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Chemical and Physical Properties of Douglas Fir Bark Relevant to the Production of Container Plants

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***Abstract*. A 1-year survey on the chemical and physical properties of Douglas fir [*Pseudotsuga menziesii* (Mirbel) Franco] bark was conducted with the following objectives: 1) to document baseline chemical and physical properties of Douglas fir bark (DFB) that have relevance to production of container plants; 2) to determine the effect of DFB age on its chemical and physical properties; and 3) to document the consistency of those properties throughout the year. In June, August, October, and Dec. 2005, and February and May 2006, fresh and aged DFB samples were collected from two primary DFB suppliers (bark sources) for Oregon nurseries: source A offers a bark screened to 0.95 cm or less (fine) and source B screened to 2.2 cm or less (coarse). Samples were analyzed for pH, electrical conductivity (EC), essential plant macro- and micronutrients, bulk density, particle size distribution, and substrate moisture characteristic curves. Air space (AS), container capacity (CC), and solids were determined as a percent of container volume. Nonamended fresh and aged DFB contains appreciable extractable amounts of all measured plant macro- and micronutrients, except N. In general, the aging process reduced pH; and increased EC, 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. In terms of physical properties, aged DFB had lower AS and higher CC compared with fresh DFB. Average differences in AS and CC between fresh and aged DFB within a source were 8% or less. Similar to chemical properties, uniformity of DFB physical properties was more affected by bark source than age.**

Container crops in the Pacific Northwest (PNW) are grown primarily in Douglas fir [*Pseudotsuga menziesii* (Mirbel) Franco] bark (DFB). Similar to Loblolly pine (*Pinus taeda* L.) bark in the southeast United States, DFB comprises the highest portion of most nursery substrates (60% to 80% of the substrate mix, personal observation in the PNW). Douglas fir bark is often incorporated with peatmoss, sand, compost, pumice, or other materials. Despite its widespread use, little information is available on the chemical and physical properties of DFB as it pertains to use as a container substrate. Most literature on this subject refers to the chemical properties of soluble components extracted for pulpwood or other industrial chemical purposes (Bowyer et al., 2003; Harkin and Rowe, 1971).

Chemical properties of pine bark (based on water extractions) have been documented and summarized in a review by Ogden et al. (1987). Tucker (1995) reported for non-amended pine bark; low pH (3.4 to 4.5), high phosphorous (P; 11.5 to 23 $mg\cdot L^{-1}$) and potassium (K; 134 to 215 $mg\cdot L^{-1}$); sufficient manganese (Mn; 4.5 to 15 $mg\cdot L^{-1}$) and copper (Cu; 0.22 to 0.50 $mg\cdot L^{-1}$); and low calcium (Ca; 8.5% to 24% of cation exchange capacity [CEC]), magnesium (Mg; 4.5% to 6.2% of CEC), and zinc (Zn; 1.8 to 4.4 $mg\cdot L^{-1}$) when compared with established sufficiency ranges (Warncke, 1998). Niemiera (1992) reported pine bark alone provided 0.10 $mg\cdot L^{-1}$ Cu, 22.7 $mg\cdot L^{-1}$ iron (Fe), 9.7 $mg\cdot L^{-1}$ Mn, and 3.9 $mg\cdot L^{-1}$ Zn, 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 commonly in Oregon container nurseries. Fresh bark refers to material sold soon after tree debarking, grinding, and screening to size; aged bark refers to material that goes through the same preparation process but 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 (Jack Hoeck, Rexius Bark, Eugene, OR, personal communication). Some of those preferring fresh DFB often claim it is more consistent from batch to batch than aged DFB. Skogholm cotoneaster (*Cotoneaster dammeri* C.K.Schneid 'Skogholm') grown in aged pine bark was 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 concentration 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 with established sufficiency ranges (Warncke, 1998; Yeager et al., 2000). Bollen (1969) 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, carbon to nitrogen (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.

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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 peatmoss or pine bark. Milled pine bark needs a range of both fine and coarse particle sizes to be suitable as a container substrate; 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% to 30% air space (AS), 45% to 65% container capacity (CC), 25% to 35% available water, 25% to 35% unavailable water, and 0.19 to 0.70 $g \cdot cm^{-3}$ bulk density (D_b) (Yeager et al., 2000). Most of the available water in a pine bark substrate is held at tensions less than 2.5 kPa, whereas water held at tensions greater than 10 kPa is not readily available for plants (Ingram et al., 1993). In the PNW, substrates are compared with the aforementioned guidelines for pine bark.

