AN ABSTRACT OF THE THESIS OF

Maria Gabriela Buamscha for the degree of Master of Science in Soil Science presented on November 7, 2006.

Title: Chemical and Physical Properties of Douglas Fir Bark Relevant for the Production of Container Crops in Oregon.

Abstract approved:

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Dan M. Sullivan

It is widely accepted among nursery producers that [*Pseudotsuga menziesii* (Mirbel) Franco] bark (DFB) is an excellent substrate for container production, hence its widespread use in Oregon and other regions where Douglas fir constitutes a significant portion of the forest products industry. Despite its widespread use, little information is available on the chemical and physical properties of DFB as it pertains to use in container substrates. Therefore, three studies were conducted with the following objectives; (i) document baseline chemical and physical properties of fresh and aged DFB that have relevance to production of container plants; (ii) evaluate micronutrient availability in fresh and aged DFB; and (iii) determine if differential plant growth measured between fresh and aged DFB could be explained by differences in nitrogen immobilization and decomposition rates between the two bark ages.

In the first study, the chemical and physical properties of DFB were monitored for one-year between June 2005 and May 2006. During that period fresh and aged DFB samples were collected from two sources in Oregon; source A offering a finer

micronutrients, particle size distribution, bulk density, air space (AS), container capacity (CC), and solids. Native fresh and aged DFB contains significant extractable amounts of the measured plant macronutrients and micronutrients, except N. In general, the aging process reduced pH, increased electrical conductivity, and extractability of phosphorous, calcium, magnesium, boron, iron, and aluminum. Uniformity of DFB chemical properties throughout the year was affected by bark source and less so by age; source B (coarse) was more consistent. Aged DFB had lower AS and higher CC compared to fresh DFB. Average differences in AS and CC between fresh and aged DFB within a source were $\leq 8\%$, and may impact plant growth. Douglas fir bark from source B (coarse) had higher AS and lower CC than source A (fine). Similar to chemical properties, uniformity of DFB physical properties was more affected by the bark source than age; source A (fine) had more consistent physical properties throughout the year.

The second study focusing on micronutrient availability in DFB used annual vinca [*Catharanthus roseus* (L.) G. Don 'Peppermint Cooler'] as the test species. Annual vinca plugs were transplanted to containers filled with DFB on May and June 2005 (Expts. 1 and 2, respectively). Treatments were arranged in a 2 × 3 factorial with two DFB ages (fresh and aged) and three micronutrient sources (DFB alone, 10% by volume yard debris compost, or 0.9 $kg \cdot m^{-3}$ Micromax fertilizer). Plants were measured for shoot dry weight and foliar color. Substrate and foliar samples of each plant were analyzed for 13 essential macronutrients and micronutrients, plus substrate pH and electrical conductivity. Douglas fir bark alone appears to provide sufficient micronutrients for annual vinca grown at pH 4.7-5.7 over a two-month period. In Expt. 1 there were no differences in shoot dry weight and foliar color regardless of DFB age or micronutrient source. At the end of Expt. 2, plants in aged DFB were larger than those in fresh DFB, but differences were primarily due to nitrogen availability. None of the treatments developed color symptoms that could be associated with micronutrient deficiency. Micronutrient availability in DFB should be considered in container fertilizer management plans.

The final study intended to determine if there are differences in plant growth due to N competition between the plant and microorganisms within fresh and aged DFB; then document nitrogen immobilization and decomposition rates of fresh and aged DFB to validate the cause of growth differences. A series of experiments to measure plant response, N draw-down index and percent cumulative carbon loss (C loss) were conducted on fresh and aged DFB. On 16 June 2005, geranium (Pelargonium xhortorum Bailey 'Maverick Red') plugs were transplanted to #1 containers filled with fresh or aged DFB. Treatments were arranged in a 2 x 3 factorial with two DFB ages (fresh and aged) and three N fertilizer rates (100, 200, and 300 ppm). On 19 June 2006, a second repetition of the geranium experiment was conducted with the exception that N fertilizer rates were increased to 200, 300, and 400 ppm. Plant growth was affected by DFB age; geranium stem growth was always smaller in the fresh material. Besides N availability, other variables such as container capacity may be playing an important role. Nitrogen draw-down analysis determined that a large fraction of N in solution was immobilized in fresh and aged DFB, but differences were at best marginally significant. Carbon loss occurred at low predictable rates for a well-decomposed material, but there were no differences between fresh and aged DFB. The similarities in C loss between fresh and aged DFB agree with the similar N immobilization measured in the two materials. Differential geranium growth in fresh and aged DFB observed in these studies cannot be explained by similarities in N immobilization or decomposition rate between the two barks. Nitrogen immobilization in fresh and aged DFB may differ between sources. The source used for this study showed no clear differences in N immobilization between the fresh and aged material. While another source with a finer particle size presented a higher N immobilization in fresh than in aged bark.

Chemical and Physical Properties of Douglas Fir Bark Relevant for the Production of Container Crops in Oregon

by

Maria Gabriela Buamscha

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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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Maria Gabriela Buamscha, Author

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DEDICATION

To Joseph Donnegan. My partner in life and my dearest friend.

To my mother Lita (a mi mamá Lita).

CHEMICAL AND PHYSICAL PROPERTIES OF DOUGLAS FIR BARK RELEVANT FOR THE PRODUCTION OF CONTAINER CROPS IN OREGON

GENERAL INTRODUCTION

The North Willamette Valley is the center point of the ornamental nursery industry in Oregon (OR). Container crops are grown primarily in Douglas fir [*Pseudotsuga menziesii* (Mirbel) Franco] bark (DFB); a unique substrate used almost exclusively by OR nurseries. Douglas fir bark comprises the highest portion of most nursery substrates (60 to 80% of the substrate mix, personal observation) and is often incorporated to some extent with peat moss, sand, compost, pumice, and other materials.

Fresh and aged DFB are used in OR container nurseries. Fresh DFB refers to material sold soon after bark is removed from the tree, ground to smaller particle size, and screened; aged DFB refers to material which goes through the same process but then sits in undisturbed piles (7 to 12 m tall) for an average of 7 months before use. Container nurseries are equally divided in their preference for fresh and aged bark (personal communication, Jack Hoeck, Rexius Bark, Eugene, OR). Little is known about the properties of DFB with respect to its use as a container substrate. There is also little knowledge of the effect of DFB age on its chemical or physical properties. Most literature on this subject refers to the chemical properties of soluble components extracted for pulpwood or other industrial chemical purposes (Harkin and Rowe, 1971; Bowyer et al., 2003).

Douglas fir bark in the Pacific Northwest (PNW) is used similarly to pine bark in the southeast U.S. Both bark types are irrigated frequently, fertilized with similar products and rates, and mixed with similar components (sand, peat moss, etc.). Despite similarities in these two resources, several chemical properties of DFB have been found to differ from other conifer barks. For example, bark pH, nitrogen (N), phosphorous (P), potassium (K), calcium (Ca), magnesium (Mg) and C/N ratio differ between Douglas fir, ponderosa pine (*Pinus ponderosa* P. & C.

Lawson), and redwood [*Sequoia sempervirens* (Lamb ex D. Don) Endl] (Bollen, 1969). Research conducted on pine bark with respect to nursery container nutrition cannot be assumed applicable to DFB.

The chemical properties of pine bark have been documented and summarized in a review by Ogden et al. (1987). Non-amended pine bark has a low pH (3.4-4.5), high P (11.5-23 ppm) and K (134-215 ppm), sufficient manganese (Mn) (4.5-15 ppm) and copper (Cu) (0.22-0.50 ppm), and low Ca (8.5-24 % of cation exchange capacity, CEC), Mg (4.5-6.2 % of CEC), and zinc (Zn) (1.8-4.4 ppm) (Tucker, 1995) when compared to established sufficiency ranges for container substrates (Warncke, 1998).

Research has shown that pine bark media contains sufficient micronutrients to produce woody plants. Niemiera (1992) extracted slightly lower levels of iron (Fe), Cu, Mn, and Zn from pine bark alone compared to pine bark amended with Micromax (The Scotts Co., Marysville, OH) or Ironite (Ironite Products Co., Scottsdale, AZ); Niemera speculated that such small differences would not be physiologically significant in terms of plant growth. Svenson and Witte (1992) showed that pine bark amended with 25-50% composted hardwood bark provided sufficient boron (B), Fe, Mn, and Zn for geranium (*Pelargonium ×hortorum* L.) growth.

Micronutrient additions to container media and its effect on plant growth have found contrasting results. Rose and Wang (1999) reported no improvement in rhododendron (*Rhododendron* L. ×'Girards Scarlet') growth when adding compost or micronutrient fertilizer to a 3.0 pine bark : 1.0 hardwood bark : 1.0 peat : 0.2 sand (by volume) medium compared to a non-amended control. In contrast, vinca [*Catharanthus roseus* (L.) G. Don] shoot length and dry weight were greatest in a peat-based media with sulfated micronutrients (pH not adjusted) or chelated micronutrients (pH adjusted to 5.5) compared to a non-amended control (Thomas and Latimer, 1995). Wright et al. (1999) analyzed the effect of micronutrient and lime additions on substrate pH and growth of nine container tree species in pine

bark; micronutrient additions resulted in the best growth responses for all species, while lime depressed growth.

Container nurseries in OR use similar fertility programs for fresh and aged DFB. Probably because of the assumption that they have similar chemical and biological properties. Different results have been reported on the effect of fresh and aged pine bark on plant growth. Holly (*Ilex crenata* Thunb. 'Rotundifolia') had similar size and quality when grown under a standard fertilization program in either fresh or aged bark and with or without preplant N (Pokorny, 1979). However, he continued saying that 0.15 kg $N \cdot m^{-3}$ provides adequate N for microorganisms present in pine bark but without presenting supporting data. Cobb and Keever (1984) compared fresh and aged pine bark amended with 1 kg $N \cdot m^{-3}$ Osmocote (17N-3P-10K) (The Scotts Co.) at four levels of supplemental N (0, 100, 200, and 300 ppm): Growth of dwarf japanese euonymus (*Euonymus japonica* Thunb. 'Microphylla') and japanese holly (*Ilex crenata* Thunb. 'Compacta') in fresh bark equaled or exceeded that in aged bark at all levels of supplemental N. Harrelson et al. (2004) compared fresh and aged pine bark and three rates of controlled release N fertilizer; Skogholm cotoneaster (*Cotoneaster dammeri* C.K.Schneid 'Skogholm') grown in aged pine bark were larger than cotoneaster grown in fresh pine bark. The authors attributed the reduction in growth in fresh bark to its lower container capacity and available water compared to aged bark.

Physical properties of a substrate must also be considered. Container substrates are often developed or chosen by nursery growers based primarily on their perceived physical properties. The physical properties of a substrate affect key resources in the container such as water, air, and nutrient availability (Bilderback et al., 2005). A substrate's efficiency in capturing, holding, and transporting water to the plant roots is also dependent on its physical properties (Argo, 1998). Important physical parameters used to characterize soilless growing media are total pore space (TPS), air space (AS), and container capacity (CC). Those terms were first defined for soilless media by DeBoodt and Verdonck (1971) and subsequently used by Fonteno et al. (1981), Bilderback et al. (1982), Milks et

al. (1989), and Argo (1998): Total pore space is the moisture content at zero pressure, when all pores are filled with water. Air space is the difference between TPS and moisture content at 1 kPa of moisture tension (MT). Container capacity was initially referred as water holding capacity by DeBoodt and Verdonck (1971) and defined as the moisture content at 1 kPa of MT. The current definition for CC is the percent volume of a substrate that is filled with water after the material is saturated and allowed to drain (Fonteno and Harden, 2003). Container capacity is divided into three classes: (i) easily available water, the quantity of water release between 1 and 5 kPa MT and optimally represents 75-90% of the CC; (ii) water buffering capacity, the amount of water released between 5 and 10 kPa MT, optimal being 4-5% of CC; and (iii) difficult available water, the volume percent difference between 10 and 1,500 kPa MT and is considered unavailable to plants. Bulk density (D_b), the ratio of the mass of dry solids to the total volume (solids and pores together) (Hillel, 1998) is another important physical property of container substrates. Container weight is a function of the substrate's D_b. Heavier containers will be less likely to blow-over in the nursery but their shipping cost will be higher. In addition, some insecticide applications utilize rates based on substrate D_b (for example, bifenthrin (Talstar ®)). Substrate physical properties affect also the incidence of plant diseases such as phytophthora root rot (*Phytophthora cinnamoni* Rands); root rot severity in rhododendron (*Rhododendron* L. 'Nova Zembla') was negatively correlated with TPS and AS and positively correlated with D_b and water held between 5 and 10 kPa (Ownley et al., 1990).

