NOTE
Forest pathology / Pathologie forestière

Black stain root disease progression in coastal Douglas-fir in British Columbia

William R. Jacobi, Stefan Zeglen, and Jeffrey D. Beale

Abstract: Periodic monitoring of black stain root disease (*Leptographium wageneri* var. *pseudotsugae)* in coastal Douglas-fir (*Pseudotsuga menziesii*) on Vancouver Island and mainland British Columbia, Canada, provided intensification and mortality rates for this disease. Fifteen plots with Douglas-firs of varying ages and sizes and growing on sites with different conditions were established in 1989 and assessed in 1994 and 2000. Overall mortality from black stain root disease increased from 11.4% in 1989 to 19.0% in 2000, or 0.7% per year. A further 6.5% of trees succumbed to other root diseases and 9.4% to unknown causes but most likely black stain root disease. When trees were placed in three diameter classes, there were no significant differences in disease incidence among size classes or over time. Based on plot-level data, the incidence of disease increased with an increase in elevation ($P < 0.09$) and with an increase in slope ($P < 0.08$). Mean tree age and aspect were not significantly related to disease incidence. Crown condition rating of trees within the black stain root disease centers was a good predictor of future mortality and further disease progression. Trees with crown condition classes of slightly yellow foliage, moderately yellow foliage, totally yellow foliage, and >50% defoliated in 1989 died at a higher rate as crown condition deteriorated with 26%, 45%, 64%, and 77% tree mortality, respectively, by 2000.

Key words: Douglas-fir, *Leptographium wageneri,* black stain root disease, British Columbia.

Résumé : Le suivi périodique de la maladie du noircissement des racines (*Leptographium wagneri* var. *pseudotsugae*) chez le Douglas taxifolié des régions côtières (*Pseudotsuga menziesii*) de l'île de Vancouver et de la partie continentale de la Colombie-Britannique, au Canada, a permis de déterminer les taux d'aggravation et de mortalité pour cette maladie. Quinze parcelles dont les conditions de croissance variaient et sur lesquelles poussaient des Douglas taxifoliés de tailles et d'âges différents furent délimitées en 1989 et évaluées en 1994 et 2000. Le taux global de mortalité due à la maladie du noircissement des racines est passé de 11,4 % en 1989 à 19,0 % en 2000, ce qui correspond à une augmentation de 0,7 % par année. Un 6,5 % additionnel de sujets a succombé à d'autres maladies des racines et 9,4 % sont mort de causes inconnues, mais très vraisemblablement de la maladie du noircissement des racines. Lorsque les arbres étaient répartis dans trois classes de diamètres, ni ces classes ni le temps ne semblaient faire une différence notable en ce qui a trait à l'incidence des maladies. Par contre, si on se rapporte aux données relatives à l'élévation des parcelles, on remarque que l'incidence de la maladie augmente en fonction de l'augmentation de l'altitude ($P < 0{,}09$) et de la pente ($P < 0{,}08$). Par ailleurs, l'âge moyen des arbres et leur apparence n'étaient pas outre mesure fonction de l'incidence de la maladie. L'évaluation de l'état de la couronne des arbres poussant dans les secteurs où la maladie était établie était un bon indicateur de la mortalité future et de la progression subséquente de la maladie. Les arbres dont le feuillage des couronnes était légèrement jaune, moyennement jaune, complètement jaune et qui étaient à plus de 50 % défoliés en 1989 sont morts plus rapidement, affichant, en 2000, des taux de mortalité respectifs de 26 %, 45 %, 64 % et 77%.

Mots-clés : Douglas taxifolié, *Leptographium wagneri*, maladie du noircissement des racines, Colombie-Britannique.

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Introduction

Black stain root disease (BSRD) of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), caused by the fungus *Leptographium wageneri* (Kendrick) Wingfield var. *pseudotsugae* Harrington & Cobb, is a serious forest management problem in some areas of western North America including northwestern California, southwestern Oregon, and southern British Columbia (Cobb and Platt 1967; Goheen and Hansen 1978; Hansen 1978; Harrington et al. 1983; Hunt and Morrison 1995). The vectors of the pathogen are root-feeding bark beetles and weevils that attack stressed or injured trees (Harrington et al. 1985; Witcosky and Hansen 1985). In some cases, the occurrence of freshly cut stumps in thinned stands causes an increase in insect vector populations (Harrington et al. 1983). The pathogen can spread to new roots by mycelial growth through root to root contact, wounds, root grafts, dead fine roots, and limited mycelial growth through soil (Hansen et al. 1988; Hessburg and Hansen 1986, 2000). Trees are killed when water transport is blocked by fungal growth in the vascular xylem system (Hessburg and Hansen 1987).

Two pathotypes of *L. wageneri* are found in southern British Columbia. *Leptographium wageneri* var. *ponderosum* (Harrington & Cobb) Harrington & Cobb occurs primarily on lodgepole pine (*Pinus contorta* Douglas & Loud. var. *latifolia* Engelm. ex S. Wats.) and is restricted to the southern interior portion of the province on 45- to 100-year-old trees, especially those at elevations >1000 m (Hunt and Morrison 1986). *Leptographium wageneri* var. *pseudotsugae* is found on 15- to 60-year-old Douglas-fir trees on the coast with most mortality noted prior to stand age 25–30 years (Hunt and Morrison 1995; Morrison and Hunt 1988). In Oregon, disease incidence appears to be higher in young stands subject to disturbance from road construction, skid trails, and precommercial thinning compared with undisturbed sites. Damage often associated with these disturbance activities may predispose trees to colonization by insects that are vectors of BSRD (Hessburg et al. 2001). In British Columbia, the disease also is encountered on rocky and dry sites and is associated with other root pathogens, such as *Armillaria ostoyae* (Romagnesi) Herink causing armillaria root disease and *Phellinus sulphurascens* Pilat causing laminated root disease (Morrison and Hunt 1988).