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 Oregon receives ≈1.1 m precipitation annually, most of which occurs between November and March (Taylor, 2005). Consequently, time of the year relative to rainfall may affect particle size distribution and other properties of DFB (Scott Leavengood, Wood Products Extension Agent, Oregon State University, personal communication).

Douglas fir bark is widely accepted as an excellent substrate for container production among nursery producers, 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 is known about DFB as it pertains to use as a container substrate. Therefore, the objectives of this study were: 1) to document baseline chemical and physical properties of DFB that have relevance to production of container plants; 2) to determine the effect of age on DFB chemical and physical properties; and 3) to 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, August, October, and Dec. 2005 as well as February 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, source A offering a finer screened bark at 0.95 cm or less (fine) and source B offering a coarser screened bark at 2.2 cm or less (coarse). At each visit, fresh bark samples were collected from a pile that was processed within the previous 48 h; aged bark was collected from piles that had been stored at the processing site for an average of 7 months. The exact duration of the aging process at the time of sampling could not be determined. Fresh and aged bark occurs 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 subsamples were randomly taken from each pile of differing screen size and bark age. Bark subsamples were collected from each pile by scraping away the surface 0.3 m of bark and collecting 0.019 m^3 into a plastic bucket. Samples were stored in the sealed buckets and placed in a cooler (1 °C) until samples could be processed (all samples were processed within 2 d).

A representative 0.004 m^3 of each subsample was placed in a plastic bag and sent immediately to a laboratory: Samples were analyzed for pH, EC, ammonium (NH_4-N), nitrate (NO_3-N), P, K, Ca, Mg, sulfate (SO_4^--S), and aluminum (Al) using the Saturated Media Extract (SME) method with water as the extractant (Warncke, 1998) and modified by Gavlak et al. (2003). Boron (B), Fe, Mn, Cu, and Zn were analyzed using a SME as well, but with diethylenetriaminepentaacetic acid (DTPA) as the extractant. Modifications by Gavlak et al. (2003) to the SME procedure involved soaking DFB in the extractant (either water or DTPA) for 24 h instead of 1 h recommended by Warncke (1998). Extracted solutions were analyzed for the mentioned elements, except N, by inductively coupled plasma–emission spectrometry (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 D_b ($g \cdot cm^{-3}$), percent AS, CC, and solids using an aluminum core (7.6 cm tall and 7.6 cm diameter) packed with each substrate and attached to a North Carolina State University (NCSU) Porometer (Fonteno and Bilderback, 1993). Particle size distribution 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 or less screen size) DFB collected from source B on May 2006. Volumetric water content at complete saturation and after saturation and drainage for 1 h (CC) was obtained from an aluminum core (3.8 cm tall and 7.6 cm diameter) attached to a 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 bark age and source on chemical and physical properties. Coefficient of variance (CV) for each parameter was calculated to assess data consistency over time (SAS Institute, 1999).

Results and Discussion

Douglas fir bark chemical properties. Nonamended DFB chemical properties were compared with nutrient guidelines for greenhouse growth media analyzed with a SME (Warncke, 1998) and recommended substrate pH for container plant production (Yeager et al., 2000) (Table 1). Currently, there are no established macro- and micronutrient sufficiency ranges for container substrates analyzed with the SME method. Yeager et al. (2000) report nutrient guidelines for container substrates analyzed with the Virginia Tech Extraction Method, which cannot be compared with the SME results of our study.

Average 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 (Ogden et al., 1987), DFB-extractable NH_4-N and NO_3-N levels were low (1.3 and 0.3 $mg \cdot L^{-1}$, respectively, averaged over bark type and collection date). Across all bark types, DFB had higher than recommended levels of extractable P, sufficient to high K and Cu, and sufficient Mn. Extractable P levels in DFB were several times higher than the recommended range for a well-fertilized substrate (Warncke, 1998). Longevity of high P levels in a plant-available form is not certain. Yeager and Wright (1982) reported that high indigenous P levels in pine bark are rapidly leached from the substrate, reducing the potential for plant uptake. 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 nutrient programs. Extractable Ca, Mg, SO_4^-, B, and Zn were below recommended levels but still in notable quantities that should be accounted for in nutrient programs. Low pH, Ca, and Mg are of little consequence considering the industry-wide practice of preplant incorporation with dolomitic limestone (personal observation). Extractable Fe was high in aged bark and within recommended levels

Table 1. Average chemical properties of fresh and aged Douglas fir bark from two bark sources and over six sampling dates (n = 3).