Most research on growing media physical properties has been done with pine bark. Milled pine bark needs a range of both fine and coarse particle sizes to be suitable as a container growing media; as a general rule, 70 to 80% of the particles should be within a range of 0.6 to 9.5 mm in diameter and the remaining particles less than 0.6 mm (Pokorny, 1979). After irrigation and drainage, pine bark-based substrates should have 10-30% air space (AS), 45-65% container capacity (CC), 25-35% available water, 25-35% unavailable water, and 0.19-0.70 $g \cdot cm^{-3}$ D_b (Yeager et al., 2000). Most of the available water in a pine bark media is

held at tensions less than 2.5 kPa. While water held at tensions greater than 10 kPa is not readily available for plants (Ingram et al., 1993). In the PNW, substrates are compared to the aforementioned guidelines for pine bark. Some nursery managers believe PNW substrates, particularly those used in Oregon, must have more AS and less CC compared to what is recommended in the southeast U.S. in order to compensate for the typically higher precipitation rates during the dormant winter season. Lack of drainage during the winter, when plants are transpiring little or no water through foliage, coupled with high precipitation rates, has caused root rot problems with many species (personal observation).

The uniformity of DFB properties throughout the year has not been studied. Trees are harvested by lumber mills virtually year-round. Bark removal is easy during the spring when water flows readily through the xylem. However, during fall and winter, bark is more difficult to remove thus lumber mills scrape more wood off the tree in an effort to remove all the undesirable bark. Higher concentration of wood in bark supplies is one way that chemical and physical properties of bark may change throughout the year. Moisture can also impact the bark screening process; moisture causes small particles to stick to large particles, making the screening less precise. The North Willamette Valley in OR receives approximately 1.1 m precipitation annually, most of which occurs between Nov. and March (Taylor, 2005). Consequently, time of the year in relation to rainfall may affect particle size distribution and other properties of DFB (personal communication with Scott Leavengood, Wood Products Extension Agent, Oregon State University).

It is widely accepted among nursery producers that DFB is an excellent substrate for container production, hence its widespread use in Oregon and other regions where Douglas fir constitutes a significant portion of the forest products industry. Despite its widespread use, little information is available on the chemical and physical properties of DFB as it pertains to use in container substrates. Therefore, the main objectives of this study were: (i) document baseline chemical and physical properties of DFB that have relevance to production of container

plants; (ii) evaluate micronutrient availability in fresh and aged DFB; and (iii) determine if there are differences in nitrogen immobilization between the two.

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MONITORING OF THE CHEMICAL AND PHYSICAL PROPERTIES OF DOUGLAS FIR BARK RELEVANT FOR THE PRODUCTION OF CONTAINER CROPS

Abstract

A one-year survey on the chemical and physical properties of Douglas fir [*Pseudotsuga menziesii* (Mirbel) Franco] bark was conducted with the following objectives; (i) document baseline chemical and physical properties of Douglas fir bark (DFB) that have relevance to production of container plants; (ii) determine the effect of DFB age on its chemical and physical properties; and (iii) document the consistency of those properties throughout the year. In June, Aug., Oct., and Dec. 2005, and Feb. and May 2006, fresh and aged DFB samples were collected from the two primary DFB suppliers (bark sources) for Oregon nurseries. One supplier offers a bark screened to ≤ 2.2 cm (coarse) and the other a bark screened to ≤ 0.95 cm (fine). Samples were analyzed for pH, electrical conductivity, essential plant macronutrients and micronutrients, bulk density, substrate moisture characteristic curves, and particle size distribution. Air space (AS), container capacity (CC), and solids were determined as a percent of container volume. Native fresh and aged DFB contains significant extractable amounts of the measured plant macronutrients and micronutrients, except N. In general, the aging process reduced pH, increased electrical conductivity, and extractability of phosphorous, calcium, magnesium, boron, iron, and aluminum. Uniformity of DFB chemical properties throughout the year was affected by bark source and less so by age; source B (coarse) being more consistent. Aged DFB had lower AS and higher CC compared to fresh DFB. Average differences in AS and CC between fresh and aged DFB within a source were $\leq 8\%$, and may impact plant growth. Douglas fir bark from source B (coarse) had higher AS and lower CC than source A (fine). Similar to chemical properties, uniformity of DFB physical properties was more affected by the bark source than age; source A (fine) had more consistent physical properties throughout the year.

Introduction

Container crops in the Pacific Northwest (PNW) are grown primarily in Douglas fir [*Pseudotsuga menziesii* (Mirbel) Franco] bark (DFB). Similar to pine (*Pinus taeda L.*) bark in the southeast U.S., DFB comprises the highest portion of most nursery substrates (60 to 80% of the substrate mix, personal observation). Douglas fir bark is often incorporated to some extent with peat moss, sand, compost, pumice, and other materials.

The chemical properties of pine bark have been documented and summarized in a review by Ogden et al. (1987). Non-amended pine bark has a low pH (3.4-4.5), high phosphorous (P) (11.5-23 ppm) and potassium (K) (134-215 ppm), sufficient manganese (Mn) (4.5-15 ppm) and copper (Cu) (0.22-0.50 ppm), and low calcium (Ca) (8.5-24 % of cation exchange capacity, CEC), magnesium (Mg) (4.5-6.2 % of CEC), and zinc (Zn) (1.8-4.4 ppm) (Tucker, 1995) when compared to established sufficiency ranges for container substrates (Warncke, 1998). Niemiera (1992) reported pine bark alone to provide 0.10 ppm Cu, 22.7 ppm iron (Fe), 9.7 ppm Mn, and 3.9 ppm, just slightly lower than bark amended with Micromax (Scotts Co., Marysville, OH) and Ironite (Ironite Products Co., Scottsdale, AZ).

Fresh and aged DFB are used in OR container nurseries. Fresh bark refers to material sold soon after tree debarking, grinding, and screening to size; aged bark refers to material which also sits in undisturbed piles (7 to 12 m tall) for an average of 7 months before use. Container nurseries are equally divided in their preference for fresh and aged bark (personal communication, Jack Hoeck, Rexius Bark, Eugene, OR). Those preferring fresh DFB often claim it is more consistent from batch to batch than is aged DFB. Little is known about the properties of DFB with respect to its use as a container substrate, and little is known about the effect of DFB age on its chemical or physical properties. Most literature on this subject refers to the chemical properties of soluble components extracted for pulpwood or other industrial chemical purposes (Harkin and Rowe, 1971; Bowyer et al., 2003).

Skogholm cotoneaster (*Cotoneaster dammeri* C.K.Schneid 'Skogholm') grown in aged pine bark were larger than cotoneaster grown in fresh pine bark (Harrelson et al., 2004). The authors attributed the reduction in growth in fresh bark to differences in physical properties. Container capacity and available water in fresh pine bark were significantly lower than in aged bark, in particular at the beginning of the study. In the same study, pine bark age had no effect on substrate pH or electrical conductivity (EC).

Nutrient content of bark differs not only between species but also with tree age, environmental factors, and growing site (Bollen, 1969). Bollen also stated that DFB has almost no plant nutrient value in terms of nitrogen (N), P, K, Ca, and Mg. This statement is based on percent content of each nutrient on a dry matter basis. Buamscha and Altland (2005) contradict this notion in that they reported high levels of water extractable P and sufficient levels of water extractable K compared to established sufficiency ranges (Warncke, 1998; Yeager et al., 2000). Bollen also reported that bark of Douglas fir, ponderosa pine (*Pinus ponderosa* P. & C. Lawson), and redwood [*Sequoia sempervirens* (Lamb ex D. Don) Endl] differ in pH, C/N ratio, and content of the mentioned nutrients. Considering the differences in chemical properties of DFB and other conifer barks, research conducted on pine bark with respect to nursery container nutrition cannot be assumed completely applicable to DFB.

Physical properties of a substrate must also be considered. Container substrates are often developed or chosen by nursery growers based primarily on their perceived physical properties. Most research on the physical and hydraulic properties of container substrates has been done with pine bark. Milled pine bark needs a range of both fine and coarse particle sizes to be suitable as a container growing media; as a general rule, 70 to 80% of the particles should be within a range of 0.6 to 9.5 mm in diameter and the remaining particles less than 0.6 mm (Pokorny, 1979). After irrigation and drainage, pine bark based substrates should have 10-30% air space (AS), 45-65% container capacity (CC), 25-35% available water, 25-35% unavailable water, and 0.19-0.70 $g \cdot cm^{-3}$ bulk density (D_b) (Yeager et

al., 2000). Most of the available water in a pine bark media is held at tensions less than 2.5 kPa; while water held at tensions greater than 10 kPa is not readily available for plants (Ingram et al., 1993). In the PNW, substrates are compared to the aforementioned guidelines for pine bark.

The uniformity of DFB properties throughout the year has not been studied. Trees are harvested by lumber mills virtually year-round. Bark removal is easy during the spring when water flows readily through the xylem. However, during fall and winter, bark is more difficult to remove thus lumber mills scrape more wood off the tree in an effort to remove all the undesirable bark. Higher concentration of wood in bark supplies is one way that chemical and physical properties of bark may change throughout the year. Moisture can also impact the bark screening process; moisture causes small particles to stick to large particles, making the screening less precise. The North Willamette Valley in OR receives approximately 1.1 m precipitation annually, most of which occurs between Nov. and March (Taylor, 2005). Consequently, time of the year in relation to rainfall may affect particle size distribution and other properties of DFB (personal communication with Scott Leavengood, Wood Products Extension Agent, Oregon State University).

It is widely accepted among nursery producers that DFB is an excellent substrate for container production, hence its widespread use in Oregon and other regions where Douglas fir constitutes a significant portion of the forest products industry. Despite its widespread use, little information is available on the chemical and physical properties of DFB as it pertains to use in container substrates. Therefore, the objectives of this study were: (i) document baseline chemical and physical properties of DFB that have relevance to production of container plants; (ii) determine the effect of age on DFB chemical and physical properties; and (iii) document the consistency of those properties throughout the year.

Materials and Methods

Fresh and aged DFB samples were collected from two Oregon bark suppliers in June, Aug., Oct., and Dec. 2005, as well as Feb. and May 2006. The two companies are the primary sources of DFB for nursery growers in Oregon. They differ with respect to the particle size of the finished material; one offering a coarser screened bark at $\leq$ 2.2 cm (coarse) and the other a finer screened bark at $\leq$ 0.95 cm (fine). Barks of different age and screen size occur in single and separate piles at each of the bark suppliers. Each pile was roughly 5 m tall and 10 m wide, although pile size was never constant. At each collection date, three sub-samples were randomly taken from each pile of differing screen size and bark age. Bark sub-samples were collected from each pile by scraping away the surface 0.3 m of bark and collecting 0.019 m^3.

Samples were analyzed for pH, EC, ammonium (NH_4-N), nitrate (NO_3-N), P, K, Ca, Mg, sulfur (S), and aluminum (Al) using the Saturated Media Extract (SME) method with water as the extractant (Wrancke, 1998; Gavlak et al., 2003). While boron (B), Fe, Mn, Cu, Zn, were analyzed using a SME with diethylenetriaminepentaacetic acid (DTPA) as the extractants (Warncke, 1998; Gavlak et al., 2003). Following Gavlak et al. (2003) recommendations, DFB was soaked in the extractant (either water or DTPA) for 24 h. Extracted solutions were analyzed for the mentioned elements, except N, by inductively coupled plasma-emission spectrometry (ICP) (Thermo Jarrel Ash, Offenbach, Germany). Ammonium and NO_3-N were analyzed colorimetrically using a Lachat Quick Chem 8000 (Lachat Instruments, Milwaukee, WI).

Each bark sample was analyzed for bulk density (D_b) ($g \cdot cm^{-3}$), percent air space (AS), container capacity (CC), and solids using an aluminum core (7.6 cm tall and 7.6 cm diameter) packed with each substrate and attached to a Porometer™ (Fonteno and Bilderback, 1993). Particle size distribution (PSD) of each sample was determined with 14 sieves (19.0, 12.5, 6.3, 4.0, 2.8, 2.0, 1.4, 1.0, 0.71, 0.50, 0.35, 0.25, 0.18, and 0.11 mm) plus a bottom pan (Bilderback et al., 1982). Sieves

and pan were shaken for 5 min with a RX-29 Ro-Tap® sieve shaker (278 oscillations min^{-1}, 150 taps min^{-1}) (W.S. Tyler, Mentor, OH).

