00
		12	19.2	55.5	B	1.89
		18	70.0	58.1	B	4.17
		24	75.7	59.5	B	16.14
		30	78.5	62.1	B	17.44
		36	86.4	91.5	C	18.77
	T. versicolor	6	0.0	0.0	A	0.00
		12	-1.6	50.7	B	1.68
		18	-3.7	53.7	BC	2.11
		24	1.7	54.9	BC	2.81
		30	23.3	57.9	CD	4.67
		36	7.9	62.7	D	5.00
80-100%	*G. trabeum*	6	0.0	0.0	A	0.00
		12	49.4	52.1	B	0.45
		18	60.7	54.9	B	2.42
		24	61.0	55.6	BC	5.16
		30	62.8	58.2	BC	15.95
		36	54.1	62.4	C	15.85
	P. placenta	6	0.0	0.0	A	0.00
		12	52.1	51.5	B	0.89
		18	56.6	52.3	B	4.84
		24	61.8	56.1	B	15.15
		30	73.7	55.7	B	17.26
		36	65.4	56.8	B	21.53
	T. versicolor	6	0.0	0.0	A	0.00
		12	-31.9	51.8	B	0.79
		18	2.5	53.6	BC	3.18
		24	1.8	56.2	BC	3.33
		30	4.0	58.2	D	4.00
		36	8.2	64.6	C	5.90
100-130%	*G. trabeum*	6	0.0	0.0	A	0.00
		12	2.4	63.6	B	1.19
		18	53.6	65.6	BC	4.76
		24	71.8	67.2	CD	5.48
		30	81.6	68.7	DE	7.13
		36	91.3	71.3	E	7.67
	P. placenta	6	0.0	0.0	A	0.00
		12	-2.6	48.5	B	3.99
		18	10.1	51.9	BC	5.91
		24	20.7	52.0	BC	5.49
		30	41.2	56.3	C	21.83
		36	51.9	56.9	C	22.91
	T. versicolor	6	0.0	0.0	A	0.00
		12	1.9	56.9	B	0.55
		18	-0.7	58.4	B	2.17
		24	17.3	60.2	B	3.64
		30	6.5	62.4	B	3.75
		36	-14.1	65.6	B	4.35

Table 7. Mean MOR, MOE, and mass loss values for southern pine beams inoculated with one of three fungi (*G. trabeum*, *P. placenta* or *T. versicolor*) at three moisture content regimes (40-60, 80-100, and 100-130%) and incubated at 15°C for 6 to 36 weeks. Values followed by the same capital letter within a category are not significantly different (α = 0.05) by the Tukey-Kramer method.

TARGET MOISTURE CONTENT	TEST FUNGUS	INCUBATION PERIOD (WEEKS)	MOR LOSS (%)	MOE LOSS (%)		MASS LOSS (%)
40-60%	*G. trabeum*	6	24.8	55.5	A	2.21
		12	45.4	65.0	B	7.22
		18	77.3	82.1	C	18.50
		24	88.2	91.2	D	27.41
		30	100.0	97.0	E	29.46
		36	97.0	98.9	E	33.10
	P. placenta	6	7.4	56.3	A	1.58
		12	54.2	67.9	B	9.80
		18	46.2	86.9	C	19.00
		24	53.2	94.0	D	18.77
		30	70.3	98.1	DE	23.34
		36	100.0	100.0	E	29.45
	T. versicolor	6	13.1	50.3	A	0.27
		12	24.6	62.7	B	1.19
		18	24.9	76.4	C	1.60
		24	31.6	85.8	D	1.02
		30	31.9	93.2	E	1.82
		36	32.9	97.4	E	0.63
80-100%	*G. trabeum*	6	20.2	51.7	A	2.91
		12	35.7	61.2	B	10.61
		18	79.6	82.8	C	23.90
		24	77.7	92.9	D	31.64
		30	89.3	97.6	DE	35.90
		36	100.0	100.0	E	43.25
	P. placenta	6	-17.2	53.6	A	0.20
		12	56.9	64.5	B	13.64
		18	86.9	86.1	C	31.00
		24	94.1	94.5	D	63.00
		30	95.9	97.8	DE	64.34
		36	100.0	100.0	E	64.47
	T. versicolor	6	9.6	54.1	A	1.02
		12	15.6	60.5	B	3.24
		18	27.3	73.2	C	0.10
		24	14.9	84.6	D	1.98
		30	32.8	91.2	E	3.01
		36	34.2	95.8	E	3.49
100-130%	*G. trabeum*	6	12.6	52.8	A	0.96
		12	20.3	64.5	B	9.95
		18	28.1	79.0	C	13.50
		24	32.2	89.1	D	23.56
		30	45.3	97.7	E	23.45
		36	100.0	100.0	E	29.61
	P. placenta	6	5.4	52.8	A	1.63
		12	13.1	64.0	B	11.87
		18	66.0	76.3	C	24.50
		24	86.5	85.5	D	28.79
		30	86.5	92.2	E	33.20
		36	93.1	95.7	E	32.87
	T. versicolor	6	-0.4	53.3	A	1.67
		12	6.4	64.7	B	1.44
		18	-0.6	76.5	C	0.40
		24	18.1	84.3	D	2.49
		30	19.9	90.2	E	4.30
		36	22.1	96.4	F	4.82

Table 8. Mean MOR, MOE, and mass loss values for Douglas-fir beams inoculated with one of three fungi (*G. trabeum*, *P. placenta* or *T. versicolor*) at three moisture content regimes (40-60, 80-100, and 100-130%) and incubated at 25°C for 6 to 36 weeks. Values followed by the same capital letter within a category are not significantly different (α = 0.05) by the Tukey-Kramer method.

TARGET MOISTURE CONTENT	TEST FUNGUS	INCUBATION PERIOD (WEEKS)	MOR LOSS (%)	MOE LOSS (%)		MASS LOSS (%)
40-60%	*G. trabeum*	6	46.5	53.3	A	3.88
		12	70.8	64.4	B	13.74
		18	88.5	88.6	C	26.90
		24	93.3	96.7	D	36.19
		30	95.0	99.5	D	37.87
		36	100.0	100.0	D	41.08
	P. placenta	6	32.0	53.8	A	1.04
		12	67.3	63.0	B	13.34
		18	98.3	78.9	C	29.20
		24	100.0	90.2	D	31.46
		30	99.0	94.5	D	31.67
		36	100.0	95.4	D	33.32
	T. versicolor	6	15.2	46.6	A	1.03
		12	20.6	59.0	B	0.43
		18	12.3	75.4	C	3.30
		24	13.7	86.2	D	2.51
		30	21.6	91.1	DE	2.01
		36	25.8	96.1	E	1.90
80-100%	*G. trabeum*	6	46.9	61.1	A	2.56
		12	34.0	71.4	B	13.85
		18	42.2	87.1	C	21.50
		24	47.4	95.8	D	40.42
		30	79.0	98.7	DE	49.73
		36	83.5	100.0	E	55.85
	P. placenta	6	29.4	67.7	A	2.00
		12	47.3	73.2	B	10.00
		18	94.9	91.6	C	31.00
		24	80.6	98.0	D	34.13
		30	100.0	100.0	D	45.43
		36	100.0	100.0	D	47.40
	T. versicolor	6	19.6	36.9	A	1.77
		12	23.4	55.8	B	1.49
		18	15.5	77.8	C	2.00
		24	25.7	87.8	D	2.37
		30	31.7	93.0	DE	4.54
		36	37.5	96.4	E	6.33
100-130%	*G. trabeum*	6	44.1	52.2	A	1.47
		12	28.8	63.1	B	4.07
		18	43.3	85.8	C	8.40
		24	45.7	95.2	D	30.68
		30	48.7	97.7	D	32.79
		36	61.1	98.9	D	35.45
	P. placenta	6	26.1	45.0	A	2.43
		12	28.3	57.1	B	3.80
		18	62.7	79.8	C	22.30
		24	66.2	88.6	D	23.93
		30	65.5	97.5	E	37.09
		36	97.1	99.8	E	39.19
	T. versicolor	6	28.8	49.1	A	0.34
		12	32.3	60.6	B	0.31
		18	29.2	72.5	C	1.90
		24	37.2	83.2	D	0.54
		30	39.2	92.0	E	1.23
		36	57.9	97.5	E	0.42

Table 9. Mean MOR, MOE, and mass loss values for western hemlock beams inoculated with one of three fungi (*G. trabeum*, *P. placenta* or *T. versicolor*) at three moisture content regimes (40-60, 80-100, and 100-130%) and incubated at 25°C for 6 to 36 weeks. Values followed by the same capital letter within a category are not significantly different (α = 0.05) by the Tukey-Kramer method.

TARGET MOISTURE CONTENT	TEST FUNGUS	INCUBATION PERIOD (WEEKS)	MOR LOSS (%)	MOE LOSS (%)		MASS LOSS (%)
40-60%	*G. trabeum*	6	5.1	53.0	A	0.56
		12	66.6	69.2	B	13.31
		18	89.7	84.4	C	1.70
		24	95.0	92.6	D	53.66
		30	96.3	96.6	DE	67.04
		36	100.0	100.0	E	69.61
	P. placenta	6	37.4	57.1	A	1.71
		12	75.1	66.3	B	11.34
		18	95.2	78.4	C	18.10
		24	96.3	88.6	D	30.60
		30	99.5	91.2	D	31.55
		36	98.7	94.3	D	39.75
	T. versicolor	6	11.1	41.1	A	0.96
		12	-21.9	50.0	B	4.37
		18	-2.7	77.7	C	10.50
		24	8.1	89.8	D	12.78
		30	9.2	94.6	D	16.12
		36	15.0	97.4	D	16.66
80-100%	*G. trabeum*	6	23.7	57.1	A	6.88
		12	60.6	65.7	B	39.52
		18	81.9	85.0	C	56.10
		24	87.0	94.0	D	57.18
		30	92.8	98.3	D	62.54
		36	100.0	100.0	D	61.78
	P. placenta	6	31.8	49.6	A	0.00
		12	80.2	59.6	B	22.28
		18	96.3	89.8	C	51.00
		24	97.0	97.2	D	53.10
		30	100.0	100.0	D	59.07
		36	100.0	100.0	D	64.91
	T. versicolor	6	3.1	34.0	A	0.24
		12	9.4	48.6	B	5.38
		18	52.1	73.8	C	14.40
		24	56.2	84.5	D	18.10
		30	69.7	89.8	D	17.02
		36	87.5	93.6	D	18.86
100-130%	*G. trabeum*	6	26.0	47.5	A	1.33
		12	42.8	61.7	B	20.24
		18	94.0	82.9	C	39.80
		24	97.0	92.6	D	46.70
		30	93.0	94.8	D	58.15
		36	92.8	97.2	D	60.44
	P. placenta	6	4.9	48.4	A	0.42
		12	6.6	55.7	B	32.24
		18	83.8	76.6	C	43.60
		24	87.5	85.5	D	47.39
		30	78.8	94.3	E	44.99
		36	100.0	100.0	F	52.16
	T. versicolor	6	-9.4	44.9	A	1.59
		12	32.6	53.8	B	5.37
		18	27.4	71.6	C	10.40
		24	35.8	81.3	D	15.81
		30	40.2	93.2	E	18.37
		36	42.5	96.7	E	19.18

Table 10. Mean MOR, MOE, and mass loss values for southern pine beams inoculated with one of three fungi (*G. trabeum*, *P. placenta* or *T. versicolor*) at three moisture content regimes (40-60, 80-100, and 100-130%) and incubated at 25°C for 6 to 36 weeks. Values followed by the same capital letter within a category are not significantly different (α = 0.05) by the Tukey-Kramer method.

TARGET MOISTURE CONTENT	TEST FUNGUS	INCUBATION PERIOD (WEEKS)	MOR LOSS (%)	MOE LOSS (%)		MASS LOSS (%)
40-60%	*G. trabeum*	6	32.0	56.1	A	2.31
		12	24.3	74.5	B	11.09
		18	75.9	86.4	C	15.80
		24	84.5	90.7	CD	21.05
		30	95.2	92.1	D	24.49
		36	100.0	100.0	E	25.36
	P. placenta	6	14.9	56.4	A	1.60
		12	66.0	73.1	B	10.63
		18	85.9	85.7	C	23.50
		24	91.0	88.5	CD	24.52
		30	100.0	94.5	DE	35.44
		36	95.4	99.3	E	35.19
	T. versicolor	6	11.8	49.7	A	0.27
		12	-10.0	53.1	B	0.75
		18	-5.1	74.6	C	3.20
		24	4.9	78.1	CD	1.67
		30	10.1	81.6	D	2.58
		36	11.9	92.1	E	2.73
80-100%	*G. trabeum*	6	17.7	47.2	A	2.78
		12	29.8	66.5	B	6.82
		18	36.6	88.4	C	16.70
		24	42.8	93.0	CD	22.71
		30	39.7	95.9	D	39.90
		36	48.4	98.6	D	42.91
	P. placenta	6	-21.0	53.9	A	0.47
		12	-4.8	78.1	B	2.03
		18	90.7	92.0	C	24.30
		24	96.5	96.7	D	30.01
		30	100.0	100.0	D	34.52
		36	100.0	100.0	D	35.94
	T. versicolor	6	7.2	52.8	A	1.06
		12	-17.9	57.4	B	2.06
		18	-12.2	72.6	C	4.20
		24	-1.2	79.9	D	4.63
		30	-2.7	85.7	DE	4.81
		36	4.3	91.4	E	3.40
100-130%	*G. trabeum*	6	17.1	53.9	A	1.12
		12	18.8	73.1	B	5.78
		18	26.8	91.6	C	12.30
		24	23.8	94.5	C	13.24
		30	30.7	97.3	C	23.63
		36	54.3	97.8	C	33.78
	P. placenta	6	8.0	53.2	A	1.66
		12	32.4	65.0	B	2.57
		18	37.8	86.5	C	20.50
		24	37.4	92.4	D	10.08
		30	44.2	94.3	D	12.56
		36	76.8	96.4	D	13.65
	T. versicolor	6	4.5	53.3	A	1.37
		12	-5.4	64.3	AB	1.68
		18	-2.4	76.9	BC	2.30
		24	5.2	87.1	C	18.97
		30	9.9	90.0	C	41.78
		36	6.4	92.5	C	45.30

Table 11. Mean MOR, MOE, and mass loss values for Douglas-fir beams inoculated with one of three fungi (*G. trabeum*, *P. placenta* or *T. versicolor*) at three moisture content regimes (40-60, 80-100, and 100-130%) and incubated at 35°C for 6 to 36 weeks. Values followed by the same capital letter within a category are not significantly different (α = 0.05) by the Tukey-Kramer method.

TARGET MOISTURE CONTENT	TEST FUNGUS	INCUBATION PERIOD (WEEKS)	MOR LOSS (%)	MOE LOSS (%)		MASS LOSS (%)
40-60%	*G. trabeum*	6	48.7	51.7	A	3.88
		12	62.4	82.0	B	7.09
		18	62.2	92.4	C	28.30
		24	69.8	98.2	D	29.62
		30	100.0	100.0	D	31.54
		36	100.0	100.0	D	31.40
	P. placenta	6	24.1	54.7	A	0.64
		12	74.8	86.6	B	11.64
		18	84.7	94.1	C	33.50
		24	92.5	95.7	CD	24.29
		30	97.4	99.5	D	45.81
		36	100.0	100.0	D	46.20
	T. versicolor	6	10.8	47.8	A	0.27
		12	15.2	53.9	B	1.36
		18	15.1	68.3	C	1.70
		24	16.1	71.3	CD	2.64
		30	24.3	73.1	D	4.06
		36	25.5	98.8		5.37
80-100%	*G. trabeum*	6	42.2	60.7	A	2.48
		12	62.6	75.9	B	13.68
		18	61.6	93.2	C	29.80
		24	71.4	97.0	D	39.17
		30	59.7	98.8	D	41.49
		36	100.0	100.0	D	42.25
	P. placenta	6	32.0	68.2	A	0.31
		12	20.7	85.8	B	4.23
		18	26.4	97.2	C	30.20
		24	34.6	99.3	C	31.88
		30	100.0	99.8	C	31.19
		36	100.0	100.0	C	34.61
	T. versicolor	6	15.5	36.2	A	1.58
		12	23.6	49.1	B	3.38
		18	28.5	79.6	C	4.10
		24	35.6	84.2	CD	5.41
		30	55.8	87.2	DE	5.50
		36	59.7	93.8	E	5.87
100-130%	*G. trabeum*	6	46.1	56.8	A	1.39
		12	40.9	70.8	B	6.56
		18	67.8	93.1	C	27.50
		24	65.4	97.3	CD	29.10
		30	92.5	99.2	D	29.58
		36	100.0	100.0	D	31.90
	P. placenta	6	31.8	45.3	A	1.54
		12	37.6	52.9	B	2.92
		18	64.2	80.3	C	2.80
		24	74.1	86.7	D	4.38
		30	94.8	91.8	D	5.82
		36	100.0	100.0	E	18.12
	T. versicolor	6	16.6	49.4	A	0.27
		12	18.3	52.4	A	2.19
		18	17.3	75.7	B	2.00
		24	21.2	81.6	C	4.67
		30	22.6	85.9	C	1.03
		36	26.6	91.6	D	8.80

Table 12. Mean MOR, MOE, and mass loss values for western hemlock beams inoculated with one of three fungi (*G. trabeum*, *P. placenta* or *T. versicolor*) at three moisture content regimes (40-60, 80-100, and 100-130%) and incubated at 35°C for 6 to 36 weeks. Values followed by the same capital letter within a category are not significantly different (α = 0.05) by the Tukey-Kramer method.