		Water extraction[z]									DTPA extraction[z]				
		pH	EC[y]	P	K	Ca	Mg	SO_4	Na	Al	B	Fe	Mn	Cu	Zn
Bark age	Date		mg·L^{-1}												
Fresh	June 2005	4.4	267	14.8	101.0	19.9	9.4	12.1	10.9	13.2	0.20	28.6	10.7	0.36	2.4
	Aug. 2005	5.0	310	19.2	110.0	20.0	9.3	15.6	12.3	9.4	0.19	23.2	11.2	0.34	2.2
	Oct. 2005	4.2	293	13.8	97.3	20.9	9.6	18.0	15.8	9.4	0.27	22.7	9.3	0.46	2.3
	Dec. 2005	4.0	257	8.8	77.2	17.3	7.3	11.1	16.2	7.8	0.27	21.7	9.0	0.41	2.3
	Feb. 2006	4.2	235	12.2	95.9	26.7	11.0	10.4	10.4	10.4	0.25	28.6	8.1	0.45	2.2
	May 2006	4.5	219	10.5	78.4	20.4	8.1	13.0	12.3	9.7	0.23	30.6	12.1	0.47	3.6
Aged	June 2005	3.7	466	28.0	110.3	38.7	28.3	13.7	9.7	51.5	0.38	63.1	8.5	0.34	2.4
	Aug. 2005	4.4	264	10.3	78.8	21.5	14.6	11.2	12.6	10.4	0.37	84.6	7.9	0.30	2.6
	Oct. 2005	3.7	680	26.5	162.0	71.2	44.4	20.5	15.1	32.4	0.56	92.4	13.0	0.34	2.3
	Dec. 2005	4.2	386	18.1	117.6	38.7	21.7	13.1	14.3	15.9	0.51	77.2	11.6	0.43	3.2
	Feb. 2006	4.0	328	20.5	120.1	36.2	19.9	9.8	8.6	18.6	0.45	61.4	8.4	0.47	2.8
	May 2006	3.8	406	21.8	130.8	37.8	21.3	17.6	19.0	17.1	0.41	63.6	9.1	0.45	3.1
Recommended ranges		5–6[x]	480–1280[w]	3–5[w]	60–149[w]	80–199[w]	30–69[w]	30–150[w]	0–40[w]	—	0.7–2.5[w]	15–40[w]	5–30[w]	0–0.35[v]	5–30[w]
Sources of variation		Pr>F													
Bark age (B)		0.0257	0.0443	0.0779	0.1309	0.0319	0.0133	0.4397	0.7762	0.0451	<.0001	0.0008	0.8618	0.2544	0.3042
Bark source (S)		0.4475	0.4052	0.9026	0.1800	0.5614	0.3568	0.7068	0.2800	0.1089	0.1369	0.6817	0.5619	0.4280	0.0857
S*B		0.1644	0.8855	0.5939	0.7189	0.7101	0.5448	0.9007	0.2955	0.1108	0.1471	0.2913	0.6846	0.6110	0.2461
Date (D)		0.4851	0.7436	0.7005	0.9591	0.7262	0.6787	0.5445	0.0132	0.4129	0.6252	0.9536	0.7375	0.3605	0.6601
B*D		0.1194	0.0434	0.3820	0.0519	0.0104	0.0498	0.4821	0.8591	0.0125	0.8308	0.5279	0.4392	0.7313	0.4156
S*D		0.0387	0.0354	0.6516	0.0191	0.0184	0.0796	0.0932	0.7575	0.0866	0.5405	0.2019	0.5948	0.3664	0.1231
B*S*D		0.5080	0.5263	0.0137	0.5463	0.8692	0.5304	0.2995	0.0103	0.8190	0.0579	0.0004	0.0010	0.1071	0.6775

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

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. (2007) demonstrated that DFB alone provided sufficient micronutrients for annual vinca [*Catharanthus roseus* (L.) G. Don 'Peppermint Cooler'] grown over a 2-month period at pH 4.7 to 5.7. Similarly, pine bark amended with 25% to 50% composted hardwood bark provided sufficient B, Fe, Mn, and Zn for geranium (*Pelargonium* ×*hortorum* L.) growth (Svenson and Witte, 1992). These data contradict Bollen's (1969) assessment that DFB has virtually no nutrient value.