Substrate moisture characteristic curves expressed as volumetric water content at increasing tension were obtained for fresh and aged coarse (≤2.2 cm screen size) DFB collected from source B on May 2006. Volumetric water content at complete saturation and after saturation and drainage for one hour (CC) was obtained from an aluminum core (3.8 cm tall and 7.6 cm diameter) attached to a North Carolina State University (NCSU) Porometer™. The same core was then placed in an apparatus described in Fonteno et al. (1981) and Milks et al. (1989) and modified as follows. The stem of a 600 mL Pyrex Buchner filter funnel with fritted plate of medium porosity (VWR, Westchester, PA) was connected to a 1 L Erlenmeyer flask using plastic tubing (0.32 cm internal diameter). The Erlenmeyer flask was half filled with water and served to apply tension by changing the head difference at the base of the fritted plate between 1 and 6.1 kPa.

Data were subjected to multivariate analysis of variance to determine the influence of age on chemical and physical properties. Coefficients of variance (CV) for each parameter were calculated to assess data consistency over time (SAS Institute, 1999).

Results and Discussion

Douglas fir bark chemical properties

Chemical properties of fresh and aged DFB were analyzed over 1 year and are presented in Table 2.1. The data can be used as a baseline for future comparative studies of DFB substrates and amendments, and as a reference for nursery growers and consultants.

Native DFB chemical properties were compared to fertility guidelines for container plant production (Warncke, 1998; Yeager et al., 2000). Bark pH ranged from 3.7 to 5.0, and thus considered low by most guidelines. Electrical conductivity was below or near the lower limit of recommended levels. Similar to

pine bark (Odgen et al., 1987), DFB extractable NH_4-N and NO_3-N levels were low independently of bark type and collection date (data not presented). Across all bark types, DFB had high levels of extractable P, sufficient to high K and Cu, and sufficient Mn. Extractable P levels in DFB were within or above the range reported for pine bark by Tucker (1995). In addition, native DFB tended to have higher P levels than pine and hardwood bark amended with a P fertilizer (Rose and Wang, 1999). Unlike P, potassium (K) is not considered a pollutant (Handreck and Black, 2002). However, the high K levels extracted from DFB should be taken into account with fertility programs. Extractable Ca, Mg, SO_4^-, B, and Zn levels were below recommended levels, but still in notable quantities that should be accounted for in fertility programs. Low pH, Ca, and Mg are of little consequence considering the industry-wide practice of pre-plant incorporation with dolomitic limestone (personal observation). Extractable Fe was high in aged bark and within recommended levels in fresh bark. Sodium in all bark samples was sufficiently low. Micronutrients in DFB seem to be sufficient for production of some container crops. Buamscha et al. (2006) demonstrated that DFB alone provided sufficient micronutrients for annual vinca [*Catharanthus roseus* (L.) G. Don 'Peppermint Cooler'] grown over a two-month period at pH 4.7-5.7. Similarly, pine bark amended with 25-50% composted hardwood bark provided sufficient B, Fe, Mn, and Zn for geranium (*Pelargonium* ×*hortorum* L.) growth (Svenson and Witte, 1992).

The age of DFB influenced pH, EC, and soluble P (p-value 0.0779), Ca, Mg, B, Fe, and Al. Across both sources and collection dates, aged DFB had lower pH than fresh DFB; however, the interaction between collection date and bark source indicates that this general trend is not consistently true at each date. Bark pH was negatively correlated to EC, and extractable P, Ca, Mg, B, and Fe ($r < -0.339$ across all parameters). Not surprising, aged DFB, which had lower pH than fresh DFB, also had higher levels of each of these parameters than fresh bark. These results differ from Harrelson et al. (2004) who did not find an effect of pine bark age on substrate pH, and Cobb and Keever (1984) who reported higher pH in

aged pine bark compared to fresh bark. Research concurrent with this study has documented greater plant growth in aged than fresh DFB (Buamscha et al., 2007), which was attributed to greater N immobilization in fresh bark.

Date of sampling influenced most measured chemical parameters by interacting with bark age or bark source (with the exception of SO_4^-,Cu, and Zn). Coefficients of variation (CV, calculated as σ/μ) were calculated as a measure of data consistency over time (Table 2.2). Within both fresh and aged bark, nutritional parameters of source B (coarse) had lower CV than source A (fine) with few exceptions. Conversely, within source A, fresh bark had lower CV in 11 of the 14 measured parameters; in source B, CV were lower in seven parameters each for fresh and aged bark. Considering the primary difference in bark sources is the screening size (0.95 cm for source A and 2.2 cm for source B), this implies that chemical properties of DFB might be more uniform or consistent throughout the year in coarser bark grades. Bark age seems to be less important in terms of consistency than the source from which it was collected.

No documented Al testing exists for soilless media such as tree bark. This is possibly due to the general agreement that organic soils and soilless media contain low amounts of Al (Lucas and Davis, 1961; Yeager and Barret, 1985). Significant amounts of Al were extracted in DFB throughout the survey (7.8 – 51.5 ppm), which among other things could impact bloom color of hydrangea [(*Hydrangea macrophylla* (Thunb.) Ser.]. Aged DFB had higher water extractable Al than fresh bark.

Douglas fir bark physical properties

Native DFB has high AS, low CC, adequate solids, and low D_b (Table 2.3) compared to guidelines developed for pine bark in the southeastern U.S. (Yeager et al., 2000). Some nursery managers believe PNW substrates, particularly those used in Oregon, must have more AS and less CC compared to what is recommended in the southeast U.S. in order to compensate for the typically higher precipitation rates during the dormant winter season. Lack of drainage during the winter, when plants

are transpiring little or no water through foliage, coupled with high precipitation, rates has caused root rot problems with many species (personal observation).

Air space, CC, and solids were analyzed collectively with multivariate analysis of variance due to inherent correlations between each parameter. Collectively, these parameters were affected by an interaction between bark age, bark source, and date of collection. Air space was lower and CC higher in aged compared to fresh DFB. Average differences in AS and CC between fresh and aged DFB within a source were $\leq 8\%$, and may impact plant growth. Harrelson et al. (2004) reported larger differences in physical properties between fresh and aged pine bark right after potting; CC was 61% for aged and 49% for fresh, while available water was 26% for aged and 10% for fresh bark. In their study, skogholm cotoneaster grew larger in aged compared to fresh pine bark, and the authors attributed this response to the aforementioned differences in physical properties. Not surprising, coarser DFB from source B generally had higher AS and lower CC than finer DFB from source A. Differences in physical properties were more pronounced between bark sources than bark age.

Sampling date influenced physical parameters. Each parameter fluctuated slightly over time, with no discernible pattern in relation to time of year. An attempt was made to trace bark supplies back to the lumber yard and further back to the forest from which the trees originated in order to better understand how time of year affects bark properties. However, due to safety and privacy concerns, lumber mills contacted were unwilling to accommodate us. Consistency of DFB physical properties over time were estimated using coefficients of variation (Table 2.2). Container capacity, D_b, and solids were more consistent (lower CV) over time from source A (fine) compared to source B (coarse).

Bulk density was influenced by an interaction between bark age, bark source, and collection date, although measured differences were minor (Table 2.3). Container weight is a function of the substrate's D_b and CC. Heavier containers will be less likely to blow-over in the nursery but their shipping cost will be higher. In addition, some insecticide applications utilize rates based on substrate D_b (for

example, bifenthrin (Talstar ®)). Our data show that DFB age or source (particle size) did not have an economically important effect on D_b.

Analysis of variance indicated that particle size distribution was affected by an interaction between all variables (bark age, source, and date of collection) (Table 2.4). Casual scanning of the table reveals some inconsistencies in the 6.3 mm screen between fresh and aged bark. Bark of two different screen sizes had different particle size distributions, as would be expected. Source B (coarse) generally had greater mass in screens > 4 mm while source A (fine) had greater mass in screens 0.25 to 2.8 mm. For pine bark, Pokorny (1979) recommended a substrate contain 70% to 80% coarse particles (0.6 to 9.5 mm in diameter) and 20% to 30% fine particles (less than 0.6 mm). Source A (fine) fell within these guidelines, while source B (coarse) had more coarse particles and fewer fine particles than recommended. As mentioned previously, coarser substrates for wet winters characteristic of the PNW are likely beneficial.

A single sample of fresh and aged DFB for source B (coarse) was analyzed for its substrate moisture characteristic curve (Fig. 2.1), consequently curves cannot be compared statistically. Nevertheless, they provide an insight on the moisture-releasing properties of DFB. Container capacity for fresh and aged bark were 36 and 44%, respectively. Easily available water (EAW), the amount of moisture released between 1 and 5 kPa (De Boodt and Verdonck, 1972) was 69% and 86% of the total available water (CC) for fresh and aged bark, respectively. De Boodt and Verdonck (1972) suggest that optimal range for EAW is 75% to 90% of total available water. Unavailable water (UW) has been defined as that which is still held by a substrate at pressure higher than 10 kPa by Ingram et al. (1993) or 1500 kPa by De Boodt and Verdonck (1972). There is no agreement on the exact pressure at which water is unavailable to plants in a soilless substrate. Our curves were terminated at 6.1 kPa, at which there was 14% and 11% of the total available water still held by fresh and aged DFB, respectively. Even though terminated at a lower pressure, UW calculated for DFB was substantially lower than that calculated for pine bark (Harrelson et al., 2004).

In summary, native fresh and aged DFB contains appreciable amounts of measured plant macronutrients and micronutrients, except for N (data not shown). In general, the aging process reduced pH and increased the extractability of P, Ca, Mg, B, Fe, and Al. DFB chemical properties throughout the year were more consistent within a bark source more than bark age; source B (coarse) being most consistent. Aged DFB had lower AS and higher CC as expected. Similar to the chemical data, the uniformity of DFB physical properties (except for AS) was most influenced by source and not by age; source A (fine) had more consistent physical properties throughout the year. These findings do not support the belief of some OR nursery growers that fresh DFB has more consistent properties than aged DFB.

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Table 2.1. Average chemical properties of Douglas fir bark resulting from two bark ages, two bark sources, and six sampling dates (n = 3).

Bark age	Date	Water extraction[z] pH	EC[v]	P	K	Ca	Mg
				mg·L^{-1}			
Fresh	Jun-05	4.4	267	14.8	101.0	19.9	9.4
	Aug-05	5.0	310	19.2	110.0	20.0	9.3
	Oct-05	4.2	293	13.8	97.3	20.9	9.6
	Dec-05	4.0	257	8.8	77.2	17.3	7.3
	Feb-06	4.2	235	12.2	95.9	26.7	11.0
	May-06	4.5	219	10.5	78.4	20.4	8.1
Aged	Jun-05	3.7	466	28.0	110.3	38.7	28.3
	Aug-05	4.4	264	10.3	78.8	21.5	14.6
	Oct-05	3.7	680	26.5	162.0	71.2	44.4
	Dec-05	4.2	386	18.1	117.6	38.7	21.7
	Feb-06	4.0	328	20.5	120.1	36.2	19.9
	May-06	3.8	406	21.8	130.8	37.8	21.3
Adequate ranges		5-6[y]	480-1280[w]	3-5[w]	60-149[w]	80-199[w]	30-69[w]
Sources of variat.		Pr > F					
Bark age (B)		0.0257	0.0443	0.0779	0.1309	0.0319	0.0133
Bark source (S)		0.4475	0.4052	0.9026	0.1800	0.5614	0.3568
S*B		0.1644	0.8855	0.5939	0.7189	0.7101	0.5448
Date (D)		0.4851	0.7436	0.7005	0.9591	0.7262	0.6787
B*D		0.1194	0.0434	0.3820	0.0519	0.0104	0.0498
S*D		0.0387	0.0354	0.6516	0.0191	0.0184	0.0796
B*S*D		0.5080	0.5263	0.0137	0.5463	0.8692	0.5304

[z] water and DTPA extractions using the Saturated Media Extract (SME) method (Wrancke, 1998; Gavlak et al., 2003). [y] Yeager et al., 2000. [x] Guidelines provided by Brookside Laboratories (New Knoxville, OH). [w] General guidelines for substrates analyzed by the SME method (Warncke, 1998). [v] Electrical conductivity (EC) in ppm = (mmhos/cm) x 640.

Table 2.1. Average chemical properties of Douglas fir bark resulting from two bark ages, two bark sources, and six sampling dates (n = 3) (Continued).