TARGET MOISTURE CONTENT	TEST FUNGUS	INCUBATION PERIOD (WEEKS)	MOR LOSS (%)	MOE LOSS (%)		MASS LOSS (%)
40-60%	*G. trabeum*	6	1.8	53.2	A	0.76
		12	82.4	87.9	B	20.70
		18	84.0	91.6	BC	41.20
		24	75.1	95.9	CD	47.32
		30	100.0	100.0	D	49.54
		36	100.0	100.0	D	53.00
	P. placenta	6	41.0	58.6	A	2.01
		12	54.0	89.8	B	10.81
		18	75.3	93.1	B	16.60
		24	77.4	97.0	C	17.50
		30	100.0	100.0	C	21.60
		36	100.0	100.0	C	30.50
	T. versicolor	6	7.7	38.7	A	0.85
		12	2.2	64.0	B	1.29
		18	4.4	76.6	C	2.40
		24	8.7	83.9	C	6.69
		30	8.8	93.0	D	7.11
		36	13.7	94.3	D	9.97
80-100%	*G. trabeum*	6	51.6	57.3	A	7.40
		12	79.0	88.0	B	49.41
		18	79.1	96.3	C	31.31
		24	78.2	98.0	C	18.83
		30	100.0	100.0	C	52.65
		36	100.0	100.0	C	53.60
	P. placenta	6	13.3	49.8	A	1.03
		12	31.6	71.6	B	4.28
		18	69.6	77.3	BC	7.90
		24	72.3	80.5	C	14.50
		30	70.5	84.5	CD	20.02
		36	83.7	90.8	D	35.70
	T. versicolor	6	12.2	32.5	A	0.30
		12	10.9	68.8	B	3.00
		18	10.9	77.0	C	5.30
		24	8.5	85.1	D	6.75
		30	15.9	92.0	E	11.99
		36	28.8	97.8	E	16.10
100-130%	*G. trabeum*	6	30.0	47.9	A	3.10
		12	26.6	82.4	B	6.68
		18	33.7	93.9	C	10.50
		24	37.7	96.3	C	32.59
		30	44.7	98.3	C	57.09
		36	61.1	98.5	C	59.40
	P. placenta	6	1.1	48.7	A	0.88
		12	29.6	76.5	B	3.12
		18	74.7	89.2	C	5.10
		24	72.7	92.8	CD	11.10
		30	79.7	96.1	DE	15.70
		36	100.0	100.0	E	19.86
	T. versicolor	6	-12.2	45.5	A	1.83
		12	24.1	66.1	B	6.50
		18	23.1	78.6	C	4.90
		24	22.4	85.8	D	4.88
		30	22.2	88.5	D	4.21
		36	25.1	96.7	E	3.81

Table 13. Mean MOR, MOE, and mass loss values for southern pine beams inoculated with one of three fungi (*G. trabeum*, *P. placenta* or *T. versicolor*) at three moisture content regimes (40-60, 80-100, and 100-130%) and incubated at 35°C for 6 to 36 weeks. Values followed by the same capital letter within a category are not significantly different (α = 0.05) by the Tukey-Kramer method.

TEMP	TARGET MOISTURE CONTENT	INCUBATION PERIOD (WEEKS)	MOR LOSS (%)	MOE LOSS (%)		MASS LOSS (%)
15°C	*40-60%*	6		0.0	A	
		12		5.3	AB	
		18		8.9	ABC	
		24		12.2	BC	
		30		14.1	CD	
		36	-0.8	16.4	D	0.93
	80-100%	6		0.0	A	
		12		5.1	AB	
		18		7.7	ABC	
		24		13.1	BCD	
		30		16.2	CD	
		36	-2.6	18.4	CD	0.82
	100-130%	6		0.0	A	
		12		6.1	AB	
		18		10.8	BC	
		24		13.4	BC	
		30		16.6	C	
		36	0.4	17.7	C	1.40
25°C	*40-60%*	6		2.9	A	
		12		7.2	AB	
		18		11.2	BC	
		24		13.0	C	
		30		16.0	CD	
		36	10.1	20.0	D	0.79
	80-100%	6		5.5	A	
		12		7.3	A	
		18		10.9	AB	
		24		13.1	ABC	
		30		16.2	BC	
		36	4.8	19.8	C	2.66
	100-130%	6		3.7	A	
		12		6.7	AB	
		18		9.0	AB	
		24		12.4	ABC	
		30		15.7	BC	
		36	7.2	19.9	C	1.96
35°C	*40-60%*	6		5.1	A	
		12		11.8	B	
		18		36.5	C	
		24		38.6	C	
		30		39.9	C	
		36	7.7	41.8	C	1.18
	80-100%	6		5.1	A	
		12		11.0	B	
		18		36.7	C	
		24		38.9	CD	
		30		40.8	CD	
		36	10.2	42.4	D	0.92
	100-130%	6		2.6	A	
		12		10.8	B	
		18		44.7	C	
		24		46.2	C	
		30		47.8	C	
		36	8.2	49.5	C	0.56

Table 14. Mean MOR, MOE, and mass loss values for Douglas-fir non-inoculated beams at 15, 25 and 35°C at three moisture content regimes (40-60, 80-100, and 100-130%). Values followed by the same capital letter within a category are not significantly different (α = 0.05) by the Tukey-Kramer method.

TEMP	TARGET MOISTURE CONTENT	INCUBATION PERIOD (WEEKS)	MOR LOSS (%)	MOE LOSS (%)		MASS LOSS (%)
15°C	40-60%	6		0.0	A	
		12		4.4	AB	
		18		7.8	BC	
		24		12.4	BC	
		30		16.0	DE	
		36	-3.1	19.3	E	0.62
	80-100%	6		0.0	A	
		12		5.6	AB	
		18		9.0	BC	
		24		14.7	CD	
		30		16.9	D	
		36	-0.7	19.5	D	1.80
	100-130%	6		0.0	A	
		12		5.1	AB	
		18		10.6	BC	
		24		16.3	CD	
		30		18.5	CD	
		36	0.9	19.8	D	2.19
25°C	40-60%	6		4.0	A	
		12		6.6	AB	
		18		11.6	BC	
		24		15.5	CD	
		30		18.7	D	
		36	4.7	21.6	D	0.29
	80-100%	6		2.6	A	
		12		6.6	A	
		18		13.2	BC	
		24		15.0	BC	
		30		18.9	BC	
		36	3.1	21.7	C	1.19
	100-130%	6		2.9	A	
		12		7.7	AB	
		18		12.6	BC	
		24		14.3	BC	
		30		16.9	C	
		36	4.4	19.9	C	0.64
35°C	40-60%	6		6.4	A	
		12		14.7	BC	
		18		42.0	C	
		24		44.3	CD	
		30		46.0	D	
		36	9.6	47.5	D	2.49
	80-100%	6		5.2	A	
		12		13.8	B	
		18		38.4	C	
		24		40.7	C	
		30		42.5	C	
		36	9.4	44.5	C	1.27
	100-130%	6		4.7	A	
		12		11.5	B	
		18		40.3	C	
		24		42.2	CD	
		30		44.1	CD	
		36	11.2	46.3	D	1.67

Table 15. Mean MOR, MOE, and mass loss values for western hemlock non-inoculated beams at 15, 25 and 35°C at three moisture content regimes (40-60, 80-100, and 100-130%). Values followed by the same capital letter within a category are not significantly different (α = 0.05) by the Tukey-Kramer method.

TEMP	TARGET MOISTURE CONTENT	INCUBATION PERIOD (WEEKS)	MOR LOSS (%)	MOE LOSS (%)		MASS LOSS (%)
15°C	40-60%	6		0.0	A	
		12		3.4	A	
		18		9.5	B	
		24		13.0	BC	
		30		16.0	CD	
		36	1.5	20.3	D	0.18
	80-100%	6		0.0	A	
		12		4.1	AB	
		18		8.2	BC	
		24		12.8	CD	
		30		17.0	DE	
		36	-2.5	20.7	E	1.20
	100-130%	6		0.0	A	
		12		6.4	B	
		18		9.8	BC	
		24		15.9	BC	
		30		19.5	CD	
		36	-6.6	23.1	D	0.76
25°C	40-60%	6		6.1	A	
		12		20.4	B	
		18		28.6	BC	
		24		31.0	BCD	
		30		37.6	CD	
		36	5.2	40.7	D	1.42
	80-100%	6		7.3	A	
		12		12.9	AB	
		18		16.9	BC	
		24		19.9	BC	
		30		21.9	C	
		36	6.8	24.4	C	1.75
	100-130%	6		6.7	A	
		12		11.6	AB	
		18		18.1	BC	
		24		20.8	CD	
		30		23.5	CD	
		36	3.7	27.2	D	0.67
35°C	40-60%	6		7.9	A	
		12		14.3	A	
		18		44.7	B	
		24		47.4	B	
		30		48.4	B	
		36	8.3	49.9	B	1.59
	80-100%	6		8.7	A	
		12		13.5	A	
		18		37.2	B	
		24		40.4	B	
		30		42.2	B	
		36	6.0	43.7	B	1.98
	100-130%	6		6.2	A	
		12		11.8	A	
		18		46.1	B	
		24		48.1	B	
		30		49.2	B	
		36	9.5	51.0	B	1.06

Table 16. Mean MOR, MOE, and mass loss values for southern pine non-inoculated beams at 15, 25 and 35°C at three moisture content regimes (40-60, 80-100, and 100-130%). Values followed by the same capital letter within a category are not significantly different (α = 0.05) by the Tukey-Kramer method.

Chemical Analyses

Decayed Microbeams

Alkali solubilities of Douglas-fir beams that were exposed to *G. trabeum* or *P. placenta* for 6 or 12 weeks were progressively higher than those found in the controls (Fig. 17). These results were consistent with the tendency for brown rot fungi to degrade, but not fully utilize carbohydrates that are then more susceptible to solubilization in alkaline compounds. Alkali solubilities of beams exposed to *T. versicolor* declined over the 6 or 12 week exposure, which is also consistent with the tendency for the white rot fungi to consume nearly all carbohydrate breakdown products as they are produced, leaving little material to be solubilized in the sodium hydroxide.

Western hemlock samples attacked by *G. trabeum* and *T. versicolor* showed little evidence of cellulose depletion (Table 17), but these fungi were associated with substantial changes in the chemical composition of hemicelluloses (Tables 17 and 18). Arabinose decreased 20% for both brown rot and white rot fungi. Exposure to the white rot fungus was associated with a 16% loss in galactose content after 18 weeks of incubation. Galactose, xylose, mannose and glucose losses for wood attacked by *G. trabeum* were 42, 13, 6.5 and1.4 %, respectively, after only six weeks of incubation. This decline in

hemicellulose component levels corresponded to the decreases observed in mechanical properties and was consistent with previous reports on the effects of brown rot fungi on hemicelluloses (Winandy and Morrell, 1993)

Hemicellulose component losses following incubation for an additional 6 weeks were 52% for arabinose, 23 % for xylose and 10.5 % for mannose and 5.4 % for galactose. Declines in arabinose and xylose continued after 18 weeks, but no additional decreases were noted for the other hemicellulose components.

Softwoods contain two main hemicelluloses: 60% are galacto-glucomannan (70% mannan) and 40% are arabino-4-O-methyl- glucuronoxylan (65% xylan) (Timell, 1967; Highley, 1987). In a study of the relationship between mechanical properties and chemical composition of southern pine during incipient decay, Curling et al.(2002) found that 50% loss of MOR caused by *G. trabeum* corresponded with 40, 20, 10, 10, and 1% losses of galactan, arabinan, xylan, mannan, and glucan, respectively. Curling et al. (2002) found that significant loss of glucan, representing cellulose, only occurred at MOR losses greater than 75%. Preferential attack of hemicelluloses suggests that the fungus disrupts the ligno-cellulose matrix, making it difficult to share load across the matrix (Sweet and Winandy, 1999). Winandy and Morrell (1993) also suggested that hemicellulose sidechains were initially degraded during

incipient decay followed by glucomannan main chains. Decay fungi utilize this component first since hemicellulose is more readily accessible to enzymatic attack (Winandy and Morrell, 1993; Highley, 1987; Kirk and Highley, 1973). These losses in flexural properties also occur in fire retardant treated wood as the acidic fire retardants attack the hemicellulose components. These results suggest that the early effects of both processes on the wood are chemical in nature.

Non-Inoculated Microbeams

Lignin levels in non-fungal exposed Douglas-fir, western hemlock and southern pine beams ranged from 23 to 29 % depending on the wood species (Fig. 18). Lignin levels in beams that were sterilized and exposed in vermiculite at 15, 25 or 35^{o}C varied among the different treatments, but the differences were small and inconsistent. These results suggest that exposure to vermiculite had little effect on lignin content regardless of incubation temperature.

Alkali solubility is generally an indicator of carbohydrate degradation and tends to be highest at the early stages of attack by brown rot fungi. Alkali solubility tended to be highest in control beams, declined sharply in beams incubated at 15 or 25^{o}C, then appeared to increase again in beams incubated at 35^{o}C (Fig. 19). These results would suggest that elevated incubation

temperature affected alkali solubility; however, the solubilities found in beams incubated at 35^{o}C were still below those found in the control beams. These results suggest that the losses in flexural properties observed in the control beams are unrelated to changes in carbohydrate chemistry.

The potential effect of elevated pH on beam integrity was assessed by exposing Douglas-fir beams to vermiculite leachate. Exposure of beams to vermiculite leachate with and without agitation showed measurable decreases in alkali solubility and this decrease was slightly greater with agitation (Fig. 20). However, wood is generally acidic and the pH value of the vermiculite at the end of the 36 week exposure was well within range of wood (pH 5.4). These results suggest that vermiculite pH was not a factor in the observed changes in flexural properties in the controls.

Alkali solubility and lignin test results failed to explain the MOE differences observed in non-inoculated microbeams incubated at 35^{o}C. Further research will be needed in order to understand the potential effects of vermiculite pH on hemicelluloses and the subsequent potential effects on MOE.

TEST FUNGUS	EXPOSURE TIME (WEEKS)	HEMICELLULOSE (%)	CELLULOSE (%)
G. trabeum	0	21.5	39.0
	6	18.7	38.7
	12	17.6	38.6
	18	18.3	38.9
T. versicolor	0	21.6	37.3
	6	21.9	38.3
	18	21.3	38.1

Table 17. Cellulose and hemicellulose contents of western hemlock beams incubated for 6, 12 and 18 weeks after inoculation with *G. trabeum* or *T. versicolor.*

TEST FUNGUS	EXPOSURE TIME (WEEKS)	ARABINAN (%)	XYLAN (%)	MANNAN (%)	GALACTAN (%)	GLUCAN (%)
G. trabeum	0	1.0	3.8	10.7	2.4	42.6
	6	0.8	3.3	10.0	1.4	42.0
	12	0.7	2.9	9.6	1.3	41.8
	18	0.6	2.8	9.8	1.8	42.0
T. versicolor	0	1.0	3.6	11.0	2.5	40.9
	6	0.8	3.4	11.4	2.6	42.1
	18	0.8	3.6	11.1	2.1	41.8

Table 18. Arabinose, xylose, mannose, galactose and glucose content of western hemlock microbeams incubated for 6, 12 and 18 weeks after inoculation with *G. trabeum* or *T. versicolor.*

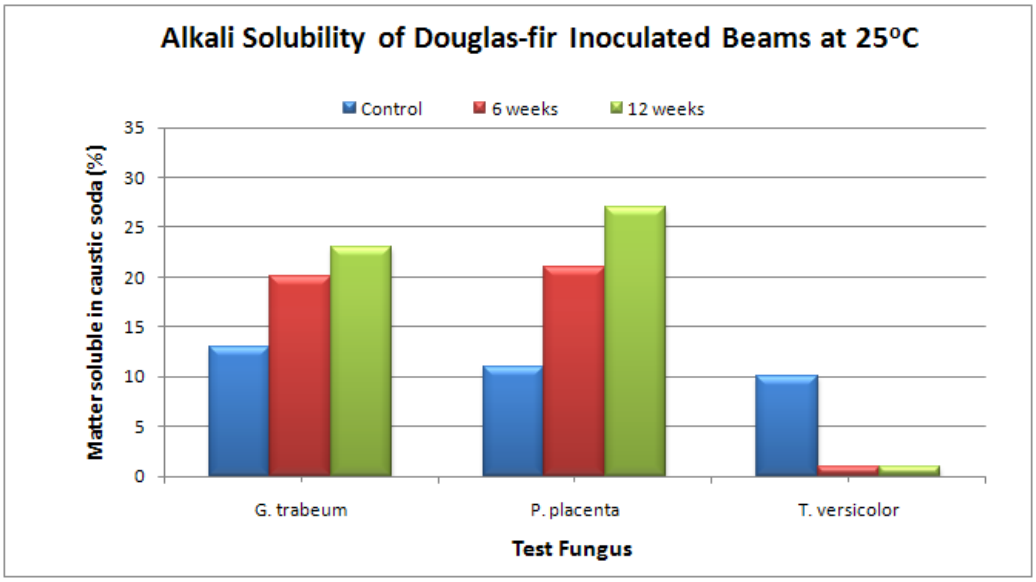


Figure 17. Alkali solubility levels of Douglas-fir microbeams incubated for 6 or 12 weeks at 25°C after inoculation with *G. trabeum*, *P. placenta* or *T. versicolor*.

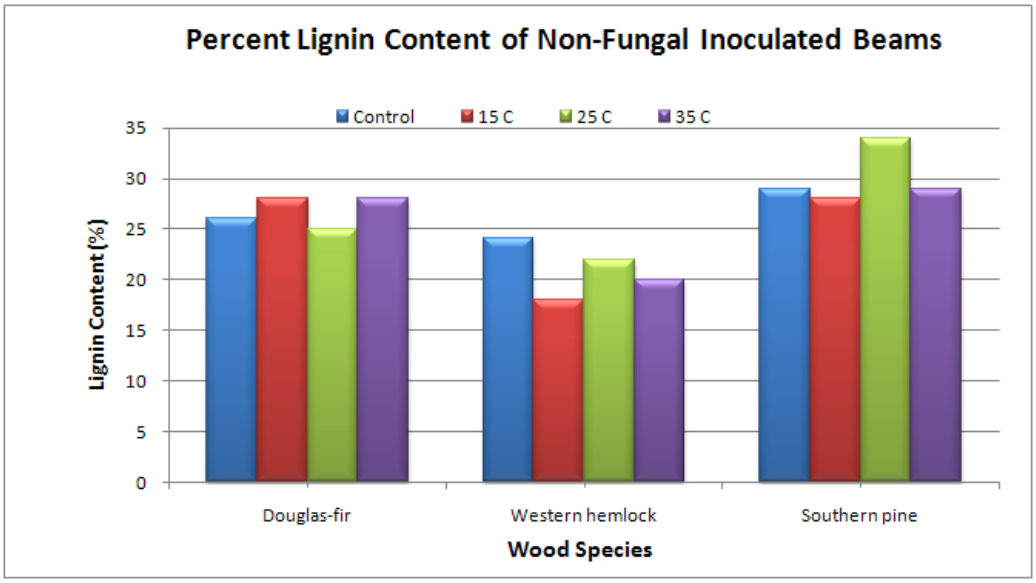


Figure 18. Percent lignin content of non-fungal inoculated Douglas-fir, western hemlock and southern pine control beams after 36 weeks of incubation in vermiculite at 15, 25 or 35°C.