The age of DFB influenced pH, EC, and soluble P (P = 0.0779), Ca, Mg, B, Fe, and Al. Across both sources and collection dates, aged DFB had lower pH than the fresh material; 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). Aged DFB had also higher levels of EC, P, Ca, Mg, B, and Fe than did fresh bark. In mineral soils, decreasing pH (below 7) results in increasing availability of P and other micronutrients. It is possible that organic acids released by decomposition of aged DFB reduced pH, which increased availability of P, Ca, B, and Fe. Another possibility is that cations released from decomposition of aged DFB displaced H^+ ions on cation exchange sites, thus depressing pH. Lower pH and increased salt levels are associated with aged DFB, although it is not clear which causes the other. Harrelson et al. (2004) did not observe an effect of pine bark age on substrate pH, and Cobb and Keever (1984) reported higher pH in aged pine bark compared with 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 (calculated as σ/μ) provided a measure of data consistency over time (Table 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.

Table 2. Coefficients of variation over 1 year for the chemical and physical properties of Douglas fir bark from two bark sources and two bark ages (n = 18).

	Source A (fine)[z]		Source B (coarse)	
Chemical properties[y]	Fresh bark	Aged bark	Fresh bark	Aged bark
pH	12	13	9	9
EC	33	70	35	28
P	50	58	45	45
K	25	57	31	27
Ca	51	79	45	32
Mg	49	87	49	37
SO_4	31	75	22	22
Na	32	80	22	32
B	28	33	16	23
Fe	39	25	31	40
Mn	41	35	16	23
Cu	23	32	24	31
Zn	67	33	17	29
Al	28	57	29	45
Physical properties[x]				
AS	8	14	12	12
CC	9	13	20	14
Solids	13	12	16	14
D_b	7	9	15	8

[z]Bark from source A and B were screened to 0.95 cm and 2.2 cm, respectively.
[y]Electrical conductivity (EC), pH, P, K, Ca, Mg, SO_4, Na, B, Fe, Mn, Cu, Zn, and Al analyzed with a Saturated Media Extract (SME) (Gavlak et al., 2003; Warncke, 1998).
[x]Air space (AS), container capacity (CC), solids, and bulk density (D_b) determined with a North Carolina State University Porometer (Fonteno and Bilderback, 1993).

Bark age was less important in terms of consistency than the source from which it was collected.

No documented Al testing exists for soilless substrates such as tree bark, which is possibly the result of the general agreement that organic soils and soilless substrate contain low amounts of Al (Lucas and Davis, 1961; Yeager and Barrett, 1985). Significant amounts of Al were extracted in DFB throughout the survey (7.8 to 51.5 $mg \cdot L^{-1}$ on average), which among other things could impact bloom color of hydrangea [(*Hydrangea macrophylla* (Thunb.) Ser.] (Blom and Piott, 1992). Aged DFB had higher water-extractable Al than did fresh bark.

Douglas fir bark physical properties. Nonamended DFB has high AS, low CC, adequate solids, and low D_b (Table 3) compared with guidelines developed for pine bark in the southeastern United States (Yeager et al., 2000). Some nursery managers believe PNW substrates, particularly those used in Oregon, must have higher AS and lower CC compared with what is recommended in the southeast United States 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 as a result of inherent correlations between each parameter. Collectively, these parameters were affected by an interaction among bark age, bark source, and date of collection. Air space was lower and CC higher in aged compared with fresh DFB. Average differences in AS and CC between fresh and aged DFB within a source were 8% or less but may be different enough to 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, whereas available water was 26% for aged and 10% for fresh bark. In their study, Skogholm cotoneaster grew larger in aged compared with 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 to better understand how time of year affects bark properties. However, as a result of 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). Container capacity, D_b, and solids were more consistent (lower CV) over time from source A (fine) compared with source B (coarse).

Bulk density was influenced by an interaction among bark age, bark source, and collection date, although measured differences were minor (Table 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 use rates based on substrate D_b (for example, bifenthrin [Talstar, FMC Corporation, Philadelphia, PA]). 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 among all variables (bark age, source, and date of collection) (Table 4). Although differences between fresh and aged bark were significant, measurable differences were negligible. 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 greater than 4 mm, whereas 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, whereas source B (coarse) had more coarse particles and fewer fine particles than recommended. As mentioned previously, coarser substrates are likely beneficial for wet winters characteristic of the PNW.