Bark age	Date	Water extraction[z]			DTPA extraction[z]	
		SO_4	Na	Al	B	Fe
Fresh	Jun-05	12.1	10.9	13.2	0.20	28.6
	Aug-05	15.6	12.3	9.4	0.19	23.2
	Oct-05	18.0	15.8	9.4	0.27	22.7
	Dec-05	11.1	16.2	7.8	0.27	21.7
	Feb-06	10.4	10.4	10.4	0.25	28.6
	May-06	13.0	12.3	9.7	0.23	30.6
Aged	Jun-05	13.7	9.7	51.5	0.38	63.1
	Aug-05	11.2	12.6	10.4	0.37	84.6
	Oct-05	20.5	15.1	32.4	0.56	92.4
	Dec-05	13.1	14.3	15.9	0.51	77.2
	Feb-06	9.8	8.6	18.6	0.45	61.4
	May-06	17.6	19.0	17.1	0.41	63.6
Adequate ranges		30-150[w]	0-40[w]	-	0.7-2.5[w]	15-40[w]
Sources of variation		Pr > F				
Bark age (B)		0.4397	0.7762	0.0451	<.0001	0.0008
Bark source (S)		0.7068	0.2800	0.1089	0.1369	0.6817
S*B		0.9007	0.2955	0.1108	0.1471	0.2913
Date (D)		0.5445	0.0132	0.4129	0.6252	0.9536
B*D		0.4821	0.8591	0.0125	0.8308	0.5279
S*D		0.0932	0.7575	0.0866	0.5405	0.2019
B*S*D		0.2995	0.0103	0.8190	0.0579	0.0004

Table 2.1. Average chemical properties of Douglas fir bark resulting from two bark ages, two bark sources, and six sampling dates (n = 3) (Continued).

Bark age	Date	DTPA extraction[z] Mn	Cu	Zn
Fresh	Jun-05	10.7	0.36	2.37
	Aug-05	11.2	0.34	2.22
	Oct-05	9.3	0.46	2.34
	Dec-05	9.0	0.41	2.26
	Feb-06	8.1	0.45	2.16
	May-06	12.1	0.47	3.61
Aged	Jun-05	8.5	0.34	2.40
	Aug-05	7.9	0.30	2.65
	Oct-05	13.0	0.34	2.26
	Dec-05	11.6	0.43	3.22
	Feb-06	8.4	0.47	2.81
	May-06	9.1	0.45	3.06
Adequate ranges		5-30[w]	0-0.35[x]	5-30[w]
Sources of variation		Pr > F		
Bark age (B)		0.8618	0.2544	0.3042
Bark source (S)		0.5619	0.4280	0.0857
S*B		0.6846	0.6110	0.2461
Date (D)		0.7375	0.3605	0.6601
B*D		0.4392	0.7313	0.4156
S*D		0.5948	0.3664	0.1231
B*S*D		0.0010	0.1071	0.6775

Table 2.2. Coefficients of variation over one year for the chemical and physical properties of Douglas fir bark from two bark sources and two bark ages (n = 3).

	Screened to 0.95 cm (fine)		Screened to 2.2 cm (coarse)	
Chemical properties[z]	Fresh bark	Aged bark	Fresh bark	Aged bark
pH	12.0	12.9	9.3	9.1
EC	32.7	69.6	35.3	28.1
P	50.0	57.8	45.3	45.3
K	25.2	57.0	30.6	26.6
Ca	50.9	78.9	44.6	32.2
Mg	49.1	87.1	49.1	36.7
SO_4	30.8	74.6	22.0	22.2
Na	31.8	79.6	21.8	31.7
B	27.9	33.4	15.8	23.3
Fe	39.1	25.4	31.1	40.1
Mn	41.1	35.2	15.8	23.4
Cu	23.5	32.5	23.6	31.4
Zn	66.8	32.9	16.6	29.0
Al	28.4	56.9	28.9	44.6
Physical properties[y]				
Air space (AS)	8.5	14.0	11.6	11.9
Container cap. (CC)	8.7	13.1	20.3	13.8
Solids	12.6	12.4	15.6	14.1
Bulk density (D_b)	7.0	9.3	14.7	7.8

[z]Analyzed with a Saturated Media Extract (Warncke, 1998). [y]Determined with a North Carolina State Univ. porometer™ (Fonteno and Bilderback, 1993).

Table 2.3. Douglas fir bark average air space (AS), container capacity (CC), solids, and bulk density (D_b)[z] resulting from two bark sources, two bark ages, and five sampling dates (n = 3).

Bark source[y]	Bark age	Date	AS	CC	Solids	D_b
				(%)		($g \cdot cm^{-3}$)
Source A (0.95 cm screen)	Fresh	Jun-05	42	42	16	0.16
		Oct-05	40	38	22	0.18
		Dec-05	40	42	18	0.18
		Feb-05	34	48	18	0.17
		May-06	39	40	20	0.17
	Aged	Jun-05	38	45	17	0.17
		Oct-05	42	40	18	0.17
		Dec-05	32	52	16	0.16
		Feb-05	31	55	14	0.16
		May-06	36	47	18	0.20
Source B (2.2 cm screen)	Fresh	Jun-05	51	28	21	0.21
		Oct-05	48	32	20	0.17
		Dec-05	54	29	16	0.14
		Feb-05	42	43	15	0.14
		May-06	51	30	20	0.16
	Aged	Jun-05	50	32	18	0.18
		Oct-05	41	42	18	0.18
		Dec-05	41	45	13	0.17
		Feb-05	39	44	17	0.17
		May-06	45	38	17	0.17
Recommended values[y]			10-30	45-65	15-50	0.19-0.70
Sources of variation				Pr > F		Pr > F
Bark source (S)				0.0001		0.7133
Bark age (B)				0.0001		0.0902
S*B				0.7316		0.5870
Date (D)				0.0001		0.5650
S*D				0.0135		0.4609
B*D				0.0111		0.8173
S*B*D				0.0042		0.0088

[z]Determined with a North Carolina State University porometer™ (Fonteno and Bilderback, 1993). [y]For pine bark substrates (Yeager et al., 2000)

Table 2.4. Particle size distribution of fresh (F) and aged (A) Douglas fir bark collected on four different dates (n = 3).

	Source A (initially screened to 0.95 cm)								Source B (initially screened to 2.2 cm)							
	Oct-05		Dec-05		Feb-06		May-06		Oct-05		Dec-05		Feb-06		May-06	
Sieve size (mm)	F	A	F	A	F	A	F	A	F	A	F	A	F	A	F	A
	%															
19.00	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12.50	0	1	0	0	0	0	0	1	2	5	1	1	1	0	0	0
6.30	7	2	6	1	5	5	7	4	22	30	24	34	24	18	29	29
4.00	19	16	14	15	15	15	16	13	17	17	19	23	20	18	22	21
2.80	16	17	12	18	15	17	14	14	11	10	12	12	12	15	12	13
2.00	12	12	10	13	12	13	11	11	9	7	9	7	9	12	8	8
1.40	9	9	8	9	10	11	9	9	6	5	6	4	7	9	5	6
1.00	7	7	7	7	8	9	7	8	5	5	5	3	5	6	4	5
0.71	7	7	7	8	7	9	6	7	5	4	5	3	4	5	3	4
0.50	6	8	9	9	8	8	7	8	5	4	5	3	5	5	4	4
0.35	5	7	8	8	6	5	6	6	5	3	4	3	4	4	3	3
0.25	4	5	7	5	6	3	6	6	4	3	3	2	4	3	3	2
0.18	3	4	4	3	3	2	4	5	3	3	3	2	3	2	3	2
0.11	3	3	4	2	2	1	3	5	3	2	2	1	2	1	2	2
Pan	2	2	2	2	2	2	2	5	2	1	2	1	1	2	2	2

Source of variation	Pr > F
Bark source (S)	0.0001
Bark age (A)	0.0034
S*A	0.0464
Date (D)	0.0001
S*D	0.0001
A*D	0.0005
A*S*D	0.0146

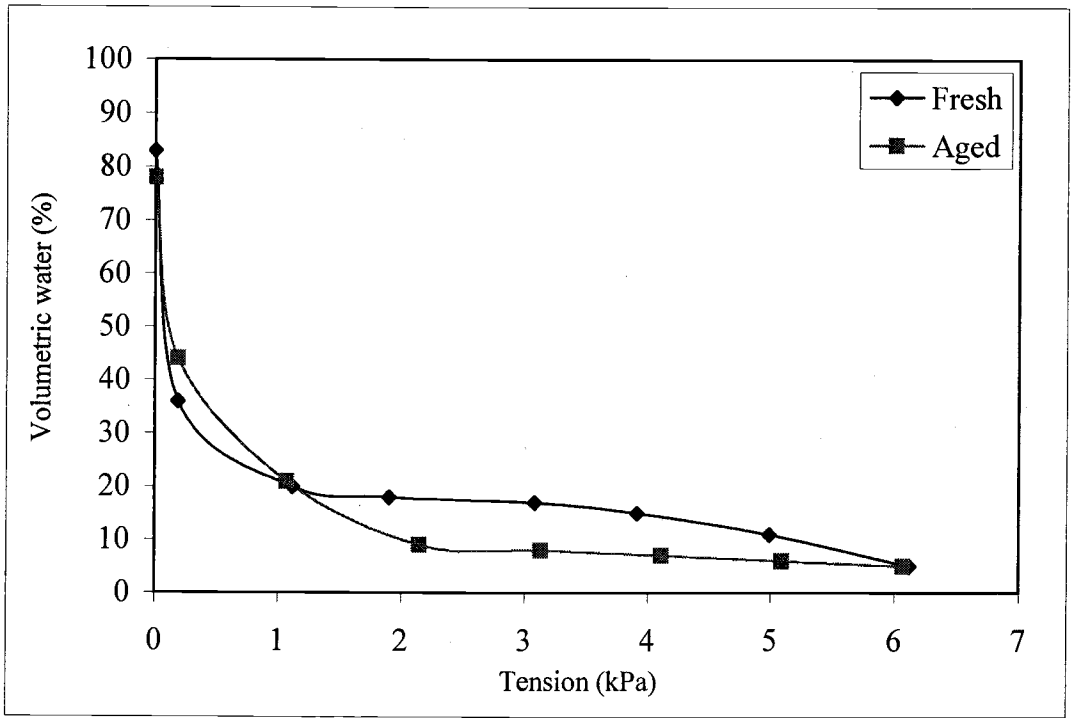

Figure 2.1. Moisture release curves for coarse (2.2 cm screen) fresh and aged Douglas fir bark collected on May 2006. Curves obtained with a North Carolina State University (NCSU) Porometer™ (Fonteno and Bilderback, 1993) and a Buchner filter funnel (modified from Fonteno et al., 1981).

MICRONUTRIENT AVAILABILITY IN FRESH AND AGED DOUGLAS FIR BARK

Abstract

Annual vinca [*Catharanthus roseus* (L.) G. Don 'Peppermint Cooler'] plugs were transplanted to containers filled with Douglas fir [*Pseudotsuga menziesii* (Mirbel) Franco] bark (DFB) on May and June 2005 (Expts. 1 and 2, respectively). Treatments were arranged in a 2 × 3 factorial with two DFB ages (fresh and aged) and three micronutrient sources (DFB alone, 10% by volume yard debris compost, or 0.9 $kg \cdot m^{-3}$ Micromax fertilizer). Plants were measured for shoot dry weight and foliar color. Substrate and foliar samples of each plant were analyzed for 13 essential macronutrients and micronutrients, plus substrate pH and electrical conductivity. Douglas fir bark alone appears to provide sufficient micronutrients for annual vinca grown at pH 4.7-5.7 over a two month period. In Expt. 1 there were no differences in shoot dry weight and foliar color regardless of DFB age or micronutrient source. At the end of Expt. 2, plants in aged DFB were larger than those in fresh DFB, but differences were primarily due to nitrogen availability. None of the treatments developed color symptoms that could be associated with micronutrient deficiency. Micronutrient availability in DFB should be considered in container fertilizer management plans.

Introduction

Container crops in the Pacific Northwest (PNW) are grown primarily in Douglas fir [*Pseudotsuga menziesii* (Mirbel) Franco] bark (DFB). Similar to pine (*Pinus taeda L.*) bark in the southeast U.S., DFB comprises the highest portion of most nursery substrates (60 to 80% of the substrate mix, personal observation) and is often incorporated to some extent with peat moss, sand, compost, pumice, and other materials including fertilizers.

Fresh and aged DFB are used in Oregon (OR) container nurseries. Fresh DFB refers to material sold soon after bark is removed from the tree, ground to smaller particle size, and screened; aged DFB refers to material which goes through the same process but then sits in undisturbed piles (7 to 12 m tall) for an average of 7 months before use. Based on personal conversations with companies that handle DFB, container nurseries are equally divided in their preference for fresh and aged DFB.