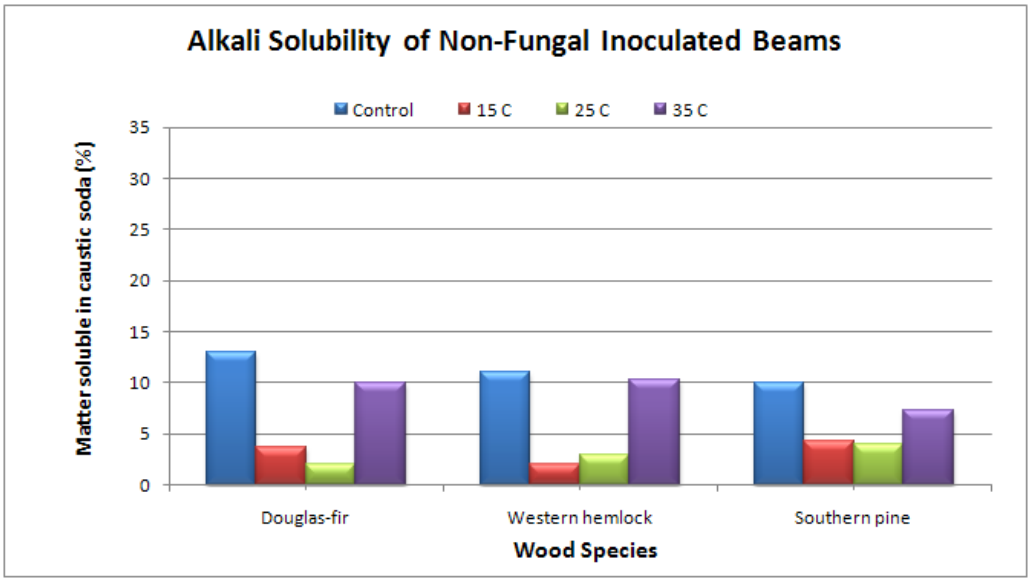


Figure 19. Alkali solubility levels of non-fungal inoculated Douglas-fir, western hemlock and southern pine control beams after 36 weeks of incubation in vermiculite at 15, 25 or 35°C.

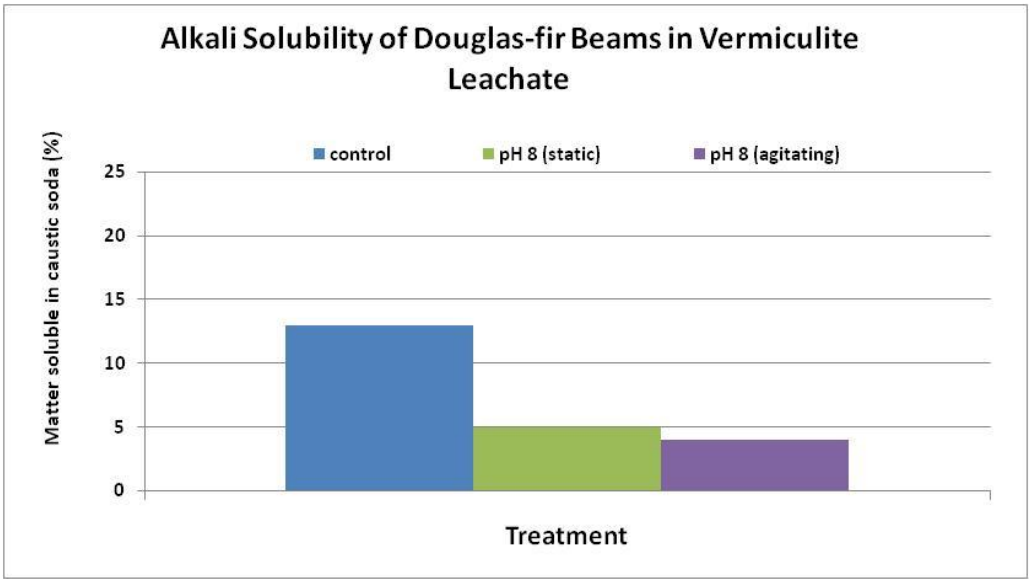


Figure 20. Alkali solubility of non-fungal inoculated Douglas-fir microbeams in a solution of vermiculite leachate at a) pH 5 with agitation, b) pH 8 with no agitation, or c) pH 8 with agitation.

Statistical Analyses and Modeling

Interactions

There were indications that temperature was a significant factor, where higher temperatures were associated with higher MOE losses; however, since data was partitioned according to wood species and temperature and it was not possible to statistically compare results obtained between each of the nine models in terms of wood species or temperature.

The effect of moisture content within each of the nine models was found to depend on both levels of fungi and time (Tables 19-27) at all temperatures for all wood species. Thus, all moisture content levels were explained for all fungi at all time points. A total of nine models were developed, each explained by three figures (Fig. 21-23) and nine equations (Equations 1-9). Every model consisted of one wood species and a temperature condition. Confidence limits show that model accuracy decreased as time progressed, but the wood had been severely decayed to the point where the prediction of fungal effects on wood properties was of less interest at the advanced stages of attack.

The effects of moisture content alone at 15 and 25^{o}C were not significant, although the interactions between fungi, moisture content and time

were significant, suggesting that fungal metabolic activity decreased at lower temperatures, thereby reducing oxygen demand. Thus, oxygen availability in wood appeared to be less critical at the lower temperature. These results were in contrast to those found at 35^{o}C where moisture content was a significant factor for MOE losses in wood. Fungal activity, and therefore respiration, might be expected to be greater at the higher temperature, and the reduced void volumes associated with the higher moisture contents might have resulted in more rapid oxygen depletion at the higher temperatures.

Fungal species had a significant effect on all nine models (Table 19-27). *T. versicolor* data was used as the control group within each model dataset and comparisons were perfomed using the Dunnett's test. MOE losses caused by *T. versicolor* were significantly lower than those produced by the two brown rot species.

As expected, the models showed that incubation at cooler temperatures had a marked effect on MOE losses for all three wood species, regardless of fungus or wood species. MOE losses were reduced at 15 C in comparison with those at either 25 or 35 C. Most houses are maintained at temperatures between 18 and 24 C; however, the entire house is rarely at that temperature. Locations nearer the outside are more likely to be at temperatures closer to ambient conditions, while those in the interior may be much warmer. In

addition, internal sources of heat (kitchen ovens, dryers, etc) can artificially increase temperatures in some locations. Thus, conditions suitable for decay may be more prevalent closer to the interior in cool climates and nearer the outer walls in warm climates, particularly if the house has air-conditioning. This information might be useful for designing air-exchange systems capable of slowing the effects of any moisture intrusion in the building cavity. It could also provide useful information when assessing the rate of decay in a given portion of a building.

MOE losses also tended to be slow initially and then increased rapidly, reflecting the need for the fungus to grow through the wood before it began to exert substantial effects on integrity of the wood polymers. Understanding the nature of this lag phase may help in developing more realistic models that incorporate biological knowledge about the rates of entry of fungal propagules into the building, their rate of germination and hyphal extension and finally, their ability to degrade various wood polymers. This information would need to be developed separately, since we did not evaluate the rate of fungal colonization, only its effects on the wood. In addition, it would also be useful to develop a better understanding of the effects of early colonization on MOE. The models developed herein were based upon beginning sampling after a 6 week incubation period and this appeared to be too long to detect the early stages of fungal attack. The incubation times were chosen based upon previous work as

well as an understanding that there were a limited number of sampling points. The initial concern was that the fungus, starting from hyphal fragments and not the mature mycelium used in many tests, would grow more slowly and therefore not cause substantial wood degradation until later in the test period. This clearly was erroneous and earlier samplings would have increased the value of the model as a predictive tool.

Wood moisture content was shown to be a significant factor in the models; however, it did not appear to have the same effect as temperature. Most decay fungi require wood that is above the fiber saturation point in order to colonize and degrade wood and their growth will cease at higher moisture contents as oxygen becomes limiting. The models suggest that there was relatively little difference in rate of decay within the broad range of moisture contents evaluated, although there was a suggestive decrease in predicted MOE losses at the highest moisture content with some wood/fungi combinations, particularly at the higher temperature. As noted earlier, this interaction between moisture content and temperature could reflect oxygen levels that were initially limited by the higher moisture levels that were exacerbated by a faster rate of fungal activity at the higher temperature. This potential effect merits further study because it could affect predictions of decay rates in warmer climates.

The models suggested that fungus and wood species were less important than temperature in predicting decay rate. This seems counterintuitive since the fungi chosen have markedly different modes of decay and the wood species have well known differences in susceptibility to decay. For example, both of the brown rot fungi tend to be more aggressive at lower moisture contents, while the white rot fungus is usually more effective at higher moisture levels. Neither of these trends was shown in the model. Once again, however, the time sequence of the data used to construct the model may have influenced the results since MOE loses were already 30 to 50 % for most treatment combination. It is possible that any effects of fungus or wood were already mitigated by the time the first samples were evaluated. Thus, the model might be improved by a second experiment wherein similar beams were subjected to more frequent sampling to capture the initial stages of MOE loss. This will be especially important if the model is to be extended to actual structures.

The models developed using our data are difficult to compare to previous prediction models since most previous studies measured decay in terms of mass loss, not strength properties. Output generated from the current models were compared to the limited previous studies describing the behavior of wood strength as decay progressed (Fig. 24) (Curling et. al., 2002; Li et. al., 2007; Machek et. al., 1997, 1998; Winandy and Morrell, 1993).

Curling et al.(2002) and Winandy and Morrell (1993) both exposed beams in various assemblies that concentrated fungal attack at the center. Machek, et.al.(1997) used a fungus cellar decay test to expose non-treated beech stakes, a non-durable species, to non-sterile soil resulting in a higher rate of decay for these samples.

The MOE models from the current study compared favorably with data from Machek et.al.(1998), who found high MOE losses after short exposure periods. These losses reached 80% MOE loss at week 12. Li et.al.,(2007) used an accelerated contact decay test in non-sterile soil and found an almost linear progression of MOE loss with time, reaching 60% loss at week 24. Curling et.al. (2002) found extremely high MOE losses within 7 to 10 weeks, with losses almost reaching 100%. Winandy and Morrell (1993) obtained much lower decay rates than those predicted by the present study. These results highlight the inherent variability in rates of fungal attack. As a result, predictive models must be capable of dealing with a wide range of outcomes depending on the wood species, fungal species and environmental conditions in a structure.

A comparison of mass losses from this study with those in prior studies (Cartwright et.al., 1931; Kennedy, 1958; Mulholland, 1954; Richards and Chidester, 1940; Smith et. al., 1992; Viitanen, 1997; Winandy and Morrell,1993;

Winandy et. al., 2000) showed an almost linear relationship between mass losses and time. Viitanen (1997) found similar results with his model. Cartwright et. al. (1931) found that mass losses of 2% were associated with a 50% MOR reduction of 50% and 55% reduction in MOE while 6% mass loss was associated with reductions of 66 and 61% for MOE and MOR, respectively. Richards and Chidester (1940) reported mass losses of 7% associated with reductions in MOR of 12 and 57% on southern pine attacked by *Peniophora gigantea* and *G. trabeum*, respectively. Kennedy (1958) found that even durable wood species like teak can have MOR reductions of 27% with 1% mass loss.

The current study found MOE losses of 40-45% and MOR losses of 30-35% with the attack of brown rot fungi at 2% mass loss and losses of 60% for MOE and 50% for MOR at 6% mass loss (Fig. 16). These data reinforce prior research showing that considerable bending and strength reduction occurs before detectable mass losses (Cartwright et.al., 1931; Clausen et.al.,1991; Kennedy, 1958; Richards and Chidester, 1940; Wilcox, 1978; Winandy and Morrell, 1993).

Kennedy (1958) related strength retention to mass loss of various species of wood attacked by *P. placenta* and *T. versicolor* and developed linear equations by plotting the common logarithm of percent strength retention

against percent mass loss. Unlike the present study, wood species were a major factor for determining the degree of strength reduction associated with mass loss although all the species Kennedy studied were hardwoods. He found that strength losses were higher for wood attacked by the brown rot than by the white rot fungus.

Kennedy also plotted MOR against percent increase in alkali solubility of wood attacked by *P. placenta*, finding that solubility of decayed wood increased 1 % for every percent in strength loss. The increased alkali solubilities suggested that accumulations of low molecular weight carbohydrates were associated with the high degree of strength loss resulting from enzymatic hydrolysis of cellulose or hemicellulose (Winandy and Morrell, 1993). Cartwright et. al. (1931) and Armstrong (1935) concluded that strength loss due to decay by brown rot fungi was more closely related to increasing alkali solubility than to mass loss. Cartwright et. al. (1936) found that strength losses were not related to increased alkali solubility for white rot fungi attack on wood. The few alkali solubility tests done on decayed samples in this study corroborated the results obtained in earlier studies; a 3% increase in alkali solubility was associated with a 30% MOR loss (from week 6 to 12) in Douglas-fir beams attacked by brown rot fungi at 25^{o}C. Attack by *T. versicolor* had no noticeable effect on alkali solubility of Douglas-fir under the same conditions.

Strength properties (MOE and MOR) are useful for evaluating decay development in wood because they can be directly used by those involved in design and construction of structures. When evaluating a building for decay, an engineer must estimate the effect of decay on a given area on the safety level. While data on strength loss would be useful, it is generally not available. Instead, the engineer must estimate residual strength based upon the extent of visible decay. This results in very conservative estimates that are often defined by the area of wetting. While it is not possible to determine mass or strength loss visually, the model could be used in combination with knowledge about when wetting occurred to predict the effects of decay of a given temperature. Although there would be almost no way to determine when the fungus had entered the wood, the assessment could assume that the fungus was present at the same time the moisture conditions were suitable.

Effect	Num DF	Den DF	F Value	Pr > F
FUNGI	2	36	3.43	0.0432
MC	2	36	0.29	0.7528
MC*FUNGI	4	36	14.51	<.0001
TIMEwk	3	108	3487.07	<.0001
FUNGI*TIMEwk	6	108	0.90	0.5007
MC*TIMEwk	6	108	8.34	<.0001
MC*FUNGI*TIMEwk	**12**	**108**	**2.56**	**0.0052**

Table 19. Statistical test of fixed effect and interaction of Douglas-fir wood at 15°C.

Effect	Num DF	Den DF	F Value	Pr > F
FUNGI	2	36	19.34	<.0001
MC	2	36	5.65	0.0073
MC*FUNGI	4	36	7.91	0.0001
TIMEwk	4	144	6002.33	<.0001
FUNGI*TIMEwk	8	144	17.00	<.0001
MC*TIMEwk	8	144	8.44	<.0001
MC*FUNGI*TIMEwk	**16**	**144**	**5.53**	**<.0001**

Table 20. Statistical test of fixed effects and interaction of Douglas-fir wood at 25°C.

Effect	Num DF	Den DF	F Value	Pr > F
FUNGI	2	36	37.79	<.0001
MC	2	36	10.85	0.0002
MC*FUNGI	4	36	5.71	0.0011
TIMEwk	4	144	2586.97	<.0001
FUNGI*TIMEwk	8	144	11.01	<.0001
MC*TIMEwk	8	144	4.66	<.0001
MC*FUNGI*TIMEwk	**16**	**144**	**4.75**	**<.0001**

Table 21. Statistical test of fixed effects and interaction of Douglas-fir wood at 35°C.

Effect	Num DF	Den DF	F Value	Pr > F
FUNGI	2	36	3.76	0.0328
MC	2	36	1.01	0.3751
MC*FUNGI	4	36	4.24	0.0065
TIMEwk	3	108	1044.57	<.0001
FUNGI*TIMEwk	6	108	1.84	0.0987
MC*TIMEwk	6	108	6.17	<.0001
MC*FUNGI*TIMEwk	**12**	**108**	**4.28**	**<.0001**

Table 22. Statistical test of fixed effects and interaction of western hemlock wood at 15°C.

Effect	Num DF	Den DF	F Value	Pr > F
FUNGI	2	36	23.16	<.0001
MC	2	36	1.67	0.2033
MC*FUNGI	4	36	4.85	0.0031
TIMEwk	4	142	2928.61	<.0001
FUNGI*TIMEwk	8	142	27.83	<.0001
MC*TIMEwk	8	142	12.12	<.0001
MC*FUNGI*TIMEwk	**16**	**142**	**13.41**	**<.0001**

Table 23. Statistical test of fixed effects and interaction of western hemlock wood at 25°C.

Effect	Num DF	Den DF	F Value	Pr > F
FUNGI	2	36	189.74	<.0001
MC	2	36	59.45	<.0001
MC*FUNGI	4	36	40.17	<.0001
TIMEwk	4	144	2600.79	<.0001
FUNGI*TIMEwk	8	144	89.38	<.0001
MC*TIMEwk	8	144	29.51	<.0001
MC*FUNGI*TIMEwk	**16**	**144**	**23.56**	**<.0001**

Table 24. Statistical test of fixed effects and interaction of western hemlock wood at 35°C.

Effect	Num DF	Den DF	F Value	Pr > F
FUNGI	2	36	8.36	0.0010
MC	2	36	1.32	0.2796
MC*FUNGI	4	36	9.21	<.0001
TIMEwk	3	108	1429.64	<.0001
FUNGI*TIMEwk	6	108	0.85	0.5328
MC*TIMEwk	6	108	2.30	0.0398
MC*FUNGI*TIMEwk	**12**	**108**	**3.52**	**0.0002**

Table 25. Statistical test of fixed effects and interaction of southern pine wood at 15°C.

Effect	Num DF	Den DF	F Value	Pr > F
FUNGI	2	36	32.45	<.0001
MC	2	36	1.10	0.3437
MC*FUNGI	4	36	5.90	0.0009
TIMEwk	4	144	1947.97	<.0001
FUNGI*TIMEwk	8	144	20.85	<.0001
MC*TIMEwk	8	144	8.88	<.0001
MC*FUNGI*TIMEwk	**16**	**144**	**8.92**	**<.0001**

Table 26. Statistical test of fixed effects and interaction of southern pine wood at 25°C.

Effect	Num DF	Den DF	F Value	Pr > F
FUNGI	2	36	57.90	<.0001
MC	2	36	8.23	0.0011
MC*FUNGI	4	36	6.53	0.0005
TIMEwk	4	144	1054.84	<.0001
FUNGI*TIMEwk	8	144	28.79	<.0001
MC*TIMEwk	8	144	3.99	0.0003
MC*FUNGI*TIMEwk	**16**	**144**	**5.85**	**<.0001**

Table 27. Statistical test of fixed effects and interaction of southern pine wood at 35°C.