A single sample of fresh and aged DFB from source B (coarse) was analyzed for its substrate moisture characteristic curve (Fig. 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 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 ended at 6.1 kPa, at which there was 14% and 11% of CC still held by

Table 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 (fine)	Fresh	June 2005	42	42	16	0.16
		Oct. 2005	40	38	22	0.18
		Dec. 2005	40	42	18	0.18
		Feb. 2005	34	48	18	0.17
		May 2006	39	40	20	0.17
	Aged	June 2005	38	45	17	0.17
		Oct. 2005	42	40	18	0.17
		Dec. 2005	32	52	16	0.16
		Feb. 2005	31	55	14	0.16
		May 2006	36	47	18	0.20
Source B (coarse)	Fresh	June 2005	51	28	21	0.21
		Oct. 2005	48	32	20	0.17
		Dec. 2005	54	29	16	0.14
		Feb. 2005	42	43	15	0.14
		May-06	51	30	20	0.16
	Aged	June 2005	50	32	18	0.18
		Oct. 2005	41	42	18	0.18
		Dec. 2005	41	45	13	0.17
		Feb. 2005	39	44	17	0.17
		May 2006	45	38	17	0.17
Recommended values[x]			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]All parameters determined with a North Carolina State University Porometer (Fonteno and Bilderback, 1993).

[y]Bark from source A and source B were screened to 0.95 cm and 2.2 cm, respectively.

[x]Recommended physical properties for pine bark substrates (Yeager et al., 2000).

Table 4. Particle size distribution of fresh and aged Douglas fir bark collected on four different dates (n = 3).

	Source A (fine)[z]								Source B (coarse)							
	Oct. 2005		Dec. 2005		Feb. 2006		May 2006		Oct. 2005		Dec. 2005		Feb. 2006		May 2006	
	F[y]	A	F	A	F	A	F	A	F	A	F	A	F	A	F	A
Sieve size (mm)	%															
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

[z]Bark from source A and source B were screened to 0.95 cm and 2.2 cm, respectively.
[y]F and A refer to fresh and aged Douglas fir bark, respectively.

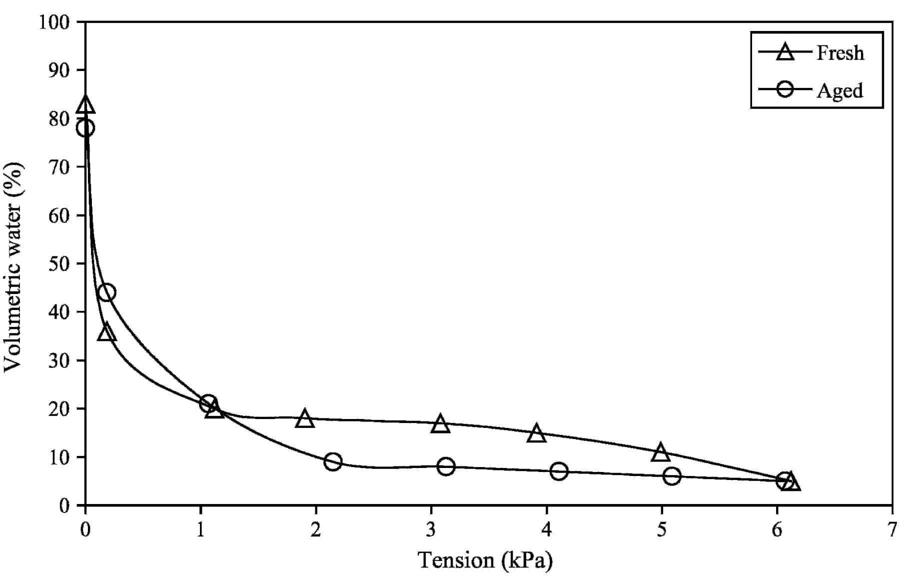

Fig. 1. Substrate moisture characteristic curves for coarse fresh and aged Douglas fir bark collected on May 2006. Curves obtained with a North Carolina State University Porometer (Fonteno and Bilderback, 1993) and a Buchner filter funnel (modified from Fonteno et al., 1981, and Milks et al., 1989). Douglas fir bark was initially passed through a 2.2-cm screen (source B) when processed by the supplier.

fresh and aged DFB, respectively. Moisture characteristic curves generated for DFB appear similar in shape as those for pine bark reported by Tilt et al. (1987). However, curves generated for pine bark appear to become asymptotic with 30% to 35% moisture still retained in the bark compared with just 10% for DFB. This suggests a greater percent of CC is available for plant uptake in DFB compared with pine bark.

In summary, nonamended fresh and aged DFB contains appreciable amounts of measured plant macro- 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. Consistency of DFB chemical properties throughout the year depended more on bark source than bark age; source B (coarse) was most consistent. Aged DFB had lower AS and higher CC. Similar to chemical data, 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 Oregon nursery growers that fresh DFB has more consistent properties than aged DFB.

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