Little is known about the chemical and physical properties of DFB with respect to its use as a container substrate, and little is known about the effect of DFB age on its chemical properties. Most information in the literature refers to the chemical properties of soluble components that might be extracted for pulpwood or other industrial chemical purposes (Harkin and Rowe, 1971). Bollen (1969) described the chemical and physical properties of DFB with respect to how surplus bark supplies could be disposed of in an agricultural setting, but provides little information relevant to its use as a container substrate.

Bollen (1969) defined Douglas fir, ponderosa pine (*Pinus ponderosa* P. & C. Lawson), redwood [*Sequoia sempervirens* (Lamb ex D. Don) Endl], and red alder (*Alnus rubra* Bong) bark as materials with low initial fertility. However, research has shown that pine bark media contains sufficient micronutrients to produce woody plants. Niemiera (1992) extracted slightly lower levels of cooper (Cu), iron (Fe), manganese (Mn), and zinc (Zn) from pine bark alone compared to pine bark amended with Micromax (The Scotts Co., Marysville, OH) or Ironite (Ironite Products Co., Scottsdale, AZ); Niemiera speculated that such small differences would not be physiologically significant in terms of plant growth. Svenson and Witte (1992) showed that pine bark amended with 25-50% composted hardwood bark provided sufficient boron (B), Fe, Mn, and Zn for geranium (*Pelargonium* ×*hortorum* L.) growth.

Research on micronutrient additions to container media and its effect on plant growth have found contrasting results. Rose and Wang (1999) reported no improvement in rhododendron (*Rhododendron* L. ×'Girards Scarlet') growth when

adding compost or micronutrient fertilizer to a 3.0 pine bark : 1.0 hardwood bark : 1.0 peat : 0.2 sand (by volume) medium compared to a non-amended control. In contrast, vinca [*Catharanthus roseus* (L.) G. Don] shoot length and dry weight were greatest in a peat-based media with sulfated micronutrients (pH not adjusted) or chelated micronutrients (pH adjusted to 5.5) compared to a non-amended control (Thomas and Latimer, 1995). Wright et al. (1999) analyzed the effect of micronutrient and lime addition on substrate pH and growth of nine container tree species in pine bark; micronutrient additions resulted in the best growth responses for all species, while lime depressed growth. Micronutrients increased growth when pH was higher than 5.2 and lime had been applied.

Douglas fir bark in the PNW is used similarly to pine bark in the southeast U.S. Both bark types are irrigated frequently, fertilized with similar products and rates, and mixed with similar components (sand, peat moss, etc.). Despite similarities in these two resources, several chemical properties of DFB have been found to differ from other conifer barks. For example, bark pH, nitrogen (N), phosphorous (P), potassium (K), calcium (Ca), magnesium (Mg) and C/N ratio differ between Doulgas fir, ponderosa pine, and redwood (Bollen, 1969). Research conducted on pine bark with respect to nursery container nutrition cannot be assumed applicable to DFB.

To accurately assess micronutrient status of DFB substrates, a reliable protocol must be used that provides values that are correlated to or predictive of plant micronutrient status. Most laboratories use water extraction for micronutrient analysis, although Warncke (1986) advocates the use of DTPA extraction primarily because it yields larger values.

The objectives of this study were: (i) to evaluate micronutrient availability in fresh and aged DFB; (ii) to determine the effect of micronutrient amendments on substrate and foliar micronutrient levels; and (iii) to compare water and DTPA extractions for measuring micronutrient availability in DFB substrates. Our initial hypothesis was that DFB alone provides sufficient micronutrients for annual vinca.

Materials and Methods

Expt. 1. On 5 May 2005, uniform plugs of annual vinca [*Catharanthus roseus* (L.) G. Don 'Peppermint Cooler'] approximately 10 cm tall were transplanted to #1 containers (2.8 L) filled with DFB. Treatments were arranged in a 2 × 3 factorial with two DFB ages (fresh and aged) and three micronutrient sources. All bark was ground with a hammermill and passed through a 0.95 cm screen. Micronutrient sources included incorporating 10% by volume yard debris compost (2.1N-0.2P-0.5K-1.4Ca-0.3Mg-0.001B-0.004Cu-0.9Fe-0.03Mn-0.01Zn) (Rexius Co., Eugene, OR), 0.9 $kg \cdot m^{-3}$ Micromax micronutrient fertilizer (6Ca-3Mg-12S-0.10B-1Cu-17Fe-2.5Mn-0.05Mo-1Zn) (The Scotts Co.), or DFB alone (non-amended). Yard debris was composted for 12 weeks and passed through a 1.6 cm screen. All treatments were amended with 1.8 $kg \cdot m^{-3}$ dolomitic limestone (22.7Ca-11.8Mg, 113 calcium carbonate equivalence) (Chemical Lime Lhoist Group, Salinas, CA), and 8.9 $kg \cdot m^{-3}$ Osmocote (14N-4.2P-11.6K) (The Scotts Co.). The experiment was conducted in a greenhouse at Oregon State University, Corvallis, OR. Heat and vent greenhouse temperatures were set at 16 and 21 °C, respectively. At six weeks after potting (WAP) all plants were measured for foliar color using a SPAD 502 Chlorophyll Meter (Minolta Camera Co., Ramsey, NJ) and shoot dry weight (SDW) by drying in an oven at 60 °C for 72 h. Recently mature leaves (Mills and Jones, 1996) and the entire growing media were sampled from each plant. Foliar samples were analyzed for N, P, K, Ca, Mg, S, B, Fe, Mn, Cu, and Zn. Foliar N was determined by combustion analysis using a 1500 N analyzer (Carlo Erba, Milan, Italy). The remaining nutrients were determined by inductively coupled plasma-emission spectrometry (ICP) (Thermo Jarrel Ash, Offenbach, Germany). Media samples were analyzed for the same nutrients plus pH and electrical conductivity (EC) using a saturated media extract (SME) method with water and diethylenetriaminepentaacetic acid (DTPA) (Warncke, 1998; Gavlak et al., 2003). Following Gavlak et al. (2003) recommendations, DFB was soaked in

the extractant (either water or DTPA) for 24 h. Each treatment was replicated seven times in a completely randomized design.

Expt. 2. On 28 July 2005 Expt. 1 was repeated with 16 replications. Eight vinca plants were sampled 5 and 8 WAP each, otherwise this experiment was conducted similarly to the previous one.

Data from both experiments were subjected to analysis of variance (SAS Institute, 1999), and repeated measures analysis in Expt. 2 where data were collected twice over time. Measured values for each nutrient parameter are compared to recommended values for substrates (Warncke, 1998) and foliage (Wilkins, 1988).

Results

Expt. 1. At the conclusion of the study, all plants were healthy and vigorous. There were no differences in SDW and foliar color regardless of DFB age and micronutrient source (Table 3.1).

Bark age and amendments affected substrate pH, although the range of substrate pH was narrow (4.7 to 5.1, Table 3.1). Substrate pH was lower in aged DFB compared to fresh DFB. Within each DFB age, containers amended with compost had higher substrate pH than non-amended or Micromax-amended substrates. DTPA-extractable micronutrients in the substrate were not correlated with substrate pH. The highest correlation coefficient was for B ($r = -0.380$), but even this correlation was weak. Micronutrients in soils and substrates are often correlated to substrate pH (Tisdale et al., 1985). The narrow pH range in this study is most likely responsible for low correlation coefficients.

DTPA B was higher in aged DFB than fresh DFB, but all were below that recommended for potting media. Within each DFB age, Micromax resulted in higher substrate B levels than compost, and compost resulted in higher B levels than DFB alone. Foliar B was correlated to substrate B extracted with DTPA and

water (Table 3.2). Foliar B concentration was below recommended levels in non-amended fresh DFB.

Substrate DTPA Fe was higher in non-amended aged than fresh DFB. All treatments had adequate substrate Fe. However, all foliar Fe remained below the recommended range. Foliar Fe was not correlated to substrate Fe extracted with either DTPA or water (Table 3.2). Bark age interacted with micronutrient source to affect foliar Fe. Micronutrient source did not influence foliar Fe when added to aged DFB, although compost increased foliar Fe in fresh DFB.

DTPA substrate Mn was higher in fresh than in aged DFB, with the exception of non-amended DFB. Substrate Mn was within recommended range for all treatments. Foliar Mn was not correlated to DTPA Mn; however, it was highly correlated to water Mn (Table 3.2). Water substrate Mn was higher in fresh than in aged DFB (data not presented) with the same trend observed in vinca foliage. Within DFB age, Micromax had the highest substrate water Mn (data not presented) and non-amended DFB resulted in the lowest extractable levels. Foliar Mn levels were sufficient in both barks. Micromax increased foliar Mn over non-amended vinca. Micromax in fresh DFB increased foliar Mn to twice the recommended levels.

DTPA substrate Cu was higher in fresh than in aged DFB when amended with Micromax, and all treatments were within or above the recommended range. Foliar Cu was correlated to DTPA Cu but not correlated to water Cu (Table 3.2). High DTPA Cu in Micromax treatments resulted in adequate foliar Cu, while adequate DTPA Cu in the other treatments resulted in less than recommended foliar Cu.

Substrate DTPA Zn was higher in fresh than in aged DFB. Substrate Zn was below the recommended range except for Micromax treatments. Foliar Zn was correlated with DTPA Zn and water Zn (Table 3.2). Low DTPA Zn in non-amended and compost treatments resulted in sufficient foliar Zn across DFB age. Acceptable DTPA Zn from Micromax caused high foliar Zn in both DFB ages.

Expt. 2. At 5 WAP, micronutrient source did not influence plants size in fresh DFB, however, compost increased plant size in aged DFB (Table 3.3). At 8 WAP, the aged DFB plants were larger than fresh DFB due to differences in N availability (data not shown). Research concurrent with this project has documented greater N immobilization in fresh than aged DFB (Buamscha et al., 2005). In fresh DFB, non-amended vinca were smaller than those amended with compost and Micromax. Aged DFB treatments showed no differences in size between non-amended and amended plants.

Neither DFB age nor micronutrient source affected SPAD levels at 5 and 8 WAP. Although, visual observations at 8 WAP indicated a darker green color in aged vs. fresh DFB (data not shown). Altland et al. (2002) previously reported the inability of SPAD meters to accurately predict N status of annual bedding plants. SPAD meter measurements should be interpreted with caution. No plants developed growth or foliar color symptoms that could be related to micronutrients deficiency or toxicity.

Bark age and micronutrient source interacted to affect substrate pH at 5 and 8 WAP. Similar to Expt. 1, pH differences among treatments were minor and correlations between substrate pH and extractable micronutrients (water or DTPA) were weak ($r \leq 0.377$).

Repeated measures analysis indicates that substrate and foliar B, Fe, Mn, Cu, and Zn decreased between 5 and 8 WAP ($p < 0.0001$). The observed reduction in substrate nutrients may be a consequence of plant uptake and leaching.

At 5 and 8 WAP, compost and Micromax increased substrate B (water and DTPA) in both DFB ages compared to non-amended treatments (Table 3.3). Similar to Expt. 1, foliar B was correlated with DTPA and water B (Table 3.2), explaining similarity of treatment effects on substrate and foliar B.

Bark age effect on DTPA-extractable Fe at both sampling dates was similar to Expt. 1. Vinca in aged DFB had higher foliar Fe levels than in fresh DFB, which mimicked the substrate treatment response. Foliar Fe was not correlated to water Fe and weakly correlated to DTPA Fe (Table 3.2).

Substrate DTPA Mn was similar between fresh and aged DFB at 5 WAP. At 8 WAP, fresh DFB was higher in Mn than aged DFB. Similar to Expt. 1, substrate Mn was within recommended range across treatments and sampling dates. Foliar Mn was again more correlated to water Mn than to DTPA Mn (Table 3.2). Only Micromax increased substrate water Mn and foliar Mn. Foliar Mn levels were within or above the recommended range across all treatments.

Foliar Cu was more correlated to DTPA than water Cu (Table 3.2). As in Expt. 1, Micromax resulted in excessive DTPA Cu but foliar Cu was within the recommended range across DFB ages. Fresh and aged non-amended barks resulted in DTPA Cu levels within or just above recommended ranges but deficient foliar Cu.