MOE MODEL -- DOUGLAS-FIR

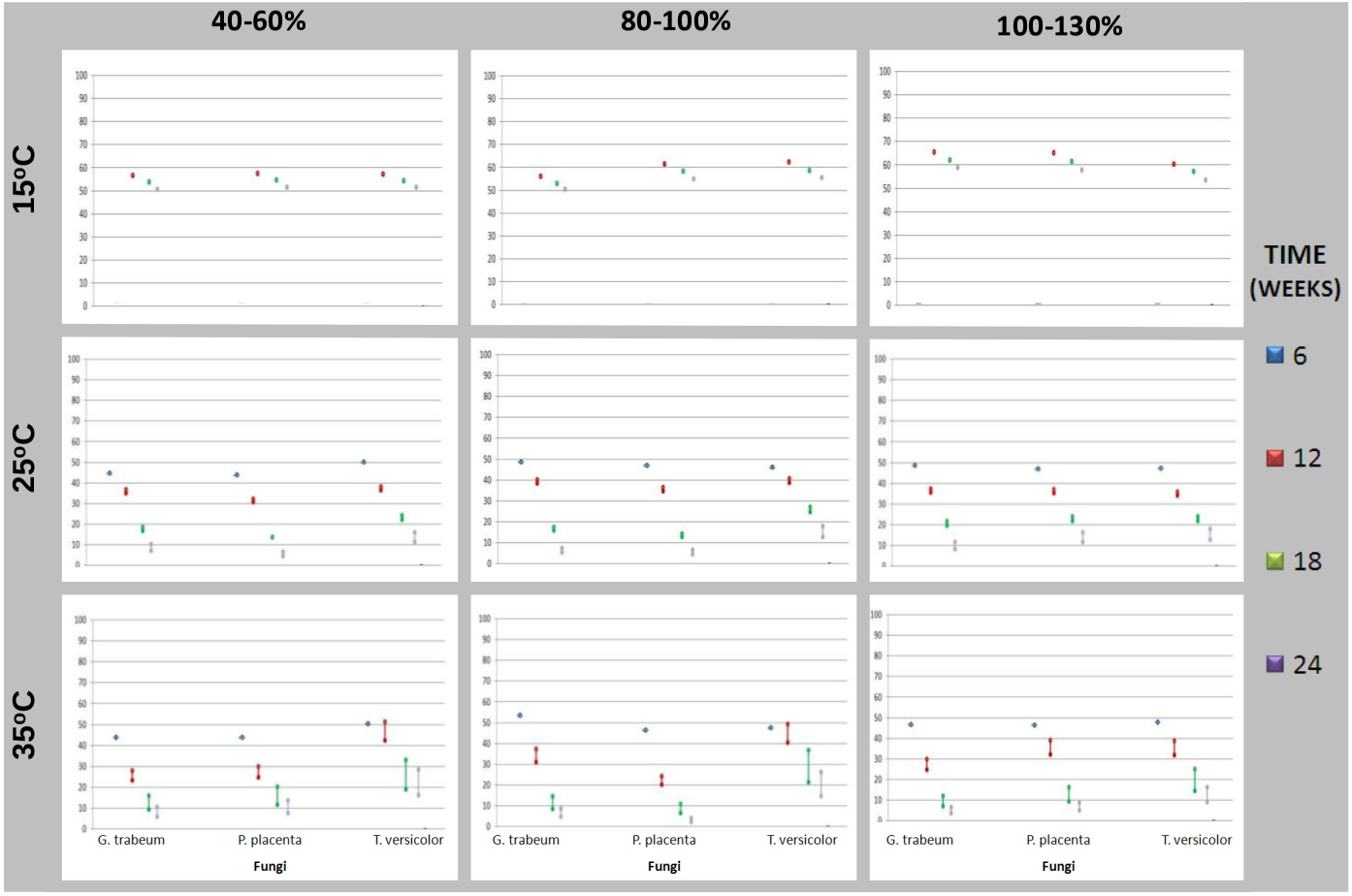


Figure 21. Model predicting residual MOE of Douglas-fir microbeams 6, 12, 18 and 24 weeks after inoculation with *G. trabeum, P. placenta* or *T. versicolor* and incubated at 15, 25, or 35°C at moisture content of 40-60%, 60-80% or 100-130% with 95% confidence interval bars.

MOE MODEL -- WESTERN HEMLOCK

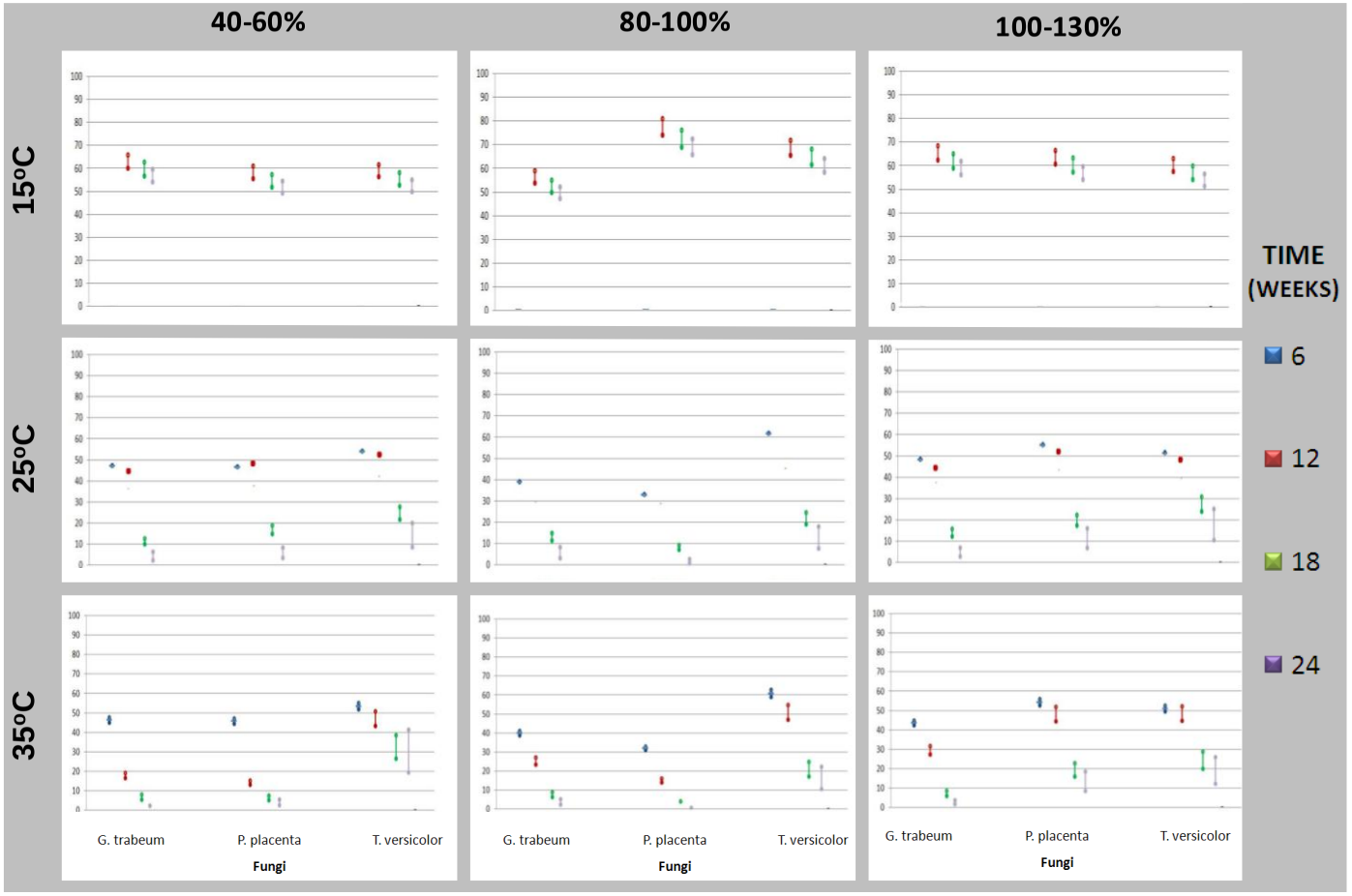


Figure 22. Model predicting residual MOE of western hemlock microbeams 6, 12, 18 and 24 weeks after inoculation with *G. trabeum, P. placenta* or *T. versicolor* and incubated at 15, 25, or 35°C and at moisture content of 40-60%, 60-80% or 100-130% with 95% confidence interval bars.

MOE MODEL -- SOUTHERN PINE

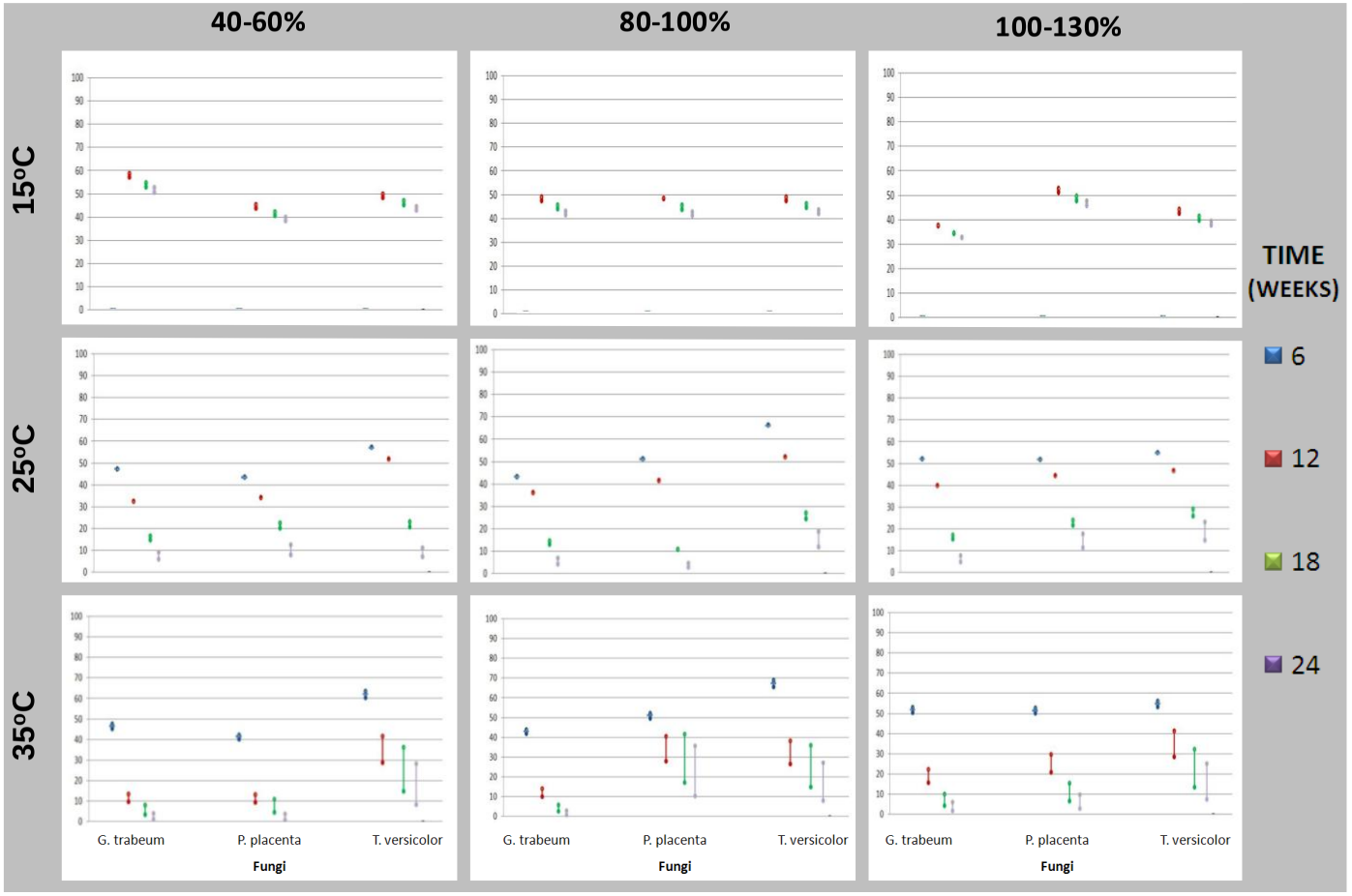


Figure 23. Model predicting residual MOE of southern pine microbeams 6, 12, 18 and 24 weeks after inoculation with *G. trabeum, P. placenta* or *T. versicolor* and incubated at 15, 25, or 35°C and at moisture content of 40-60%, 60-80% or 100-130% with 95% confidence interval bars.

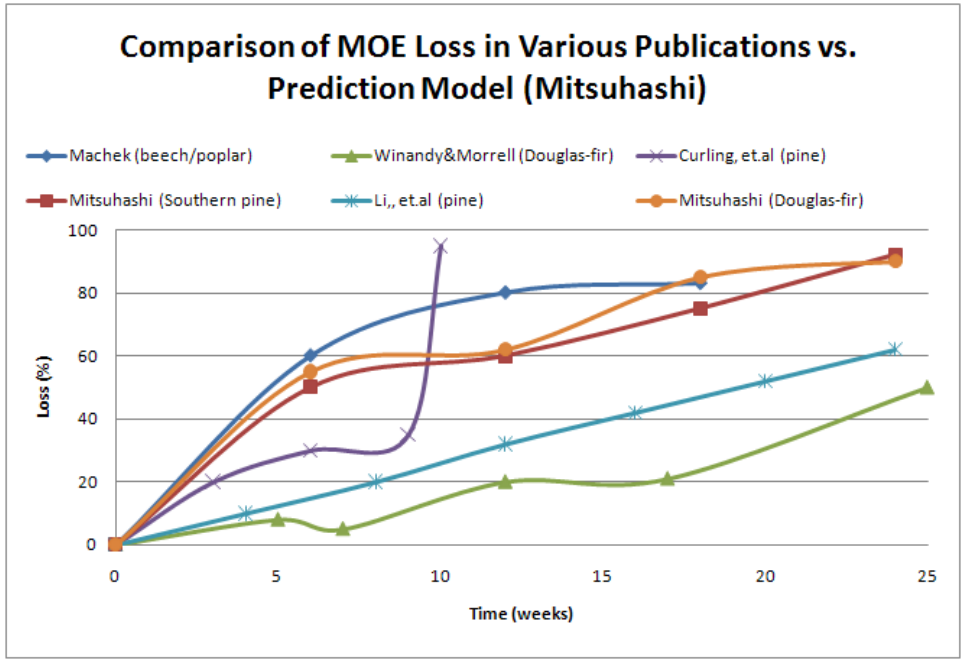
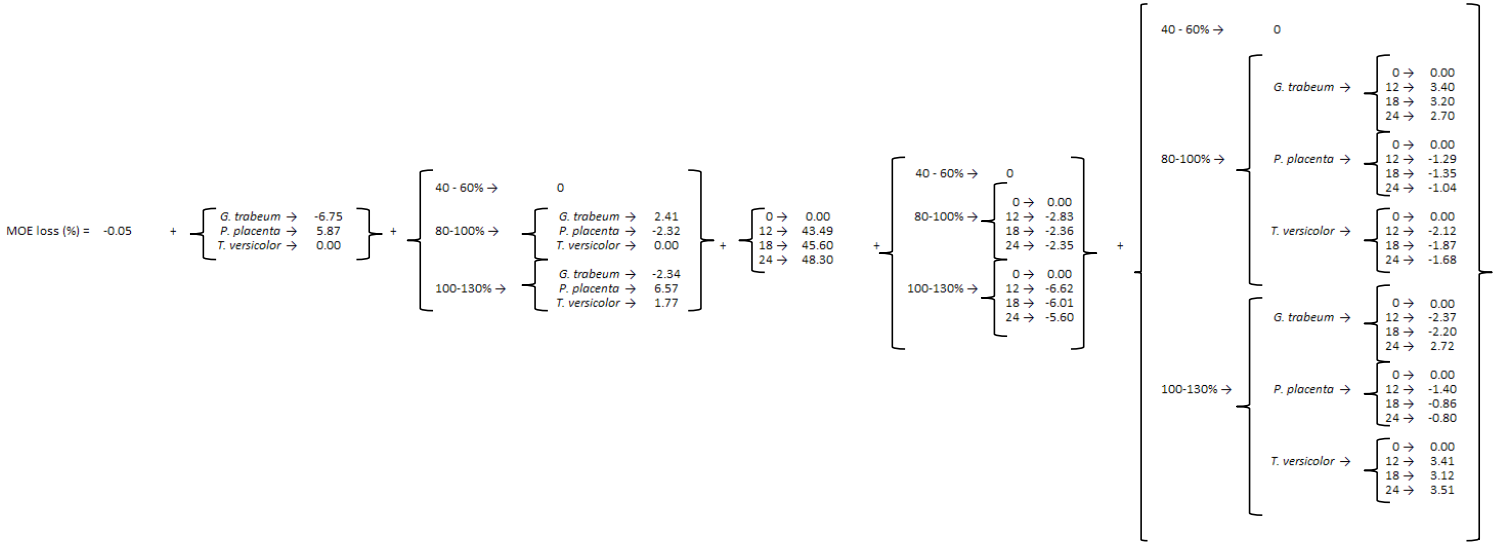
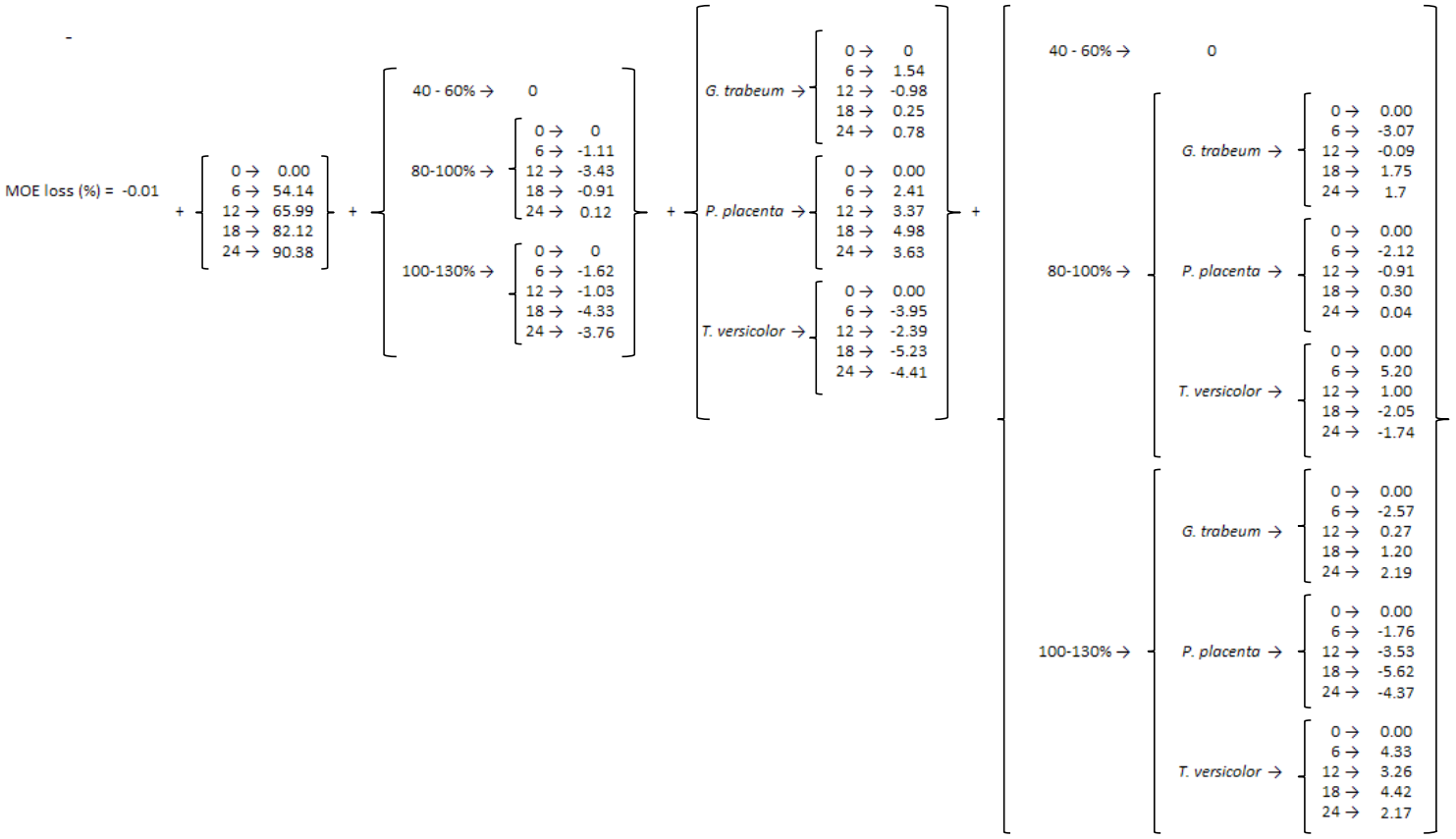


Figure 24. Comparison of the Mitsuhashi model with results of previous studies on MOE losses under similar conditions (25-28°C and moisture content above the fiber saturation point).