Substrate DTPA Zn was higher in aged than in fresh DFB at 5 WAP, while no differences existed at 8 WAP. Independent of DFB age and sampling date, DTPA Zn were deficient, near the lower limit, and adequate for the non-amended, compost, and Micromax treatments, respectively. Foliar Zn was correlated to DTPA and water Zn (Table 3.2). Low DTPA Zn in the non-amended treatments resulted in higher than recommended foliar Zn. Micromax increased foliar Zn far higher than recommended even though substrate Zn was within recommended range.

Discussion

Douglas fir bark without amendment provides sufficient micronutrients for annual vinca over a two month period. The findings are similar to research of Niemiera (1992), Svenson and Witte (1992), and Rose and Wang (1999) in pine bark substrates. Substrate and foliage micronutrients declined from 5 to 8 WAP, and might decline even more over the course of a long production period (several months) for woody crops. Others have found that substrate micronutrient supply over the course of a growing season is relatively constant and unaffected by irrigation (Niemiera, 1992; Broschat and Donselman, 1985). Substrate pH was low

in this experiment. Because micronutrients are responsive to substrate pH, elevated pH might reduce micronutrients levels and impact plant growth more than what occurred in this study. Increase in substrate pH due to water alkalinity might gradually reduce micronutrient availability in woody crops with longer production cycles. Until more research addresses longevity of micronutrient availability in DFB and responsiveness to substrate pH, it can only be concluded that DFB is a reliable micronutrient source for crops with short production cycles being grown at pH 4.7 to 5.7.

Non-amended plants in fresh bark were smaller than amended ones at the end of Expt. 2. Micronutrient nutrition cannot explain these growth differences for two reasons: (i) compost and non-amended plants had similar foliar nutrients levels except for B, and (ii) Micromax amended plants had higher foliar Ca, Mg, S (data not presented), Mn, Cu, and Zn than non-amended, however the same trend occurred in aged DFB and did not affect plant growth. Foliar N was reduced in plants growing in fresh compared to aged DFB (3.2 vs. 4.7 %, respectively, data not presented). Micronutrient source did not affect N and thus does not explain differences observed between the two DFB ages.

No broad generalization can be made as to which DFB age (fresh or aged) provides greater micronutrient nutrition. After 8 weeks, plants in both barks had the highest foliar levels of Mn, Cu, and Zn when amended with Micromax. Higher foliar micronutrient concentrations did not improve crop dry weight or color. Within both DFB ages, plants amended with compost and Micromax were similar in size and color. Similarly, Rose and Wang (1999) found no growth differences between treatments amended with compost and micronutrient fertilizers.

Guidelines for soilless substrates developed by Warnke (1998) do not always match foliar guidelines developed for individual crops. Warncke's guidelines indicate that non-amended fresh and aged DFB do not have adequate B and Zn by 8 WAP. However, foliar guidelines for annual vinca by Wilkins (1988) indicate that fresh and aged DFB supplies sufficient foliar Zn. Specific foliar guidelines for annual vinca are probably more reliable than general substrate

guidelines; however, Wilkins' foliar micronutrient guidelines for annual vinca are not always supported by our observations. For example, in Expt.1 Micromax increased foliar Mn in fresh DFB and foliar Zn in both barks to levels considerably higher than recommended, although plants did not show symptoms of Mn or Zn toxicity. A possible explanation for this discrepancy is that Wilkins' foliar guidelines were not defined by vinca growth stage.

Warncke (1998) recommends DTPA to enhance the extraction of Zn, Mn, and Fe. In this study we saw increased extraction of the mentioned micronutrients plus Cu when using DTPA compared to water. Increased extraction of a particular micronutrient does not necessarily correlate with solution concentration available for plant absorption. Handreck and Black (2002) also recommend DTPA because of increased Fe in substrates with increasing Fe amendment rates. However, increased Fe would be expected in substrates with increased amendment rates, and again this does not imply increased nutrient availability for plants. In agronomic crops, nutrient availability is measured with a variety of extractants with the most useful being that which correlates most closely to yield. Ornamental crops, and annual vinca in particular, do not produce a harvestable yield in terms of fruit or fiber. The best gauge of how well an extractant works (water or DTPA) with ornamental crops is how well it correlates to foliar nutrient levels. In this study, foliar Mn was more highly correlated with water Mn, and foliar Cu with DTPA Cu, while foliar B and Zn were correlated to both extractants. Rose and Wang (1999) reported a lack of correlation between foliar and substrate DTPA Fe, Cu, Zn, and B. More research is required to closely compare extractants for nutrient availability in DFB and other substrates.

In summary, these data demonstrate that DFB is an important source of micronutrients for container-grown crops. Boron and Cu may appear to be deficient depending on which set of guidelines or experimental results are considered. Longevity and pH-responsiveness of micronutrient availability is still not known. These results cannot rule out recommendations for use of

micronutrient amendments, however, they do suggest micronutrient availability in DFB be considered in container fertilizer management plans.

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Table 3.1. Annual vinca shoot dry weight (SDW), SPAD, and substrate and foliar micronutrients resulting from two bark ages and three micronutrient sources (Expt. 1).

Bark age	Micronutrient source	Plant response		Substrate nutrient availability					
		SDW (g)	SPAD	pH	B	Fe	Mn	Cu	Zn
					($mg \cdot L^{-1}$)				
Fresh	none	5.1 a[z]	50.0 a	4.9 b	0.13 e	21.05 c	16.24 ab	0.31 c	2.61 d
Fresh	Compost[y]	4.8 a	53.1 a	5.1 a	0.23 cd	45.85 b	16.46 ab	0.31 c	3.68 c
Fresh	Micromax[x]	5.1 a	50.7 a	4.9 b	0.32 b	56.82 a	19.06 a	5.31 a	8.48 a
Aged	none	4.7 a	50.3 a	4.8 c	0.22 d	44.07 b	15.95 b	0.32 c	3.12 cd
Aged	Compost	4.8 a	51.4 a	4.9 b	0.25 c	46.15 b	7.71 c	0.18 c	2.78 d
Aged	Micromax	4.6 a	50.1 a	4.7 c	0.36 a	46.52 b	6.40 c	2.60 b	5.47 b
Recommended ranges					0.7-2.5[w]	15-40[w]	5-30[w]	0-0.35[v]	5-30[w]
Main effects									
	Bark age	NS	NS	***	***	*	***	***	***
	Micronutrient	NS	NS	***	***	***	***	***	***
Interaction		NS	NS	NS	**	***	***	***	***

[z] Means with different letters within a column are significantly different, separated by LSD test ($\alpha \leq 0.05$). [y] 10% by volume yard debris compost. [x] 0.9 $kg \cdot m^{-3}$ Micromax micronutrient fertilizer. [w] Warncke, 1998. [v] Guideliness provided by Brookside Laboratories (New Knoxville, OH). NS represents nonsignificant response. *, **, and *** represent significance when $P \leq 0.05$, 0.01, and 0.001. Substrate pH and micronutrients analyzed with a Saturated Media Extract using water and DTPA, respectively.

Table 3.1. Annual vinca shoot dry weight (SDW), SPAD, and substrate and foliar micronutrients resulting from two bark ages and three micronutrient sources (Expt. 1) (Continued)

Bark age	Micronutrient source	Foliar nutrient levels B	Fe	Mn	Cu	Zn
		($mg \cdot kg^{-1}$)				
Fresh	none	22.9 e	78.1 cd	226.3 cd	3.8 b	46.8 c
Fresh	Compost[y]	27.2 d	90.9 a	255.4 c	4.8 b	48.7 c
Fresh	Micromax[x]	39.3 ab	73.8 d	612.2 a	9.6 a	87.9 a
Aged	none	33.1 c	79.1 bcd	188.4 de	2.0 c	44.3 c
Aged	Compost	35.1 bc	83.1 abc	153.0 e	3.6 b	43.8 c
Aged	Micromax	41.4 ab	87.2 ab	314.9 b	8.7 a	77.9 b
Recommended ranges		25-40[u]	95-150[u]	165-300[u]	5-10[u]	40-45[u]
Main effects						
Bark age		***	NS	***	**	*
Micronutrient		***	*	***	***	***
Interaction		*	*	***	NS	NS

[z] Means with different letters within a column are significantly different, separated by LSD test ($\alpha \leq 0.05$). [y] 10% by volume yard debris compost. [x] 0.9 $kg \cdot m^{-3}$ Micromax micronutrient fertilizer. [u] Wilkins, 1988. NS represents nonsignificant response. *, **, and *** represent significance when $P \leq 0.05$, 0.01, and 0.001. Foliar nutrients expressed on a dry weight basis.

Table 3.2. Correlation (r) between each foliar and water or DTPA[z]-extractable substrate micronutrients in annual vinca.

	Expt. 1		Expt. 2	
Nutrient	Water	DTPA	Water	DTPA
B	0.711	0.738	0.674	0.677
Fe	-0.309	-0.097	-0.043	0.602
Mn	0.927	0.297	0.678	0.388
Cu	0.301	0.789	0.276	0.677
Zn	0.923	0.760	0.688	0.793

[z] diethylenetriaminepentaacetic acid

Table 3.3. Annual vinca shoot dry weight (SDW), SPAD, and substrate and foliar micronutrients resulting from two bark ages and three micronutrient sources (Expt. 2).

Bark age	Micronutrient source	Plant response		Substrate nutrient availability		
		SDW (g)	SPAD	pH	B	Fe
					($mg \cdot L^{-1}$)	
		Data collected 5 weeks after planting (WAP)				
Fresh	none	4.6 bc[z]	59.4 a	5.6 a	0.14 d	29.78 d
Fresh	Compost[y]	4.7 bc	57.8 a	5.7 a	0.21 c	57.02 c
Fresh	Micromax[x]	4.9 ab	59.4 a	5.3 b	0.26 b	86.60 b
Aged	none	4.2 c	58.9 a	5.2 c	0.21 c	62.26 c
Aged	Compost	5.5 a	59.4 a	5.3 bc	0.31 a	91.06 b
Aged	Micromax	4.4 bc	61.4 a	5.3 bc	0.33 a	113.48 a
		Data collected 8 WAP				
Fresh	none	7.9 c	53.3 a	5.3 ab	0.13 d	27.07 d
Fresh	Compost	11.1 b	52.1 a	5.4 a	0.18 c	43.84 c
Fresh	Micromax	11.1 b	51.2 a	5.2 bc	0.19 bc	54.92 b
Aged	none	12.7 a	50.0 a	5.1 d	0.20 b	56.23 b
Aged	Compost	13.5 a	55.8 a	5.2 bc	0.27 a	70.24 a
Aged	Micromax	12.0 ab	51.0 a	5.2 c	0.25 a	69.81 a
Recommended ranges					0.7-2.5[w]	15-40[w]
Main effects						
Bark age (B)		***	NS	***	***	***
Micronutrient source (M)		***	NS	***	***	***
B*M		**	NS	***	NS	**
Date (D)		***	***	***	***	***
B*D		***	NS	**	NS	*
M*D		NS	NS	NS	***	***
B*M*D		***	NS	NS	NS	NS

[z]Means with different letters within a column and collection date are signif. different, separated by LSD test ($\alpha \leq 0.05$). [y] 10% by volume yard debris compost. [x] 0.9 $kg \cdot m^{-3}$ Micromax micronutrient fertilizer. [w] Warncke, 1998. [u]Wilkins, 1988. NS represents nonsignificant response. *, **, and *** represent significance when $P \leq 0.05$, 0.01, and 0.001. Substrate pH and micronutrients analyzed with a Saturated Media Extract using water and DTPA, respectively. Foliar nutrients expressed on a dry weight basis.