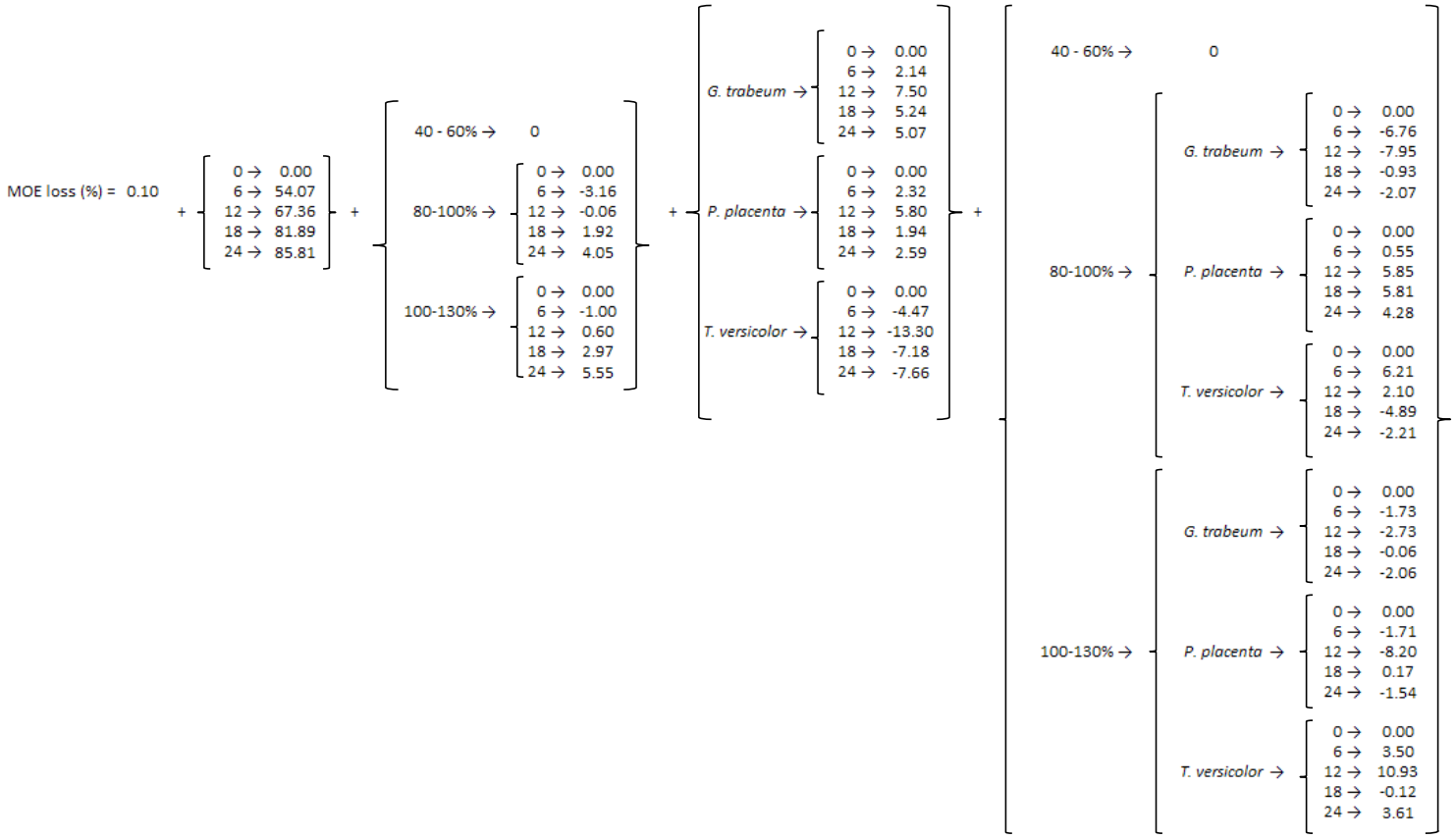
Equation 1. Predictive model of MOE loss of Douglas-fir beams inoculated with one of three decay fungi and incubated at 15°C.



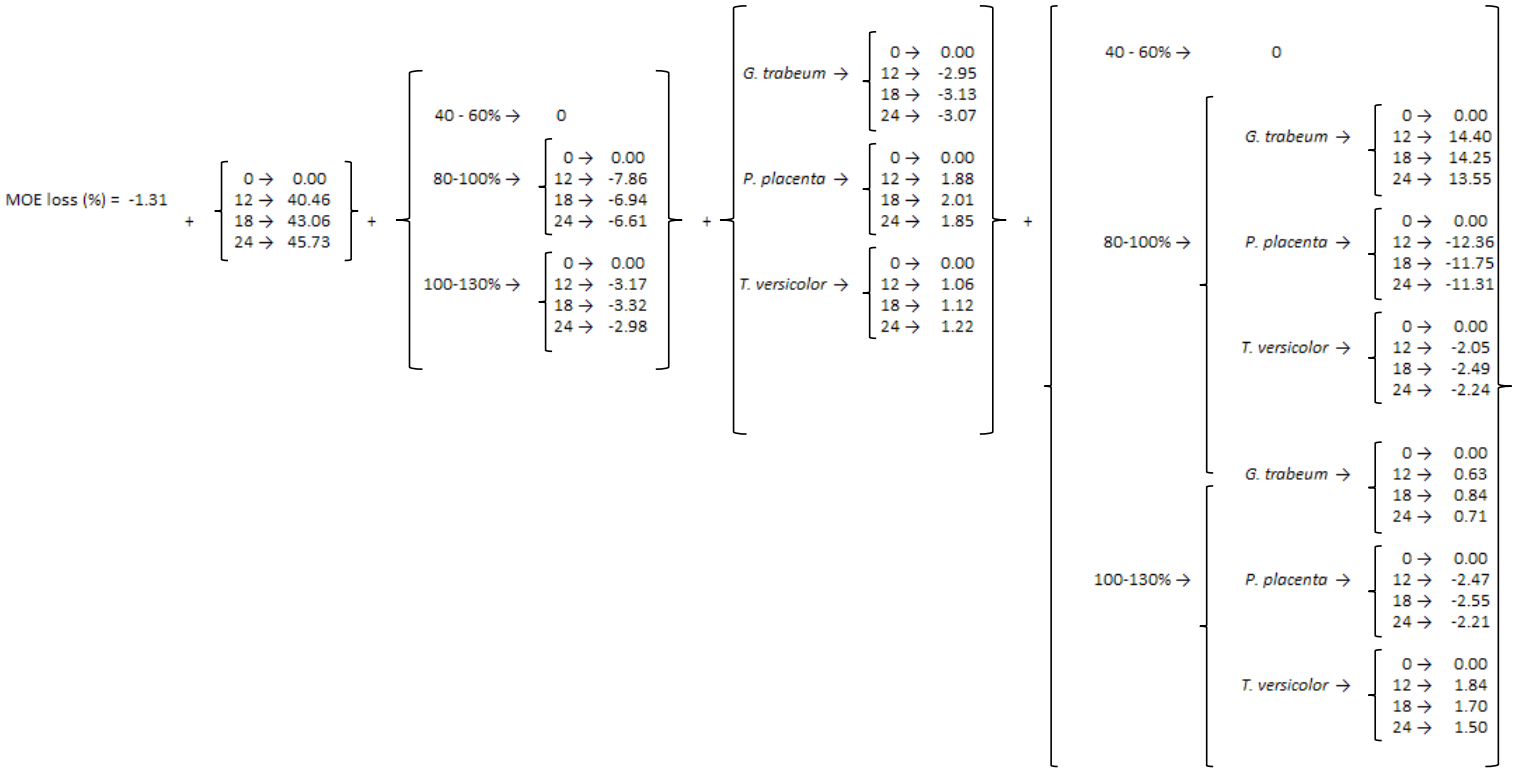
Equation 2. Predictive model of MOE loss of Douglas-fir beams inoculated with one of three decay fungi and incubated at 25°C.



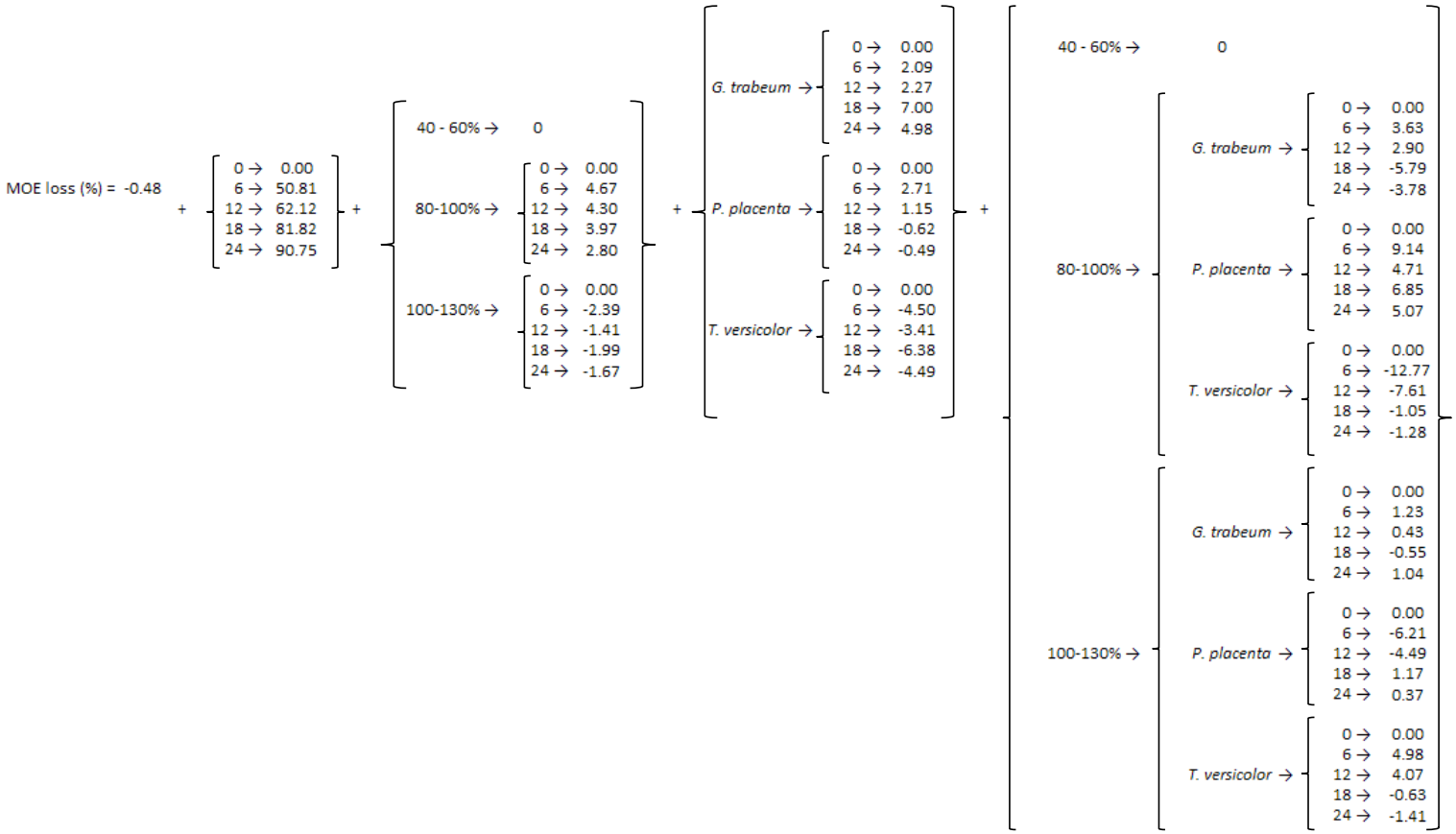
Equation 3. Predictive model of MOE loss of Douglas-fir beams inoculated with one of three decay fungi and incubated at 35°C.



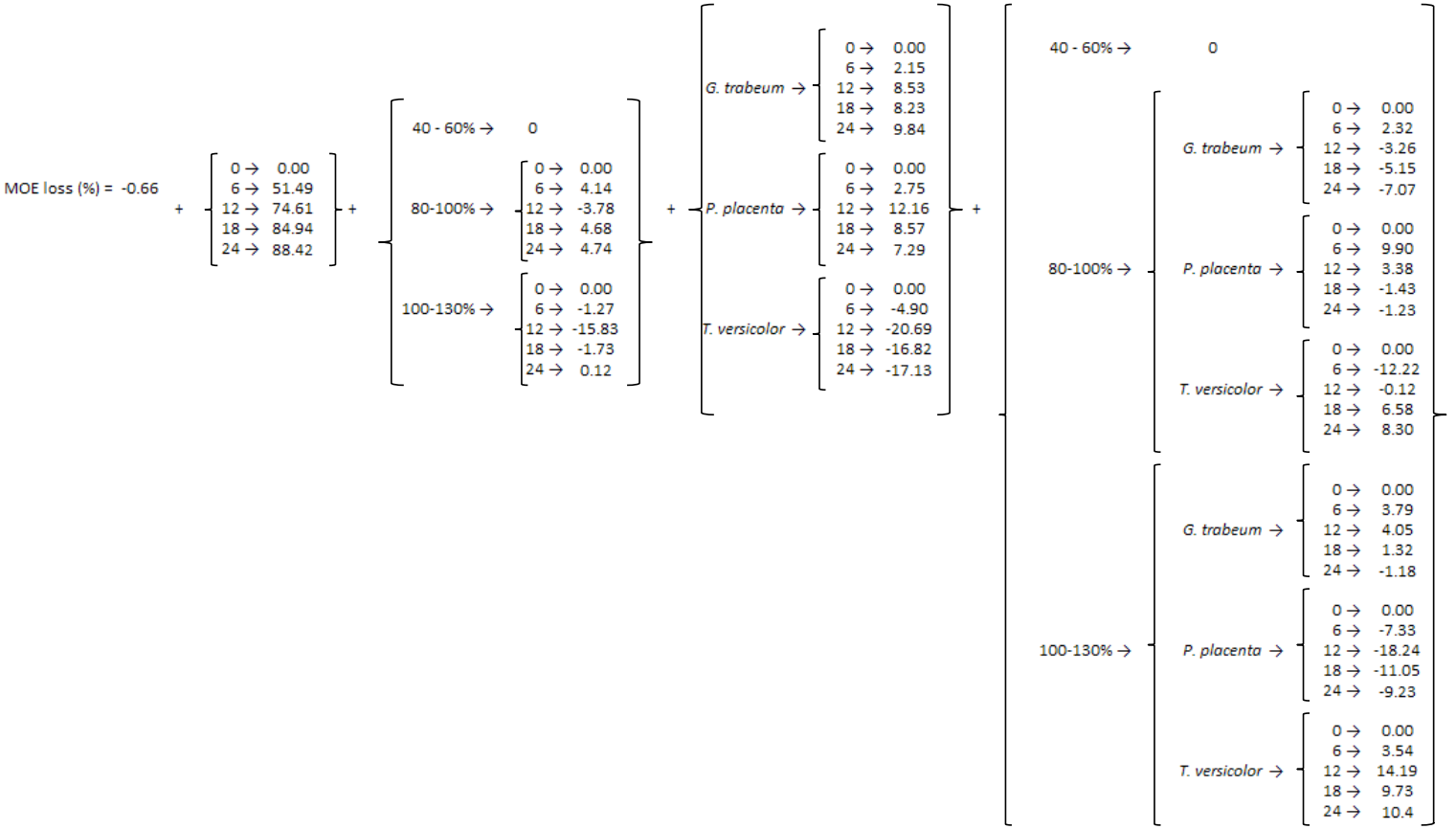
Equation 4. Predictive model of MOE loss of western hemlock beams inoculated with one of three decay fungi and incubated at 15°C.