Table 3.3. Annual vinca shoot dry weight (SDW), SPAD, and substrate and foliar micronutrients resulting from two bark ages and three micronutrient sources (Expt. 2). (Continued)

Bark age	Micronutrient source	Substrate nutrient availability Mn	Cu	Zn
		($mg \cdot L^{-1}$)		
		Data collected 5 WAP		
Fresh	none	18.88 c	0.48 cd	3.51 d
Fresh	Compost[y]	27.23 ab	0.74 c	5.42 c
Fresh	Micromax[x]	28.05 ab	4.90 a	13.39 b
Aged	none	18.31 c	0.37 d	3.95 d
Aged	Compost	25.30 b	0.71 c	5.95 c
Aged	Micromax	28.50 a	4.20 b	14.37 a
		Data collected 8 WAP		
Fresh	none	16.15 c	0.37 d	2.79 c
Fresh	Compost	22.47 a	0.61 c	4.46 b
Fresh	Micromax	18.96 b	3.44 a	9.68 a
Aged	none	12.25 d	0.33 d	3.27 c
Aged	Compost	16.74 bc	0.49 cd	4.86 b
Aged	Micromax	13.45 d	2.97 b	9.63 a
Recommended ranges		5-30[w]	0-0.35[v]	5-30[w]
Main effects				
Bark age (B)		***	***	**
Micron. source (M)		***	***	***
B*M		NS	***	NS
Date (D)		***	***	***
B*D		***	NS	NS
M*D		***	***	***
B*M*D		NS	NS	NS

Table 3.3. Annual vinca shoot dry weight (SDW), SPAD, and substrate and foliar micronutrients resulting from two bark ages and three micronutrient sources (Expt. 2). (Continued)

Bark age	Micronutrient source	Foliar nutrient levels B	Fe	Mn	Cu	Zn
		($mg \cdot kg^{-1}$)				
		Data collected 5 WAP				
Fresh	none	20.7 c	85.4 d	357.3 bc	4.7 c	58.5 c
Fresh	Compost[y]	26.7 b	90.3 cd	306.3 c	5.9 b	57.4 c
Fresh	Micromax[x]	21.6 c	94.3 c	561.7 a	8.7 a	102.6 a
Aged	none	33.9 a	115.1 a	397.8 b	3.4 d	70.9 b
Aged	Compost	34.0 a	104.2 b	380.0 b	5.1 bc	63.5 bc
Aged	Micromax	36.1 a	109.2 ab	585.3 a	8.7 a	105.6 a
		Data collected 8 WAP				
Fresh	none	15.5 d	62.2 b	228.8 c	2.5 d	47.6 c
Fresh	Compost	19.8 bc	68.8 b	202.3 c	3.1 cd	44.8 c
Fresh	Micromax	17.8 cd	65.2 b	299.7 b	4.0 bc	70.3 b
Aged	none	22.1 b	93.7 a	252.7 bc	3.5 cd	60.3 b
Aged	Compost	34.2 a	91.1 a	304.3 b	5.3 b	65.0 b
Aged	Micromax	32.7 a	94.1 a	496.1 a	8.5 a	105.5 a
Recommended ranges		25-40[u]	95-150[u]	165-300[u]	5-10[u]	40-45[u]
Main effects						
Bark age (B)		***	***	***	***	***
Micronutrient source (M)		***	NS	***	***	***
B*M		*	*	NS	***	NS
Date (D)		***	***	***	***	***
B*D		NS	*	**	***	***
M*D		*	NS	**	*	NS
B*M*D		**	NS	**	NS	*

NITROGEN AVAILABILITY IN FRESH AND AGED DOUGLAS FIR BARK

Abstract

The objective of this study was to determine if there are differences in plant growth due to N competition between the plant and microorganisms within fresh and aged Douglas fir [*Pseudotsuga menziesii* (Mirbel) Franco] bark (DFB); then document nitrogen immobilization and decomposition rates of fresh and aged DFB to validate the cause of growth differences. A series of experiments to measure plant response, N draw-down index and percent cumulative carbon loss (C loss) were conducted on fresh and aged DFB. On 16 June 2005, geranium (*Pelargonium* x*hortorum* Bailey 'Maverick Red') plugs were transplanted to #1 containers filled with fresh or aged DFB. Treatments were arranged in a 2 x 3 factorial with two DFB ages (fresh and aged) and three N fertilizer rates (100, 200, and 300 ppm). On 19 June 2006, a second repetition of the geranium experiment was conducted with the exception that N fertilizer rates were increased to 200, 300, and 400 ppm. Plant growth was affected by DFB age; geranium stem growth was always smaller in the fresh material. Besides N availability, other variables such as container capacity may be playing an important role. Nitrogen draw-down analysis determined that a large fraction of N in solution was immobilized in fresh and aged DFB, but differences were at best marginally significant. Carbon loss occurred at low predictable rates for a well-decomposed material, but there were no differences between fresh and aged DFB. The similarities in C loss between fresh and aged DFB agree with the similar N immobilization measured in the two materials. Differential geranium growth in fresh and aged DFB observed in these studies cannot be explained by similarities in N immobilization or decomposition rate between the two barks. Nitrogen immobilization in fresh and aged DFB may differ between sources. The source used for this study showed no clear differences in N

immobilization between the fresh and aged material. While another source with a finer particle size presented a higher N immobilization in fresh than in aged bark.

Introduction

Physical and chemical properties of Douglas fir [*Pseudotsuga menziesii* (Mirbel) Franco] bark (DFB) as they pertain to use in nursery container substrates have only recently been studied. Properties of DFB collected from two suppliers six times over the course of a year were determined. It was documented that fresh and aged DFB had different chemical properties; aged having lower pH and higher levels of extractable phosphorous (P), calcium (Ca), magnesium (Mg), boron (B), and iron (Fe) compared to fresh. A concurrent study used annual vinca [*Catharanthus roseus* (L.) G. Don 'Peppermint Cooler'] to evaluate micronutrient availability in DFB, and found that fresh and aged DFB provided sufficient micronutrients for vinca without supplementing micronutrient fertilizers. However, vinca growing in aged bark had higher stem biomass and foliar nitrogen (N) than those in fresh bark after 8 weeks; differences were attributed to N availability.

Comparisons of fresh and aged pine (*Pinus taeda* L.) bark on plant growth have been made with several crops. Holly (*Ilex crenata* Thun. 'Rotundifolia') had similar size and quality when grown under a standard fertilization program in either fresh or aged bark and with or without preplant N (Pokorny, 1979). Cobb and Keever (1984) compared fresh and aged pine bark amended with 1 kg $N \cdot m^{-3}$ Osmocote (17N-3P-10K) (The Scotts Co., Marysville, OH) at four levels of supplemental N (0, 100, 200, and 300 ppm). Growth of dwarf japanese euonymus (*Euonymus japonica* Thunb. 'Microphilla') and japanese holly (*Ilex crenata* Thun. 'Compacta') in fresh bark equaled or exceeded that in aged bark at all levels of supplemental N. Harrelson et al. (2004) compared fresh and aged pine bark and three rates of controlled release N fertilizer (11.2, 22.2, or 33.3 g $N \cdot pot^{-1}$); skogholm cotoneaster (*Cotoneaster dammeri* C.K.Schneid 'Skogholm') grown in aged pine bark were larger than cotoneaster grown in fresh pine bark. The authors

attributed the reduction in growth in fresh bark to its lower container capacity and available water compared to aged bark.

Container nurseries in OR use both fresh and aged DFB and there is no distinction in the fertility programs between these two bark types. Most nursery producers base their fertility rates on instructions provided by the fertilizer manufacturer written on the fertilizer bag. These rate guidelines are based solely on container size and plant requirement for 'low', 'medium', or 'high' fertility. Based on research with pine bark, and related research conducted thus far with DFB (Buamscha et al., 2007), there is reason to believe that N availability in fresh and aged DFB differs. Therefore, the objective of this study was to determine if there are differences in plant growth due to N competition between the plant and microorganisms within the substrate, then document nitrogen immobilization and decomposition rates of fresh and aged DFB to validate the cause of growth differences.

Materials and Methods

General information. Fresh and aged DFB samples were collected on June 2005, Feb. 2006, and June 2006 from one bark supplier (Marr Bros. Co., Monmouth, OR). Bark was ground with a hammermill and passed through a 2.2 cm screen. A series of experiments to measure plant response, N draw-down index (NDI), and percent cumulative carbon loss (C loss) were conducted in fresh and aged DFB. The chronological progression of experiments are detailed in Table 4.1. Methods for measuring plant response, NDI, and C loss are described not necessarily in chronological order.

Plant response (Expt.1). On 16 June 2005, uniform plugs of geranium (*Pelargonium xhortorum* Bailey 'Maverick Red') approximately 7 cm tall were transplanted to #1 containers (2.8 L) filled with DFB. Treatments were arranged in a 2 x 3 factorial with two bark ages (fresh and aged) and three N fertilizer rates (100, 200, and 300 ppm) using an NH_4NO_3 solution. Each unique treatment

combination was replicated 12 times. All treatments were amended with 3.6 $kg \cdot m^{-3}$ dolomitic limestone (22.7Ca-11.8Mg, 113 calcium carbonate equivalency) (Chemical Lime Lhoist Group, Salinas, CA) and 0.9 $kg \cdot m^{-3}$ Micromax (The Scotts Co., Marysville, OH). Containers were fertilized with 90 ppm phosphorous (P) and 225 ppm potassium (K) using a potassium phosphate (K_2HPO_4) solution. Plants received 250 mL of NPK fertilizer solution as needed. After three fertilization events, the same volume of tap water was applied to reduce salt build-up. The experiment was conducted in a retractable roof greenhouse (Cravo Equip. Ltd., Brantford, ON, Canada) in Aurora, OR. At 4 and 8 weeks after potting (WAP), six plants were measured for foliar color using a visual scale of 1 through 5 (1 = severe chlorosis or yellow color, 5 = dark green color) and shoot dry weight (SDW) by drying in an oven at 60 °C for 72 h. Recently mature leaves (Mills and Jones, 1996) and the entire growing media were sampled from each plant. Foliar samples were analyzed for N by combustion using a 1500 N analyzer (Carlo Erba, Milan, Italy). Media samples were analyzed for pH, ammonium (NH_4-N) and nitrate (NO_3-N) using a saturated media extract (SME) method with water (Warncke, 1998; Gavlak et al., 2003). Following Gavlak et al. (2003), DFB was saturated in water for 24 h. Extracted solutions were analyzed for NH_4-N and NO_3-N using a Lachat Quick Chem 8000 (Lachat Instruments, Milwaukee, WI).

Plant response (Expt. 2). On 19 June 2006, a second repetition of the geranium experiment was conducted with N fertilizer rates increased to 200, 300, and 400 ppm. Six plants were sampled 5 and 10 WAP each, otherwise this repetition was conducted similarly to the previous one. Data were subjected to analysis of variance and regression analysis (SAS Institute, 1999).

Nitrogen draw-down. Bark samples collected Feb. 2006 and June 2006 for Expt.2, were analyzed for the nitrogen draw-down index (NDI), as the rate of NO_3^- disappearance after adding a 75 ppm N solution as potassium nitrate (KNO_3) and incubating for 1 and 4 days at 22 °C (NDI-1 and NDI-4, respectively) (Handreck, 1992a) following Standards Australia (2003). This index is a dimensionless ratio between the NO_3^- concentration after incubating 1 and 4 days, respectively, and

NO_3^- concentration immediately after adding the nutrient solution (NDI-1 = $[NO_3^-]_{day\ 1}$ / $[NO_3^-]_{day\ 0}$; NDI-4 = $[NO_3^-]_{day\ 4}/[NO_3^-]_{day\ 0}$). Data were subjected to repeated measures analysis of variance, and means separation using Fisher's protected LSD ($\alpha = 0.05$) (SAS institute, 1999).

Carbon loss. Decomposition rate as percent cumulative carbon loss (C loss) was determined via incubation (Anderson, 1982) in DFB collected on Feb. and June 2006. The procedure included fresh and aged DFB incubated at four N rates (0, 75, 200, and 400 ppm) using ammonium nitrate (NH_4N0_3). Potassium nitrate (KNO_3) at 75 ppm was also included so C loss results could be compared back to NDI results and to determine if microbial populations had a N form preference. The incubation experiment is described as follows. Douglas fir bark samples were allowed to warm to room temperature for 1 day. Bark samples were thoroughly mixed and split into 500 g sub-samples. Each sub-sample was soaked for 1 hour in a N treatment. Ten grams of drained bark were placed in 0.95 L Mason jars. Treatments were replicated twice. An open vial with 20 mL of 1M sodium hydroxide (NaOH) was placed in each jar and served as a carbon dioxide (CO_2) trap ($CO_{2(gas)} + NaOH \rightarrow HCO_3^-$). Four blank jars (no bark) with CO_2 traps were included. Sealed jars were incubated at 22 °C for 7 and 14 days. Vials with fresh NaOH solution were replaced at each incubation interval. Carbon dioxide evolution at 7 and 14 days was determined by titration of the un-reacted NaOH. First, bicarbonate (HCO_3^-) present in the NaOH is removed from solution as barium carbonate ($BaCO_3$) precipitate using 1M barium chloride ($BaCl_2$). The remaining NaOH is titrated with 0.1 M hydrochloric acid (HCL) using phenolphthalein as the indicator. Data were subjected to repeated measures analysis of variance (SAS institute, 1999).

Results and Discussion

Plant response (Expt.1). Measured plant and substrate responses at 4 and 8 WAP were similar, thus only data collected 8 WAP are presented and discussed

(Table 4.2). Substrate pH was slightly lower in aged compared to fresh DFB. Previous research with unamended DFB documented a similar difference in pH (Buamscha et al., 2007). Substrate pH decreased linearly and quadratically with increasing N rate. Substrate NH_4-N and NO_3-N were affected by an interaction between bark age and N rate. Ammonium and NO_3-N levels were higher in aged than fresh DFB. Ammonium and NO_3-N levels increased linearly and quadratically with increasing N rate, although the rate of increase was greater for aged bark. Across all treatments, substrate NO_3-N levels were higher than NH_4-N. This could be a result of preferential plant absorption of ammonium or nitrification. Either process releases hydrogen ions (Mengel and Kirkby, 2001), explaining the reduction in DFB pH with increasing N rate. Cobb and Keever (1984) also reported a reduction in pH with increased supplemental N. However, contrary to results in our study, Cobb and Keever found higher pH in aged pine bark compared to fresh. Harrelson et al. (2004) reported no effect of pine bark age on substrate pH.

Plants growing in fresh DFB had lower foliar N levels than in aged DFB at N rates of 100 and 200 ppm. At the highest N rate (300 ppm), similar foliar N levels were measured in plants growing in either bark. Increasing N rate resulted in a linear and quadratic increase in foliar N. Plants in fresh bark grew less (SDW) than those in aged bark at any given N rate. Increasing N rate resulted in a linear increase in SDW. Pokorny (1979) did not find differences in fresh weight of holly grown in fresh or aged pine bark whether or not 1% of preplant N was added to compensate for potential N competition. This seems to imply no quantifiable N immobilization in pine bark. However, Pokorny seemed to contradict this finding by saying that preplant incorporation of 0.15 kg $N \cdot m^{-3}$ provides adequate N for microorganisms present in pine bark. Cobb and Keever (1984) reported higher growth of euonymus and holly in fresh compared to aged pine bark. The authors proposed that the equal or higher plant growth in fresh compared to aged pine bark, even without supplemental liquid N, suggests a low N demand by microorganisms in both barks. However, their substrates were amended with a high N rate

(1 $kg \cdot m^{-3}$) prior to planting. Similar to our findings, cotoneaster growth was greater in aged than in fresh pine bark (Harrelson et al., 2004). Harrelson concluded that plants in fresh pine bark did not require additional N to maximize growth based on the fact that the high N rate (33.3 g $N \cdot pot^{-1}$) did not produce larger plants compared to the medium N rate (22.2 g $N \cdot pot^{-1}$). If differences in N availability existed between the fresh and aged pine bark used by Cobb and Keever (1984) and Harrelson et al. (2004); they may have been masked by the high N rates used in both studies. Harrelson et al. (2004) attributed the higher plant growth in aged compared to fresh to differences in physical properties; container capacity (CC) right after potting was 61% for aged and 49% for fresh. Physical properties of our geranium study were not measured. Nevertheless, physical properties for the DFB used to grow geraniums (screen $\leq$ 2.2 cm) were monitored for one year in a concurrent study. Container capacity averaged 32% and 40% for fresh and aged DFB, respectively (Table 2.3), thus higher CC in aged DFB may have caused differences in geranium growth observed in our study.

Plant response (Expt. 2). Measured plant and substrate responses for all harvest dates and repetitions showed a similar trend, thus only data collected 10 WAP are presented and discussed (Table 4.3). Substrate pH, NH_4-N, and NO_3-N response to bark age and applied N rate was similar to Expt. 1. Contrary to Expt. 1, foliar N levels did not differ between geranium grown in fresh or aged DFB; although geranium in aged DFB had larger SDW than those in fresh DFB, and thus would have adsorbed more N. Foliar N and SDW increased linearly with increasing N rate. The same general conclusions from the first repetition of the plant response study can be drawn for this repetition: differential geranium growth seems to be a result of greater N availability in aged bark compared to fresh bark, although differences in substrate CC might also explain growth differences.

Nitrogen draw-down. NDI analyses were conducted in an effort to explain differences in geranium growth in fresh and aged DFB. In Feb. 2006, a large fraction of NO_3^- was removed from solution in both fresh and aged DFB: In the first incubation day, NDI-1 was 0.59 and 0.45 for fresh and aged (p-value = 0.592).

After four days of incubation, NDI-4 was 0.27 and 0.26 for fresh and aged (p-value = 0.934). Similar to Feb 2006, NDI results for DFB on June 2006 indicate high N immobilization in fresh and aged DFB but no clear differences between the two bark types: NDI-1 for fresh and aged DFB was 0.37 and 0.44 (p-value = 0.260). After four incubation days, NDI-4 was 0.16 for fresh and 0.29 for aged DFB (p-value = 0.078). A high correlation between NDI value and growth was found in Grand Slam cabbage (*Brassica oleracea* L.) (Handreck, 1992b) and philadelphus (*Philadelphus mexicanus* Schltdl.) (Handreck, 1993). In our study, the similar NDI values between fresh and aged DFB were not reflected in equal geranium growth. On the contrary, geraniums growing in aged DFB had always larger tops than the ones grown in fresh DFB. Differential geranium growth in fresh and aged DFB can not be explained by similarities in N immobilization between the two bark ages.

Carbon loss. Similar C loss results were measured in DFB collected in Feb. and June 2006. As a consequence, only data for Feb. 2006 is presented and discussed. Carbon loss was not affected by bark type or N rate (Table 4.4). Carbon loss did increase slightly from 7 to 14 days, but was again similar across bark type and N treatment. Adding N from 0 to 400 ppm did not influence C evolution, indicating that biological activity was not affected or limited by N. Potassium nitrate was included in the analysis to determine if microbial populations had a N form preference, and also to compare results to NDI analyses (NDI procedures used KNO_3). There were no differences between KNO_3 and NH_4NO_3 at 75 ppm, indicating no N form preference.

Similar C loss between fresh and aged DFB agree with the lack of differences in NDI values measured for both bark ages in Feb. 2006. We would expect that two materials with equal capacity to immobilize N would show similar decomposition rates (C loss).

Gale et al. (2006) reported 0.3% of C is lost per day from well composted materials compared to higher than 1% C lost per day from uncomposted materials. Decomposition rates for fresh and aged DFB were similar to those reported for well composted materials by Gale et al. Up to 7 days of incubation, C loss was 0.27% d

^{1} across both DFB types and all N rates. From 7 to 14 days C loss dropped to just 0.1% d^{-1}, indicating that decomposition rates were slowing and suggesting that most microbial competition for N would be early in the production cycle. Pokorny (1979) recommends preplant incorporation of 0.15 kg $N \cdot m^{-3}$ to satisfy microbial needs. Our data do not validate the rate offered by Pokorny, but do suggest that if there is a microbial need for N, it occurs soon after potting and thus preplant N applications are reasonable.

During the course of this study another bark source (Rexius Co., Eugene, OR), offering a material screened to 0.95 cm, was sampled and measured for NDI in Feb. 2006. Nitrogen immobilization in fresh DFB was greater than in the aged material of this source; NDI-4 was 0.04 for fresh and 0.55 for aged (p-value = 0.037). This bark source had a smaller particle size than the bark used in all other trials previously reported (screened to 2.2 cm). Finer particles would be more conducive to microbial activity and thus may be the reason for greater differences in N immobilization between fresh and aged bark. However, other variables such as age and geographic location of the trees from which bark was harvested may affected N immobilization responses.

In summary, a large fraction of N in solution was immobilized in fresh and aged DFB, but differences were at best marginally significant. Carbon loss occurred at low predictable rates for a well-decomposed material, but there were no differences between fresh and aged DFB. Similarities in C loss between fresh and aged DFB agree with similar NDI measured in the two materials. Plant growth was affected by DFB age; geranium stem growth was always smaller in fresh bark. Nevertheless, differential geranium growth between fresh and aged DFB cannot be explained by similarities in N immobilization or decomposition rates between the two barks. Other variables, such as differences in CC between the two bark types, may have affected geranium growth. Nitrogen immobilization in both bark ages likely occurs very early in the production cycle. The N rates typically used by nursery growers are probably high enough to overcome N immobilization in either

bark type. Nitrogen applied specifically for microbial needs, if deemed necessary, should be pre-plant incorporated.

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Table 4.1. Sequence of bioassays, nitrogen draw-down index (NDI), and percent cumulative carbon loss (C loss) in fresh and aged Douglas fir bark (screened to 2.2 cm)

Date	Experiment
Jun-05	Bioassay
Feb-06	NDI-1
	NDI-4
	C loss
Jun-06	Bioassay
	NDI-1
	NDI-4
	C loss

NDI = Rate of disppearance of nitrate from an initial solution containing 75 ppm N (Handreck, 1992).

NDI-1= $[NO_3]_{(day\ 1)}/[NO_3]_{(day\ 0)}$. NDI-4=$[NO_3]_{(day4)}/[NO_3]_{(day0)}$

Table 4.2. *Pelargonium xhortorum* substrate pH, ammonium (NH_4-N), nitrate (NO_3-N), foliar nitrogen, and shoot dry weight (SDW) resulting from two Douglas fir bark ages and three nitrogen rates at 8 weeks after planting (Expt. 1)

Bark age[z]	Nitrogen rate ($mg \cdot L^{-1}$)[y]	Substrate nutrient availability			Plant response	
		pH	NH_4-N	NO_3-N	Foliar N	SDW
			($mg \cdot L^{-1}$)		(%)	(g)
Fresh	100	6.7	0.3	2.1	2.1	8.8
	200	5.8	0.8	117.5	3.6	13.2
	300	5.6	62.8	196.8	4.4	18.1
Aged	100	6.3	0.5	9.3	3.0	17.0
	200	5.3	25.0	474.3	4.1	32.7
	300	5.2	149.6	700.4	4.4	33.6
Sources of variation				Pr > F		
Bark age (B)		<.0001	<.0001	<.0001	0.0107	<.0001
Nitrogen rate (N)		<.0001	<.0001	<.0001	<.0001	<.0001
B*N		0.1936	<.0001	<.0001	0.0655	0.0559
Response to N rate						
Linear		<.0001	<.0001	<.0001	<.0001	<.0001
Quadratic		<.0001	<.0001	0.0806	0.0165	0.0780

[z]Bark source B (screened to 2.2 cm). [y]Nitrogen source: ammonium nitrate (NH_4NO_3)

Table 4.3. *Pelargonium xhortorum* substrate pH, ammonium (NH_4-N), nitrate (NO_3-N), foliar nitrogen, and shoot dry weight (SDW) resulting from two Douglas fir bark ages and three nitrogen rates at 10 weeks after planting (Expt. 2)

Bark age[z]	Nitrogen rate (ppm)[y]	Substrate nutrient availability			Plant response	
		pH	NH_4-N	NO_3-N	Foliar N	SDW
			($mg \cdot L^{-1}$)		(%)	(g)
Fresh	200	6.3	0.4	37.9	2.9	19.5
	300	5.7	0.4	131.8	3.0	22.0
	400	5.4	11.3	183.4	3.3	23.5
Aged	200	5.7	0.4	85.6	2.8	33.1
	300	5.2	10.7	194.1	3.0	35.4
	400	5.1	31.1	271.0	3.3	35.1
Sources of variation				Pr > F		
Bark age (B)		<.0001	0.0007	<.0001	0.427	<.0001
Nitrogen rate (N)		<.0001	<.0001	<.0001	<.0001	0.0783
B*N		0.1366	0.0148	0.2353	0.7333	0.7055
Response to N rate						
Linear		<.0001	<.0001	<.0001	<.0001	0.0338
Quadratic		0.0053	0.0648	0.0768	0.0777	0.4436

[z]Bark source B (screened to 2.2 cm). [y]Nitrogen source: ammonium nitrate (NH_4NO_3)

Table 4.4. Percent cumulative C loss in fresh and aged Douglas fir bark (screened to 2.2 cm) collected on Feb. 2006.

Bark age	Nitrogen Source	rate (ppm)	Incubation Days 7	14
Fresh	0	0	1.7	2.5
	NH4NO3	75	1.8	2.4
	NH4NO3	200	1.7	2.3
	NH4NO3	400	2.5	3.4
			NS	NS
Aged	0	0	2.2	2.6
	NH4NO3	75	1.8	2.5
	NH4NO3	200	1.8	2.4
	NH4NO3	400	1.8	2.5
			NS	NS

Sources of variation	
Bark age (B)	NS
N rate (R)	NS
B*R	NS
Incubation time (T)	***
T*B	NS
T*R	NS
T*B*R	NS

NS represents nonsignificant response
*** represent significance when $P \leq 0.001$.

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