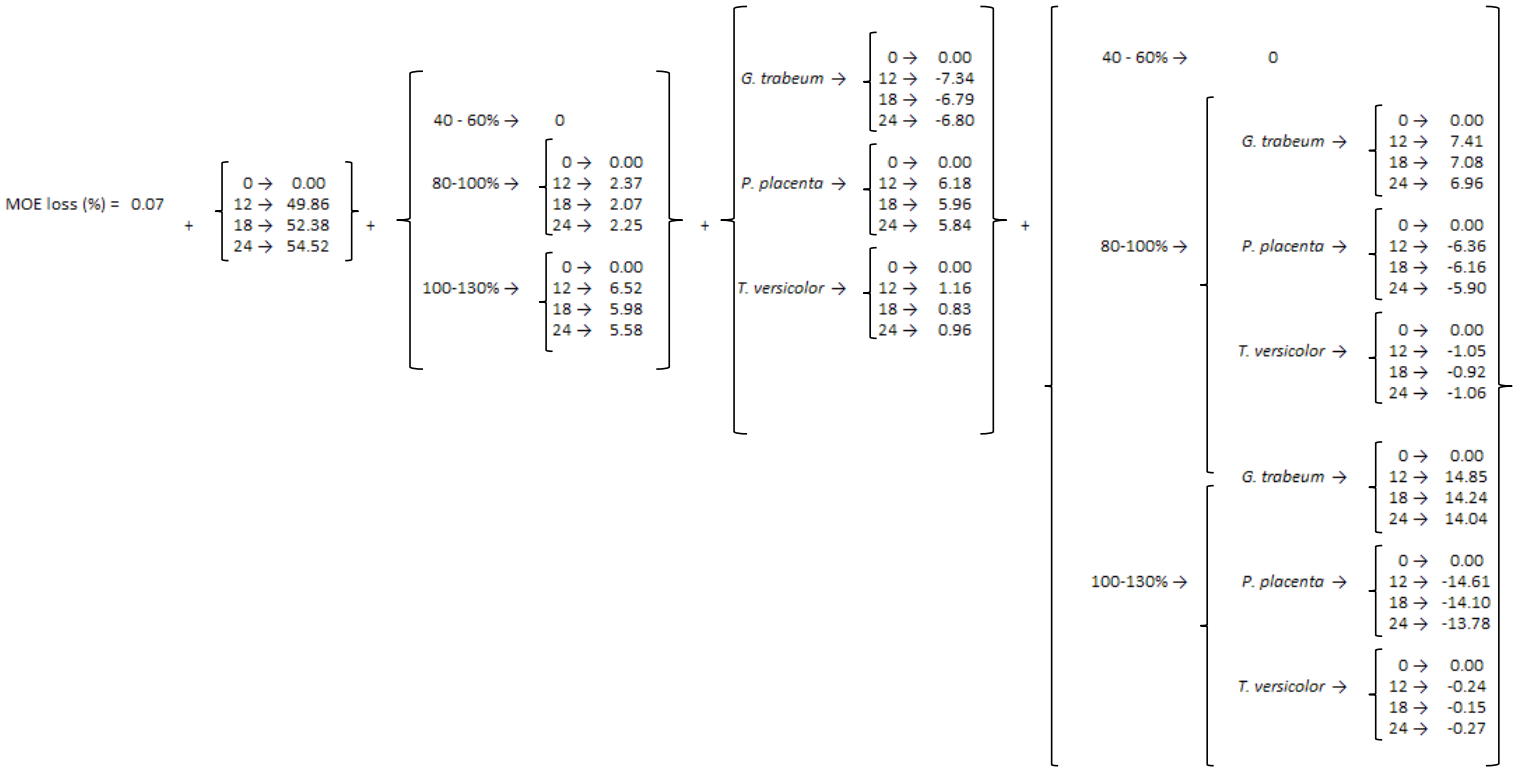
Equation 5. Predictive model of MOE loss of western hemlock beams inoculated with one of three decay fungi and incubated at 25°C.



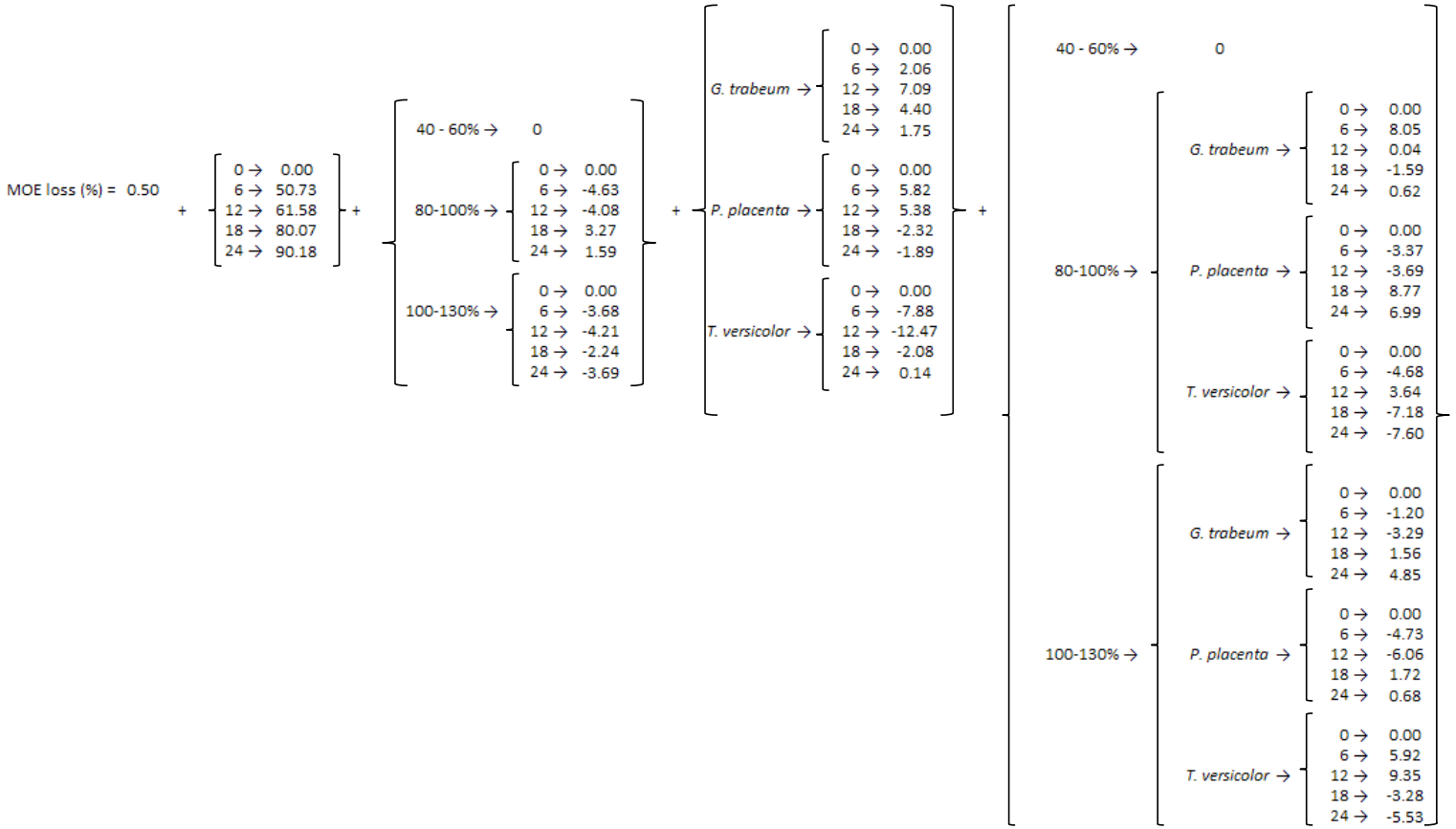
Equation 6. Predictive model of MOE loss of western hemlock beams inoculated with one of three decay fungi and incubated at 35°C.



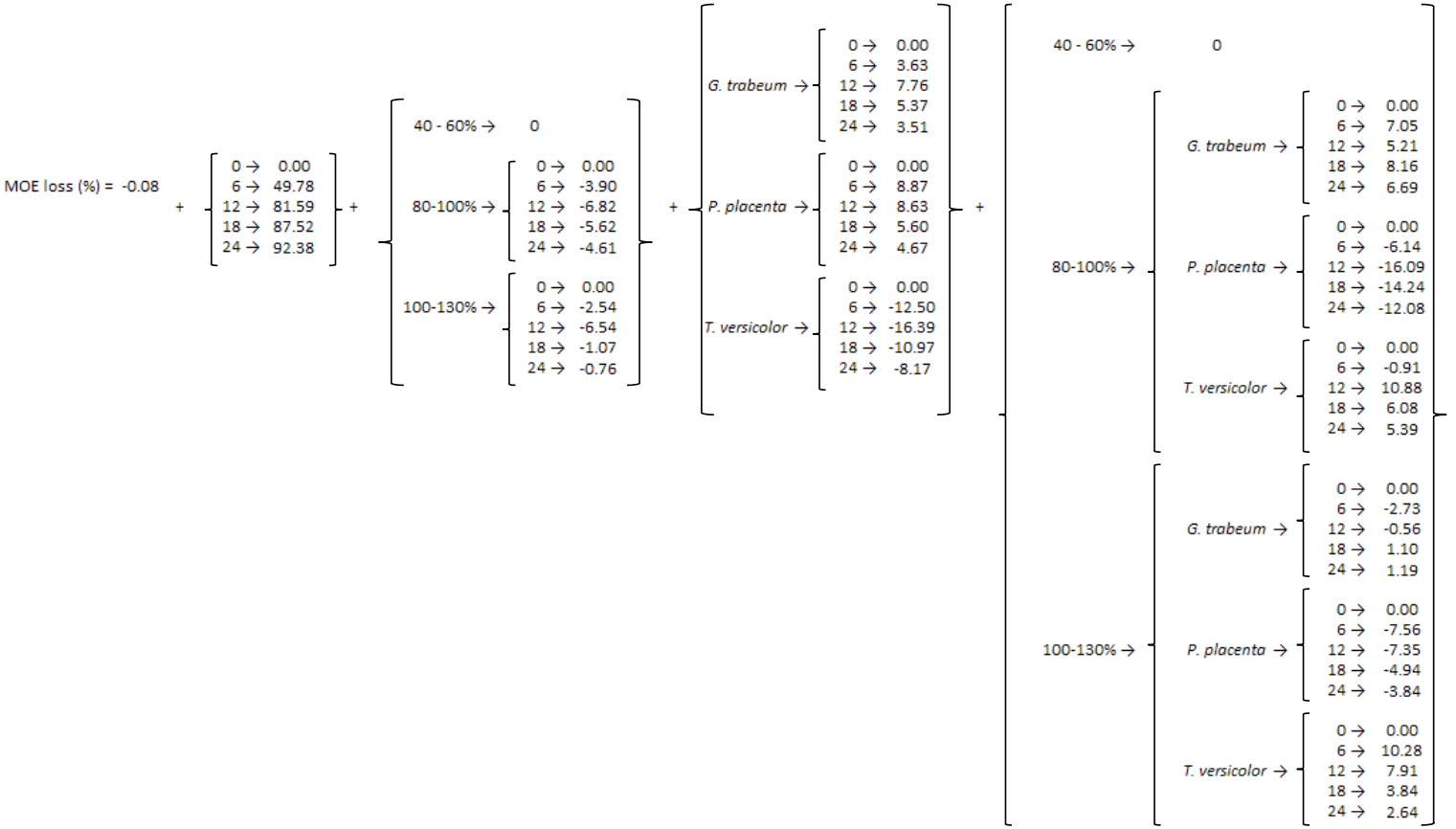
Equation 7. Predictive model of MOE loss of southern pine beams inoculated with one of three decay fungi and incubated at 15°C.



Equation 8. Predictive model of MOE loss of southern pine beams inoculated with one of three decay fungi and incubated at 25°C.



Equation 9. Predictive model of MOE loss of southern pine beams inoculated with one of three decay fungi and incubated at 35°C.



Chapter 5 – Conclusions, Implications and Recommendations

The rates at which fungi damage wood in various structures remains a perplexing problem for those who design, construct and maintain wood structures. Water intrusion or accumulation appears to be an increasingly common problem that eventually results in conditions conducive to fungal attack. Developing methods for accurately detecting and assessing the extent of damage following this moisture intrusion remains the “Holy Grail” for those involved in the field. One of the primary short-comings of previous attempts to model the effects of fungal attack on buildings has been a lack of definitive data on the effects of decay on wood properties using fungi likely to be present in wood structures.

The testing reported herein presents more accurate data on the effects of fungal attack on flexural properties under various environmental regimes. Exposure of beams of the three wood species to fungal attack produced rapid losses in flexural properties at very early stages of attack. These results were consistent with previous reports, but the range of variables evaluated allowed us to develop predictive models on a range of wood species/fungal combinations. These models clearly showed that fungal attack produced massive losses in flexural properties. These models can be used to predict the

worst case for fungal attack of wood in structure; however, they cannot be fully utilized until there is a much better understanding of the rates of colonization by various fungi in buildings. This understanding will require the development of better models to describe moisture ingress in structures that detail moisture regimes as they develop in various building features. It will also require the development of some notion of the time between wetting and introduction of fungal propagules.

At present, any model must assume that wetting and fungal attack begin simultaneously and this approach results in a very conservative model that results in the removal of more wood than necessary to limit the risk of leaving degraded material in place. A further requirement will be a better understanding of the role of decay location in an assessment. For example, shear walls would be considered critical elements in building performance under extreme loads and any decay in a shear wall might be viewed as reason for removal. However, the position of the decay can dramatically affect the effects. Decay in the middle of the shear wall will be far less serious than decay on the edge of top of the section and the effects will be property specific. Loss of flexural properties may be important, but fastener behavior will also be critical. Thus, any model that predicts the effects of fungal attack

in a building structure must be sufficiently robust to enable prediction based upon critical properties of that structural element.

At present, the data needed to develop a model of this nature are lacking. There is a critical need to systematically develop data on the effects of the more important building decay fungi on various wood properties (flexural, compression, fastener withdrawal) of other building materials (plywood, parallel strand lumber, oriented strandboard) along with solid wood and to follow this controlled testing with evaluations of these same organisms in building assemblies. Once these data are developed, they can be incorporated into moisture intrusion models to better understand the role of fungi in building performance

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APPENDICES

Appendix A

Tables of Mean MOR and MOE values for Douglas-fir, western hemlock and southern pine beams inoculated with one of three fungi (*G. trabeum*, *P. placenta* or *T. versicolor*) at three moisture content regimes (40-60, 80-100, and 100-130%) and incubated at 15, 25 or 35°C for 6 to 36 weeks.

TARGET MOISTURE CONTENT	TEST FUNGUS	INCUBATION PERIOD (WEEKS)	MOE (MPa)		MOR (MPa)	
			MEAN	STANDARD DEVIATION	MEAN	STANDARD DEVIATION
40-60%	*G. trabeum*	0	10599.8	1631.3	52.8	3.8
		12	5898.1	1086.7	49.0	12.0
		18	5726.9	994.5	50.5	12.3
		24	5387.8	1019.1	49.4	15.0
		30	4930.9	962.4	41.3	26.6
		36	4475.9	971.6	46.9	14.1
	P. placenta	0	10767.2	2131.2	52.8	3.8
		12	6043.7	1466.4	23.3	10.1
		18	5607.1	1270.5	25.7	6.3
		24	5367.1	1188.7	24.6	10.1
		30	5042.6	1049.6	23.7	5.4
		36	4588.4	967.4	29.0	7.8
	T. versicolor	0	11269.3	2363.6	55.6	4.5
		12	6447.3	1307.9	56.5	8.3
		18	6377.7	1240.8	53.4	9.5
		24	5992.8	1235.2	58.2	9.7
		30	5654.8	1119.5	51.4	12.0
		36	5152.6	1058.7	58.4	7.3
80-100%	*G. trabeum*	0	9411.2	1278.6	52.8	3.8
		12	5197.9	763.1	58.0	7.6
		18	5004.0	790.9	56.7	11.4
		24	4790.1	737.2	44.5	10.0
		30	4509.2	801.7	42.4	13.0
		36	4175.9	772.4	38.2	6.7
	P. placenta	0	11938.5	1080.5	52.8	3.8
		12	7220.8	958.1	40.5	11.0
		18	7009.4	856.1	39.4	9.0
		24	6569.4	830.8	38.4	11.3
		30	6256.8	675.6	33.1	12.9
		36	5665.6	608.8	37.7	12.6
	T. versicolor	0	10171.8	1054.5	52.8	3.8
		12	6252.8	927.7	56.9	11.5
		18	5956.7	898.2	58.6	12.5
		24	5697.7	945.1	56.1	13.8
		30	5439.4	916.4	52.5	14.1
		36	4859.6	900.1	58.0	7.5
100-130%	*G. trabeum*	0	10285.1	1666.2	52.8	3.8
		12	6654.4	1479.2	53.2	9.5
		18	6456.5	1336.3	49.5	7.7
		24	6116.3	1223.5	43.1	11.1
		30	5677.6	1138.0	37.7	12.0
		36	5347.0	1090.2	38.0	12.1
	P. placenta	0	8617.4	1196.5	52.8	3.8
		12	5526.0	1027.6	45.4	14.5
		18	5350.0	957.8	41.3	15.1
		24	5029.6	938.9	40.7	16.5
		30	4852.5	944.3	39.3	16.2
		36	4288.2	829.4	40.2	10.5
	T. versicolor	0	10587.6	803.9	52.8	3.8
		12	6096.7	1284.2	52.3	10.4
		18	5937.1	1215.0	53.8	9.5
		24	5727.4	808.3	55.4	10.1
		30	5474.0	801.3	51.8	12.8
		36	4928.9	812.4	58.1	3.5

Table 1. Mean MOR, MOE values for Douglas-fir beams inoculated with one of three fungi (*G. trabeum*, *P. placenta* or *T. versicolor*) at three moisture content regimes (40-60, 80-100, and 100-130%) and incubated at 15°C for 6 to 36 weeks.

TARGET MOISTURE CONTENT	TEST FUNGUS	INCUBATION PERIOD (WEEKS)	MOE (MPa)		MOR (MPa)	
			MEAN	STANDARD DEVIATION	MEAN	STANDARD DEVIATION
40-60%	*G. trabeum*	0	8667.6	725.0	45.0	3.7
		12	5392.4	943.9	24.5	4.4
		18	5216.5	918.1	43.7	9.2
		24	5021.4	956.7	35.1	8.3
		30	4624.4	900.0	32.8	8.1
		36	4298.4	873.8	29.5	10.4
	P. placenta	0	8963.7	1234.0	45.0	3.7
		12	5167.1	763.4	26.9	15.0
		18	4915.9	704.5	23.9	13.5
		24	4642.7	706.3	22.7	8.3
		30	4367.4	636.4	19.1	13.8
		36	4059.5	634.0	13.0	15.6
	T. versicolor	0	11076.0	1761.6	45.0	3.7
		12	6071.9	1750.4	42.8	7.3
		18	6100.7	1627.2	44.4	9.1
		24	5825.5	1583.3	39.7	10.6
		30	5556.3	1643.1	46.1	11.0
		36	4941.0	1508.0	44.2	9.4
80-100%	*G. trabeum*	0	8580.0	1008.9	45.0	3.7
		12	4757.3	1124.2	46.7	7.0
		18	4498.4	1106.9	43.3	6.4
		24	4213.4	1005.7	38.6	5.9
		30	4100.8	1033.6	27.2	15.8
		36	3733.6	895.8	27.2	3.8
	P. placenta	0	8294.9	1200.0	45.0	3.7
		12	6259.3	1541.9	42.8	7.3
		18	6075.6	1436.0	39.6	4.0
		24	5826.8	1391.8	33.1	12.6
		30	5562.3	1422.9	29.5	11.9
		36	5219.3	1460.9	25.0	4.0
	T. versicolor	0	8438.7	898.4	45.0	3.7
		12	5451.6	1058.9	48.0	8.6
		18	5358.9	950.3	42.4	7.1
		24	5140.3	857.8	43.5	6.5
		30	4876.2	931.4	45.0	7.1
		36	4562.9	659.6	44.8	7.0
100-130%	*G. trabeum*	0	8412.3	918.2	45.0	3.7
		12	5293.8	900.9	45.9	9.3
		18	5134.4	933.6	41.0	9.5
		24	5045.3	780.9	38.9	11.4
		30	4783.2	790.4	39.8	12.3
		36	4247.0	619.6	38.5	3.9
	P. placenta	0	8991.2	1773.2	45.0	3.7
		12	5591.7	1594.1	35.0	7.1
		18	5372.6	1363.5	32.5	7.7
		24	5261.4	1411.8	29.9	9.3
		30	4928.8	1247.3	26.4	7.9
		36	4244.4	800.3	27.1	5.6
	T. versicolor	0	9193.0	1524.1	45.0	3.7
		12	5448.2	961.9	44.8	7.6
		18	5186.2	885.3	43.8	8.2
		24	4853.1	789.1	42.4	8.0
		30	4594.9	754.3	43.4	8.1
		36	4283.7	621.7	46.5	10.2

Table 2. Mean MOR, MOE values for western hemlock beams inoculated with one of three fungi (*G. trabeum*, *P. placenta* or *T. versicolor*) at three moisture content regimes (40-60, 80-100, and 100-130%) and incubated at 15°C for 6 to 36 weeks.

TARGET MOISTURE CONTENT	TEST FUNGUS	INCUBATION PERIOD (WEEKS)	MOE (MPa)		MOR (MPa)	
			MEAN	STANDARD DEVIATION	MEAN	STANDARD DEVIATION
40-60%	*G. trabeum*	0	6719.3	2350.5	45.9	10.6
		12	3868.9	1493.6	34.6	10.5
		18	3894.0	1350.7	30.1	13.3
		24	3606.0	1239.5	26.6	13.7
		30	2679.5	1722.9	27.9	14.7
		36	2128.5	1735.0	17.2	3.7
	P. placenta	0	10103.2	2608.4	45.9	10.6
		12	4488.7	1889.0	37.2	9.4
		18	4113.2	1667.4	14.4	6.5
		24	3857.3	1505.3	12.1	7.2
		30	3490.8	1379.2	10.8	7.3
		36	758.4	514.3	7.1	7.1
	T. versicolor	0	10891.5	2973.6	45.9	10.6
		12	5350.4	1633.0	47.2	15.4
		18	4949.8	1497.9	48.3	16.2
		24	4830.6	1348.7	46.0	16.2
		30	4412.8	1108.9	40.1	46.3
		36	3734.9	768.2	41.4	6.2
80-100%	*G. trabeum*	0	9923.3	4156.0	45.9	10.6
		12	4424.4	1718.3	24.7	14.9
		18	4060.3	1493.0	20.1	19.6
		24	3607.5	1359.4	19.9	20.0
		30	3248.5	1207.1	19.1	19.3
		36	2990.4	1181.3	22.2	14.4
	P. placenta	0	8879.7	3281.6	45.9	10.6
		12	4285.8	1790.9	23.6	15.3
		18	4176.3	1821.0	21.4	14.4
		24	3890.8	1826.0	18.6	11.7
		30	4161.1	1654.8	13.6	11.7
		36	3919.5	1437.6	16.3	7.4
	T. versicolor	0	15561.4	3178.4	45.9	10.6
		12	7524.7	1936.5	59.2	7.8
		18	7128.1	1979.0	43.2	3.2
		24	6621.1	1917.8	44.5	8.0
		30	6089.0	1862.1	42.9	4.8
		36	5240.6	1726.8	43.0	16.2
100-130%	*G. trabeum*	0	11910.1	3277.2	45.9	10.6
		12	4375.2	1186.7	45.2	13.4
		18	4233.1	1188.1	23.9	20.2
		24	4034.1	1164.4	13.9	8.9
		30	3923.6	1133.6	9.4	7.1
		36	3600.2	1118.2	4.5	4.7
	P. placenta	0	10919.1	2743.8	45.9	10.6
		12	5494.4	1559.1	46.5	9.1
		18	5187.7	1491.2	41.1	9.7
		24	5071.8	1477.9	36.6	11.2
		30	4578.2	1389.8	28.7	18.8
		36	4278.7	1411.2	23.3	11.4
	T. versicolor	0	9524.1	1398.9	45.9	10.6
		12	4041.9	1337.0	45.4	14.2
		18	3832.9	1249.8	46.5	13.7
		24	3614.9	1171.5	41.9	7.4
		30	3377.6	1141.4	42.6	9.6
		36	3091.7	1195.3	52.8	15.2

Table 3. Mean MOR, MOE values for southern pine beams inoculated with one of three fungi (*G. trabeum*, *P. placenta* or *T. versicolor*) at three moisture content regimes (40-60, 80-100, and 100-130%) and incubated at 15°C for 6 to 36 weeks. .

TARGET MOISTURE CONTENT	TEST FUNGUS	INCUBATION PERIOD (WEEKS)	MOE (MPa)		MOR (MPa)	
			MEAN	STANDARD DEVIATION	MEAN	STANDARD DEVIATION
40-60%	*G. trabeum*	0	10989.4	2255.0	52.8	3.8
		6	4892.5	1158.1	39.9	7.7
		12	3790.9	1112.9	29.0	5.4
		18	1969.2	709.1	12.3	7.0
		24	977.2	665.1	6.3	2.3
		30	355.6	605.2	0.0	0.0
		36	124.4	341.1	1.6	1.8
	P. placenta	0	11175.4	1927.2	52.8	3.8
		6	4863.5	1081.5	49.0	6.3
		12	3536.2	899.5	24.4	5.9
		18	1452.4	568.5	29.1	15.2
		24	652.2	601.0	25.5	15.8
		30	231.9	400.5	15.9	5.5
		36	0.0	0.0	0.0	0.0
	T. versicolor	0	12194.7	2695.2	55.6	4.5
		6	6068.2	1543.6	48.4	6.4
		12	4510.3	998.1	42.2	11.4
		18	2861.7	804.6	42.1	9.7
		24	1689.2	675.2	38.1	5.6
		30	747.7	739.1	38.4	13.1
		36	276.6	385.3	39.2	33.3
80-100%	*G. trabeum*	0	12383.0	2491.4	52.8	3.8
		6	5985.6	1349.3	42.1	4.0
		12	4809.2	1376.1	34.1	7.0
		18	2109.2	793.1	11.1	6.5
		24	832.7	741.2	12.1	6.5
		30	258.1	512.5	5.8	2.6
		36	0.0	0.0	0.0	0.0
	P. placenta	0	11665.3	1811.1	52.8	3.8
		6	5435.5	1260.6	62.0	7.6
		12	4213.3	957.0	23.0	6.2
		18	1682.6	626.4	7.1	3.7
		24	700.6	697.0	3.2	1.8
		30	272.7	487.2	2.2	0.9
		36	0.0	0.0	0.0	0.0
	T. versicolor	0	11843.3	1795.3	52.8	3.8
		6	5462.7	998.3	48.0	9.0
		12	4565.7	861.8	44.8	7.0
		18	3102.4	1004.9	39.3	20.6
		24	1773.5	1159.7	45.9	23.9
		30	1000.3	978.4	36.8	28.1
		36	425.3	874.1	35.5	17.5
100-130%	*G. trabeum*	0	11685.7	2092.7	52.8	3.8
		6	5572.9	1612.2	46.3	7.6
		12	4171.7	1143.7	42.4	9.1
		18	2425.1	809.8	38.0	4.2
		24	1179.3	879.4	35.9	4.4
		30	224.6	431.0	29.4	12.2
		36	0.0	0.0	0.0	0.0
	P. placenta	0	11583.5	2521.5	52.8	3.8
		6	5506.3	1362.4	50.2	8.9
		12	4200.0	975.5	46.0	7.5
		18	2693.3	721.4	18.3	7.5
		24	1621.5	624.6	7.3	2.6
		30	847.9	837.8	7.2	2.5
		36	454.2	735.5	3.7	1.7
	T. versicolor	0	10630.4	1551.0	52.8	3.8
		6	4957.2	1018.4	53.1	7.0
		12	3793.9	892.8	49.7	10.1
		18	2505.8	441.6	53.8	16.7
		24	1678.3	662.9	43.8	12.9
		30	1040.1	674.1	42.8	12.1
		36	387.9	505.8	42.0	17.0

Table 4. Mean MOR, MOE values for Douglas-fir beams inoculated with one of three fungi (*G. trabeum*, *P. placenta* or *T. versicolor*) at three moisture content regimes (40-60, 80-100, and 100-130%) and incubated at 25°C for 6 to 36 weeks.

TARGET MOISTURE CONTENT	TEST FUNGUS	INCUBATION PERIOD (WEEKS)	MOE (MPa)		MOR (MPa)	
			MEAN	STANDARD DEVIATION	MEAN	STANDARD DEVIATION
40-60%	*G. trabeum*	0	9972.2	1529.6	45.0	3.7
		6	4633.1	890.9	24.2	5.2
		12	3529.9	1020.5	13.1	1.8
		18	1124.3	426.2	5.3	2.8
		24	332.3	379.0	3.1	2.3
		30	50.8	151.6	2.3	1.3
		36	0.0	0.0	0.0	0.0
	P. placenta	0	8841.4	894.9	45.0	3.7
		6	4075.8	923.9	30.7	4.9
		12	3254.6	781.6	14.8	2.2
		18	1856.7	1048.1	0.8	1.2
		24	856.7	962.2	0.0	0.0
		30	459.4	727.6	0.5	0.2
		36	384.5	665.7	0.0	0.0
	T. versicolor	0	9124.1	1188.2	45.0	3.7
		6	4909.7	1236.7	38.2	5.4
		12	3720.9	848.0	35.6	2.0
		18	2251.7	503.7	39.4	2.2
		24	1244.1	687.9	38.7	2.7
		30	790.8	679.9	35.4	6.0
		36	359.9	508.0	33.8	9.4
80-100%	*G. trabeum*	0	9687.2	2087.6	45.0	3.7
		6	3771.5	958.5	24.1	4.7
		12	2811.4	895.3	30.0	7.2
		18	1282.8	658.1	26.2	5.3
		24	416.3	440.0	24.1	8.7
		30	120.8	291.6	9.9	7.9
		36	0.0	0.0	7.9	7.9
	P. placenta	0	12941.4	1953.6	45.0	3.7
		6	4144.1	913.9	31.9	5.4
		12	3443.7	856.2	23.7	2.3
		18	1070.2	312.2	10.3	6.3
		24	242.6	381.8	8.9	3.2
		30	0.0	0.0	0.0	0.0
		36	0.0	0.0	0.0	0.0
	T. versicolor	0	9509.4	1470.1	45.0	3.7
		6	6028.0	1374.8	36.4	7.8
		12	4235.9	740.6	34.4	1.8
		18	2117.2	553.3	38.2	6.4
		24	1140.2	658.4	33.3	1.7
		30	658.5	579.9	30.8	3.7
		36	320.9	527.2	28.6	9.5
100-130%	*G. trabeum*	0	9043.6	1344.9	45.0	3.7
		6	4310.4	970.4	25.2	3.3
		12	3367.4	947.1	32.1	3.8
		18	1296.2	319.3	25.6	3.3
		24	442.6	435.8	24.5	3.8
		30	210.6	341.8	23.3	5.3
		36	98.0	190.4	18.0	9.4
	P. placenta	0	9108.4	1863.8	45.0	3.7
		6	5007.4	1224.0	33.2	3.1
		12	4020.2	1084.9	32.4	6.0
		18	1900.6	530.5	17.1	6.7
		24	1036.4	590.1	15.4	4.6
		30	229.2	405.8	15.8	7.1
		36	15.2	64.7	1.5	3.6
	T. versicolor	0	7959.7	984.5	45.0	3.7
		6	4038.4	614.2	32.1	3.8
		12	3113.9	730.3	30.4	2.3
		18	2153.2	390.7	31.9	3.7
		24	1323.7	523.2	28.3	4.1
		30	599.8	612.1	27.5	4.6
		36	192.7	411.2	19.2	5.3

Table 5. Mean MOR, MOE values for western hemlock beams inoculated with one of three fungi (*G. trabeum*, *P. placenta* or *T. versicolor*) at three moisture content regimes (40-60, 80-100, and 100-130%) and incubated at 25°C for 6 to 36 weeks.

TARGET MOISTURE CONTENT	TEST FUNGUS	INCUBATION PERIOD (WEEKS)	MOE (MPa)		MOR (MPa)	
			MEAN	STANDARD DEVIATION	MEAN	STANDARD DEVIATION
40-60%	*G. trabeum*	0	9659.3	2856.8	45.9	10.6
		6	4545.0	1731.1	42.6	5.4
		12	3005.1	1197.1	16.9	12.8
		18	1539.9	795.6	5.5	5.7
		24	788.1	831.4	2.5	2.2
		30	499.9	683.8	1.8	1.3
		36	0.0	0.0	0.0	0.0
	P. placenta	0	11949.4	3214.7	45.9	10.6
		6	5162.0	1748.1	29.6	11.3
		12	4010.4	1205.9	11.9	5.2
		18	2563.4	1290.6	2.4	1.5
		24	1460.8	1239.5	1.9	1.5
		30	1085.0	1296.7	0.3	0.6
		36	761.7	1418.3	0.5	0.3
	T. versicolor	0	10335.1	2819.5	45.9	10.6
		6	5989.8	1916.4	41.1	15.0
		12	5197.8	1732.0	53.7	2.5
		18	2311.6	892.4	47.2	11.8
		24	998.3	739.4	43.0	14.5
		30	523.3	720.1	42.5	14.1
		36	187.5	485.4	40.3	16.4
80-100%	*G. trabeum*	0	10522.3	3255.4	45.9	10.6
		6	4494.1	1769.4	35.0	9.5
		12	3768.7	1733.4	18.1	5.1
		18	1595.8	955.0	9.4	7.4
		24	624.5	803.3	6.8	5.9
		30	175.5	374.8	3.8	3.2
		36	0.0	0.0	0.0	0.0
	P. placenta	0	11719.2	3104.1	45.9	10.6
		6	5890.2	1911.9	32.5	14.2
		12	4792.3	1791.2	9.6	4.6
		18	1226.4	755.7	2.0	2.2
		24	376.5	655.7	1.5	1.3
		30	0.0	0.0	0.0	0.0
		36	0.0	0.0	0.0	0.0
	T. versicolor	0	10039.8	3317.9	45.9	10.6
		6	6605.4	2831.8	44.2	9.7
		12	4917.1	1797.5	40.8	6.2
		18	2433.5	1087.0	22.7	8.9
		24	1468.1	1003.1	21.0	9.3
		30	981.2	1073.8	14.5	6.5
		36	631.6	1080.0	5.9	2.9
100-130%	*G. trabeum*	0	7845.3	2849.8	45.9	10.6
		6	4121.3	1803.4	33.4	5.3
		12	3168.1	1438.8	26.9	10.0
		18	1333.7	762.4	2.8	1.3
		24	564.8	717.4	1.4	0.6
		30	334.6	555.7	3.3	1.3
		36	209.0	453.8	3.5	2.0
	P. placenta	0	7182.3	2826.4	45.9	10.6
		6	3748.2	1590.5	43.3	9.2
		12	3100.0	1310.1	43.1	11.2
		18	1696.9	731.9	9.0	11.5
		24	1058.2	731.8	6.4	5.0
		30	425.8	565.2	10.5	8.1
		36	0.0	0.0	0.0	0.0
	T. versicolor	0	12095.7	2482.6	45.9	10.6
		6	6678.8	1773.2	50.0	12.2
		12	5566.3	1436.0	32.3	13.8
		18	3383.6	1041.3	33.9	10.8
		24	2252.1	1375.6	29.8	8.3
		30	1499.7	1251.3	28.0	9.2
		36	421.7	701.1	26.9	8.8

Table 6. Mean MOR, MOE values for southern pine beams inoculated with one of three fungi (*G. trabeum*, *P. placenta* or *T. versicolor*) at three moisture content regimes (40-60, 80-100, and 100-130%) and incubated at 25°C for 6 to 36 weeks.

TARGET MOISTURE CONTENT	TEST FUNGUS	INCUBATION PERIOD (WEEKS)	MOE (MPa)		MOR (MPa)	
			MEAN	STANDARD DEVIATION	MEAN	STANDARD DEVIATION
40-60%	*G. trabeum*	0	11674.6	2880.7	52.8	3.8
		6	5135.2	1354.2	36.1	7.5
		12	3189.5	1425.0	40.2	9.2
		18	1626.9	787.9	12.8	2.6
		24	1115.8	785.3	8.5	5.7
		30	931.9	859.1	2.7	4.6
		36	0.0	0.0	0.0	0.0
	P. placenta	0	9483.6	1348.6	52.8	3.8
		6	4126.1	805.0	45.0	6.3
		12	2518.1	950.0	18.3	7.3
		18	1347.4	848.9	7.6	3.9
		24	1067.3	886.8	4.9	3.2
		30	505.1	456.7	0.0	0.0
		36	79.5	185.6	2.6	4.0
	T. versicolor	0	11510.1	2731.1	55.6	4.5
		6	5833.6	1505.3	49.1	6.3
		12	5347.2	1332.8	61.1	5.2
		18	3015.8	889.4	58.6	9.0
		24	2702.6	810.9	53.2	10.4
		30	2282.9	624.1	50.3	11.4
		36	1562.7	941.6	49.5	12.4
80-100%	*G. trabeum*	0	9416.5	1777.0	52.8	3.8
		6	4963.6	1375.2	43.4	4.2
		12	3203.1	1261.8	37.3	8.5
		18	1137.9	693.5	33.6	6.4
		24	670.4	583.1	30.4	7.8
		30	390.7	444.1	32.1	9.2
		36	174.5	279.9	27.6	8.8
	P. placenta	0	10398.1	2024.1	52.8	3.8
		6	4808.7	1246.4	64.2	11.9
		12	2231.1	1182.5	55.7	12.3
		18	785.9	525.3	5.1	5.4
		24	333.6	226.1	1.9	2.3
		30	0.0	0.0	0.0	0.0
		36	0.0	0.0	0.0	0.0
	T. versicolor	0	10692.8	1224.7	52.8	3.8
		6	5093.7	939.9	49.2	9.3
		12	4535.6	899.8	62.8	15.4
		18	2939.8	906.6	59.2	5.7
		24	2130.0	826.7	53.4	4.7
		30	1516.2	865.8	54.9	15.7
		36	889.8	698.3	50.8	8.8
100-130%	*G. trabeum*	0	8847.9	1621.6	52.8	3.8
		6	4066.2	920.6	43.9	7.5
		12	2395.7	1209.8	43.0	5.5
		18	767.6	786.7	38.9	8.2
		24	494.4	574.4	40.5	8.8
		30	230.9	354.8	37.1	12.3
		36	176.0	308.0	24.7	13.4
	P. placenta	0	10430.5	1863.1	52.8	3.8
		6	4836.6	886.8	48.8	7.9
		12	3612.7	1091.4	36.0	9.5
		18	1431.2	874.7	33.3	11.4
		24	776.4	725.1	33.5	12.7
		30	548.6	575.4	30.6	23.8
		36	338.6	504.1	12.6	6.7
	T. versicolor	0	9341.8	1886.2	52.8	3.8
		6	4317.3	1085.3	50.5	5.7
		12	3289.1	978.4	55.9	9.0
		18	2063.0	3192.6	54.1	5.3
		24	1164.8	653.7	50.3	9.3
		30	846.9	731.7	47.8	8.7
		36	581.5	666.7	49.7	9.2

Table 7. Mean MOR, MOE values for Douglas-fir beams inoculated with one of three fungi (*G. trabeum*, *P. placenta* or *T. versicolor*) at three moisture content regimes (40-60, 80-100, and 100-130%) and incubated at 35°C for 6 to 36 weeks.

TARGET MOISTURE CONTENT	TEST FUNGUS	INCUBATION PERIOD (WEEKS)	MOE (MPa)		MOR (MPa)	
			MEAN	STANDARD DEVIATION	MEAN	STANDARD DEVIATION
40-60%	*G. trabeum*	0	9991.3	2211.6	45.0	3.7
		6	4786.5	1253.3	23.3	5.6
		12	1810.3	691.7	17.3	8.0
		18	732.5	302.3	17.5	8.7
		24	178.3	5.3	14.0	8.8
		30	0.0	0.0	0.0	0.0
		36	0.0	0.0	0.0	0.0
	P. placenta	0	9911.6	1367.7	45.0	3.7
		6	4444.4	755.8	34.3	5.7
		12	1319.1	698.9	11.6	5.4
		18	568.3	440.9	7.0	2.7
		24	394.7	347.4	3.5	1.9
		30	63.4	146.9	1.3	1.8
		36	0.0	0.0	0.0	0.0
	T. versicolor	0	8759.3	1638.8	45.0	3.7
		6	4562.7	969.5	40.3	6.0
		12	4108.8	914.6	38.1	3.8
		18	2880.0	641.0	38.3	4.9
		24	2541.2	562.4	38.1	10.9
		30	2254.5	527.5	34.6	14.1
		36	104.7	167.3	33.9	10.0
80-100%	*G. trabeum*	0	8367.9	1380.8	45.0	3.7
		6	3279.0	662.9	26.0	2.9
		12	2056.2	528.8	16.9	2.7
		18	586.0	282.7	17.4	2.8
		24	313.9	292.4	13.4	9.6
		30	126.4	202.4	18.7	9.6
		36	0.0	0.0	0.0	0.0
	P. placenta	0	9314.0	2866.3	45.0	3.7
		6	2944.4	973.6	30.7	5.1
		12	1340.9	534.9	35.6	1.6
		18	283.6	304.1	33.2	4.1
		24	73.8	197.4	29.6	5.2
		30	27.0	114.6	0.0	0.0
		36	0.0	0.0	0.0	0.0
	T. versicolor	0	7811.3	1456.8	45.0	3.7
		6	4981.6	1221.7	38.3	8.1
		12	4050.5	780.3	34.4	3.8
		18	1634.5	656.8	32.3	6.2
		24	1258.8	653.0	29.2	6.7
		30	988.1	677.7	20.2	6.8
		36	452.1	669.9	18.4	7.3
100-130%	*G. trabeum*	0	8684.2	1237.6	45.0	3.7
		6	3755.2	935.8	24.3	3.7
		12	2508.1	677.1	26.6	2.1
		18	614.3	447.6	14.5	1.4
		24	241.4	321.8	15.6	1.9
		30	66.2	199.6	3.6	4.2
		36	0.0	0.0	0.0	0.0
	P. placenta	0	8476.0	1124.0	45.0	3.7
		6	4630.7	801.7	30.6	2.4
		12	3917.4	789.6	28.2	4.6
		18	1643.6	641.6	16.1	1.3
		24	1133.9	741.9	11.8	3.1
		30	691.0	768.8	2.5	2.4
		36	0.0	0.0	0.0	0.0
	T. versicolor	0	8636.8	1457.5	45.0	3.7
		6	4379.6	856.0	37.7	6.4
		12	4150.7	660.2	36.9	5.6
		18	2145.2	507.7	37.4	6.7
		24	1607.0	627.0	35.5	5.1
		30	1238.6	596.0	34.9	4.4
		36	750.4	691.5	33.1	5.0

Table 8. Mean MOR values for western hemlock beams inoculated with one of three fungi (*G. trabeum*, *P. placenta* or *T. versicolor*) at three moisture content regimes (40-60, 80-100, and 100-130%) and incubated at 35°C for 6 to 36 weeks.

TARGET MOISTURE CONTENT	TEST FUNGUS	INCUBATION PERIOD (WEEKS)	MOE (MPa)		MOR (MPa)	
			MEAN	STANDARD DEVIATION	MEAN	STANDARD DEVIATION
40-60%	*G. trabeum*	0	10466.3	2474.7	45.9	10.6
		6	4918.9	1697.2	44.0	5.4
		12	1227.5	799.4	8.6	5.1
		18	874.8	852.9	8.1	6.2
		24	443.5	655.9	12.1	7.4
		30	0.0	0.0	0.0	0.0
		36	0.0	0.0	0.0	0.0
	P. placenta	0	12972.9	1761.5	45.9	10.6
		6	5367.7	1362.1	28.0	10.8
		12	1354.9	585.4	23.6	21.8
		18	910.5	486.9	11.9	6.8
		24	378.8	359.8	10.9	6.7
		30	0.0	0.0	0.0	0.0
		36	0.0	0.0	0.0	0.0
	T. versicolor	0	8305.8	2955.5	45.9	10.6
		6	5120.6	2195.9	43.0	15.0
		12	2682.5	1017.8	44.1	6.7
		18	1783.9	873.8	42.8	5.0
		24	1184.0	637.5	41.1	6.7
		30	524.2	389.7	41.0	5.8
		36	411.9	413.6	39.4	8.5
80-100%	*G. trabeum*	0	12168.8	2661.1	45.9	10.6
		6	5148.1	1545.4	22.0	4.5
		12	1486.7	1071.5	10.8	8.1
		18	468.0	671.8	9.9	3.5
		24	244.7	393.5	10.3	3.8
		30	0.0	0.0	0.0	0.0
		36	0.0	0.0	0.0	0.0
	P. placenta	0	11776.4	2392.3	45.9	10.6
		6	5932.8	1437.3	40.3	16.5
		12	3248.9	1560.2	32.6	16.0
		18	2607.6	1553.7	14.7	10.2
		24	2266.2	1121.2	13.4	9.4
		30	1766.2	1066.6	14.2	9.5
		36	992.0	1044.9	8.3	9.3
	T. versicolor	0	9035.4	2509.2	45.9	10.6
		6	6132.6	2221.1	39.7	6.7
		12	2709.3	842.4	41.7	13.9
		18	1956.8	682.8	42.8	21.3
		24	1274.1	470.7	43.7	21.0
		30	694.1	692.9	39.1	12.5
		36	189.2	349.7	33.1	10.1
100-130%	*G. trabeum*	0	7359.7	1702.8	45.9	10.6
		6	3805.8	1010.7	31.8	6.0
		12	1344.5	644.4	32.9	4.0
		18	467.2	370.7	29.7	4.2
		24	270.2	245.2	27.8	3.9
		30	136.4	223.8	24.9	4.1
		36	124.5	225.2	18.1	6.5
	P. placenta	0	11045.4	2854.4	45.9	10.6
		6	5664.5	1638.8	44.8	8.6
		12	2593.3	909.1	33.7	14.6
		18	1246.8	1121.5	12.1	4.9
		24	859.7	865.3	12.9	4.6
		30	480.3	735.4	9.8	4.4
		36	0.0	0.0	0.0	0.0
	T. versicolor	0	10298.6	2806.7	45.9	10.6
		6	5609.4	1815.9	51.3	12.2
		12	3324.7	1068.1	35.6	12.5
		18	2138.8	601.7	36.2	12.9
		24	1392.8	498.1	35.7	10.5
		30	1116.0	543.7	35.2	5.9
		36	423.1	301.6	33.6	4.2

Table 9. Mean MOR, MOE values for southern pine beams inoculated with one of three fungi (*G. trabeum*, *P. placenta* or *T. versicolor*) at three moisture content regimes (40-60, 80-100, and 100-130%) and incubated at 35°C for 6 to 36 weeks.

Appendix B

Tables of Mean MOR and MOE values for Douglas-fir, western hemlock and southern pine non-inoculated beams at 15, 25 and 35^{o}C at three moisture content regimes (40-60, 80-100, and 100-130%).

TEMP	TARGET MOISTURE CONTENT	INCUBATION PERIOD (WEEKS)	MOE (MPa)	STANDARD DEVIATION	MOR (MPa)	STANDARD DEVIATION
15°C	*40-60%*	0	8600.5	1571.8	52.8	3.6
		12	8156.0	1720.3		
		18	7854.3	1695.2		
		24	7584.1	1752.0		
		30	7413.8	1672.3		
		36	7209.5	1618.2	53.3	5.3
	80-100%	0	9495.6	713.7	52.8	3.6
		12	9013.6	861.8		
		18	8761.0	856.7		
		24	8246.3	1235.4		
		30	7956.4	1339.4		
		36	7747.1	1287.1	54.1	4.3
	100-130%	0	10018.2	2073.1	52.8	3.6
		12	9364.2	1801.8		
		18	8935.1	1945.9		
		24	8683.1	2025.9		
		30	8354.4	2066.7		
		36	8252.0	2059.8	52.8	8.3
25°C	*40-60%*	0	9196.5	1055.5	52.8	3.6
		6	8926.0	979.8		
		12	8540.8	1091.2		
		18	8190.6	1231.4		
		24	8034.9	1321.3		
		30	7757.6	1369.7		
		36	7397.4	1348.2	47.1	3.8
	80-100%	0	10432.0	1411.3	52.8	3.6
		6	9868.2	1466.2		
		12	9680.5	1454.4		
		18	9287.5	1403.6		
		24	9071.8	1510.7		
		30	8732.3	1404.5		
		36	8369.7	1427.0	41.8	15.6
	100-130%	0	9151.3	929.4	52.8	3.6
		6	8826.5	1092.7		
		12	8548.7	1099.4		
		18	8335.2	1125.9		
		24	8018.1	1305.8		
		30	7711.3	1244.8		
		36	7323.0	1214.9	40.6	12.2
35°C	*40-60%*	0	8797.3	895.2	52.8	3.6
		6	8343.3	829.1		
		12	7747.0	797.8		
		18	5584.5	846.5		
		24	5402.8	839.4		
		30	5286.4	838.5		
		36	5117.1	822.2	47.6	3.3
	80-100%	0	9748.8	1414.0	52.8	3.6
		6	9293.5	1658.9		
		12	8742.4	1780.7		
		18	6180.3	1036.7		
		24	5974.5	1055.6		
		30	5792.6	1034.7		
		36	5633.1	1062.9	43.7	14.8
	100-130%	0	10240.9	779.7	52.8	3.6
		6	9978.9	853.9		
		12	9133.2	890.8		
		18	5661.9	727.7		
		24	5511.9	775.2		
		30	5345.6	739.9		
		36	5174.0	702.6	43.9	14.2

Table 10. Mean MOR, MOE values for Douglas-fir non-inoculated beams at 15, 25 and 35°C at three moisture content regimes (40-60, 80-100, and 100-130%).

TEMP	TARGET MOISTURE CONTENT	INCUBATION PERIOD (WEEKS)	MOE (MPa)	STANDARD DEVIATION	MOR (MPa)	STANDARD DEVIATION
15°C	40-60%	0	8310.8	492.7	45.0	3.6
		12	7943.8	581.3		
		18	7663.1	523.5		
		24	7281.9	641.8		
		30	6982.6	765.2		
		36	6704.4	716.6	46.3	2.7
	80-100%	0	8964.6	871.0	45.0	3.6
		12	8462.3	923.5		
		18	8160.7	977.4		
		24	7637.4	953.9		
		30	7443.3	974.1		
		36	7208.1	947.9	45.3	4.5
	100-130%	0	8002.2	688.2	45.0	3.6
		12	7591.8	706.7		
		18	7152.6	763.7		
		24	6696.6	1044.0		
		30	6514.1	1084.7		
		36	6409.2	1048.3	44.5	2.9
25°C	40-60%	0	9626.7	1714.0	45.0	3.6
		6	9224.4	1579.5		
		12	8979.8	1566.3		
		18	8480.2	1416.7		
		24	8095.5	1431.0		
		30	7775.4	1345.3		
		36	7496.3	1322.4	41.3	4.9
	80-100%	0	7812.6	1236.9	45.0	3.6
		6	7605.0	1157.4		
		12	7300.9	1195.4		
		18	6807.5	1375.5		
		24	6657.7	1337.3		
		30	6364.8	1355.6		
		36	6138.8	1234.9	36.7	8.8
	100-130%	0	8830.2	1475.2	45.0	3.6
		6	8582.6	1504.5		
		12	8158.4	1430.4		
		18	7727.2	1543.4		
		24	7588.4	1576.1		
		30	7359.3	1572.1		
		36	7102.6	1572.6	38.1	13.9
35°C	40-60%	0	10338.3	1544.8	45.0	3.6
		6	9650.8	1340.4		
		12	8816.8	1371.3		
		18	5984.2	861.9		
		24	5747.0	814.0		
		30	5566.0	823.0		
		36	5411.3	806.9	40.5	5.7
	80-100%	0	8686.3	1503.2	45.0	3.6
		6	8246.4	1525.3		
		12	7491.1	1509.9		
		18	5343.7	1128.5		
		24	5147.9	1105.2		
		30	4988.0	1085.9		
		36	4817.5	1028.4	37.9	13.2
	100-130%	0	7665.0	885.7	45.0	3.6
		6	7299.3	900.2		
		12	6774.5	903.4		
		18	4560.9	563.8		
		24	4419.2	578.3		
		30	4273.6	596.2		
		36	4107.2	564.7	40.1	6.0

Table 11. Mean MOR and MOE values for western hemlock non-inoculated beams at 15, 25 and 35°C at three moisture content regimes (40-60, 80-100, and 100-130%).

TEMP	TARGET MOISTURE CONTENT	INCUBATION PERIOD (WEEKS)	MOE (MPa)	STANDARD DEVIATION	MOR (MPa)	STANDARD DEVIATION
15°C	*40-60%*	0	11438.4	1799.1	45.9	10.1
		12	11057.8	1804.9		
		18	10325.4	1534.1		
		24	9913.2	1396.4		
		30	9562.4	1360.8		
		36	9047.8	1246.1	45.2	10.0
	80-100%	0	11088.1	2614.9	45.9	10.1
		12	10638.4	2560.7		
		18	10205.4	2619.9		
		24	9701.1	2646.1		
		30	9239.8	2608.7		
		36	8799.0	2490.0	47.3	11.9
	100-130%	0	7546.5	2852.8	45.9	10.1
		12	7073.9	2682.8		
		18	6792.9	2529.2		
		24	6364.4	2442.6		
		30	6095.5	2359.5		
		36	5815.4	2245.1	48.1	7.4
25°C	*40-60%*	0	7645.7	1649.8	45.9	10.1
		6	7168.5	1543.5		
		12	6087.2	1405.8		
		18	5502.3	1581.1		
		24	5337.9	1629.8		
		30	4834.4	1571.0		
		36	4592.6	1528.8	39.9	15.4
	80-100%	0	7284.0	1752.8	45.9	10.1
		6	6805.3	1895.3		
		12	6390.1	1747.9		
		18	6076.0	1587.4		
		24	5860.3	1607.8		
		30	5762.6	1885.6		
		36	5579.2	1830.3	36.8	13.4
	100-130%	0	7335.7	999.7	45.9	10.1
		6	6821.7	813.0		
		12	6479.9	882.8		
		18	5988.3	858.7		
		24	5788.2	831.8		
		30	5596.3	790.5		
		36	5322.5	793.8	38.6	13.1
35°C	*40-60%*	0	7418.0	1983.0	45.9	10.1
		6	6802.9	1784.8		
		12	6333.9	1647.6		
		18	4108.3	1297.1		
		24	3906.0	1196.5		
		30	3832.6	1201.1		
		36	3711.8	1146.4	41.3	9.8
	80-100%	0	7579.4	1733.9	45.9	10.1
		6	6914.0	1715.4		
		12	6574.5	1685.6		
		18	4777.4	1366.4		
		24	4531.3	1275.0		
		30	4392.9	1213.9		
		36	4276.4	1160.9	42.1	10.0
	100-130%	0	8348.9	1739.7	45.9	10.1
		6	7832.6	1682.7		
		12	7352.9	1571.0		
		18	4542.6	1286.9		
		24	4371.4	1258.6		
		30	4278.2	1266.0		
		36	4120.4	1172.8	38.6	14.5

Table 12. Mean MOR, MOE values for southern pine non-inoculated beams at 15, 25 and 35°C at three moisture content regimes (40-60, 80-100, and 100-130%).