The incidence of BSRD in British Columbia's coastal Douglas-fir forests is apparently low, although extensive survey data are lacking (Morrison and Hunt 1988). Mortality rates, disease spread rates, and the relationship of mortality rates to the current host condition are also not well documented in British Columbia. Thirty-two percent of Douglas-fir trees in a BSRD center near Nitinat, British Columbia, died by age 18 years, a mortality rate of 7% per year (Morrison and Hunt 1988). However, no tree was killed by BSRD alone after 19 years. In neighboring Washington and Oregon, the disease seems to be a serious problem in young Douglas-fir stands (Hansen et al. 1988).

To better assess the potential risk to managed stands and to develop mitigating strategies, information is needed on BSRD progression and mortality rates for a range of stand ages and site conditions. Thus, the objectives of this study were to quantify BSRD mortality rates of coastal Douglas-fir in BC and determine if there is a measure of current visual host condition that would be a reliable indicator of future tree mortality.

Materials and methods

Plot design

Variable-sized (100–1400 m^2) rectangular plots were established in the fall of 1989 to measure BSRD incidence and mortality rates. Plot size was determined by an apparent root disease center. Each plot included a border of a minimum of two nonsymptomatic trees around the perimeter of the disease center. Plots were located in planted coastal Douglas-fir stands <50 years of age at 11 sites across Vancouver Island, British Columbia, and four sites on the mainland midcoast, inland of Bella Coola, British Columbia. Plots were relatively uniform in degree of previous site disturbance in that they were located within commercial stands away from obvious skid roads and other disturbances. Plots encompassed, on average, a group of 59 trees that formed a BSRD center. We did not determine spatial spread rates on the plots, but rather, we recorded the mortality and occurrence of newly symptomatic trees within plots. Data collected for each plot included percent slope, aspect, topography, elevation, and mean tree age. Variables were recorded as follows: percent slope at midplot; aspect, as one of eight compass directions based on magnetic north; and elevation in meters from topographical maps.

Tree measurements

All trees within the plots, symptomatic and healthy, were assessed, and each tree had a numeric tag attached at 1.3 m. All trees on the 15 plots were remeasured in 1994 and 2000. No assessment was made of trees outside the plots. Data were collected on a total of 889 trees, 806 of which were Douglas-fir and the other species included 61 western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), 13 western red cedar (*Thuja plicata* Donn ex D. Don), 5 western white pine (*Pinus monticola* Dougl. ex D. Don), 3 shore pine (*Pinus contorta* var. *contorta* Dougl. ex. Loud.), and 1 Sitka spruce (*Picea sitchensis* (Bong.) Carr.). Black stain root disease was not noted on any species other than Douglas-fir, so these trees are not included in any of the data summaries. Data collected on each tree included crown condition, root disease occurrence, and diameter at breast height (DBH; 1.3 m). Overall tree health was based on six visual crown condition classes: healthy green needles; slightly yellow (green-yellow) needles; moderately yellow (yellow-green) needles; totally yellow needles; 50%–100% of crown defoliated; or tree dead ≥1 year (based on degradation of twigs). These crown condition classes were selected after extensive preliminary excavation of roots in several BSRD-infested areas indicated these would be good aboveground indicators of root damage. Roots of trees with crown conditions less than slightly healthy were excavated starting at the tree's base and extending out 1 m, and the following signs and symptoms were recorded: BSRD (longitudinal, dark black stain in xylem); armillaria root disease (mycelial fans or typical decay pattern—white mushy to stringy decay often with zone lines); or laminated root rot (ectotrophic mycelium and decay patterns of red to yellow color). Root diseases were coded as follows: no disease; BSRD only; armillaria root disease only; laminated root rot only; BSRD and armillaria root disease; BSRD and laminated root rot; or unknown causes. All Douglas-fir trees within the plots were reassessed for crown condition and root disease occurrence during the summers of 1994 and 2000, and their diameters were remeasured. Mean tree age was collected in 1989 by increment cores at 1.3 m on at least three trees per size class (1.0–12.0, 12.1–22.0, and >22.0 cm DBH) per plot.

Data analysis

Data were analyzed by summary tables of mean crown condition, disease incidence, and changes in individual tree condition among 1989, 1994, and 2000. Analysis of covariance was used to determine the influence of slope, aspect, elevation, mean tree age, and mean tree diameter on the percentage of diseased trees using SAS version 8.1 (SAS Institute Inc., Cary, N.C.). Analysis of variance was run on BSRD incidence comparing the three diameter classes (1.0–12.0, 12.1–22.0, and >22.0 cm DBH) over the three monitoring dates (1989, 1994, and 2000). In the diameter class analysis, we combined all trees with BSRD including those that had other root diseases present. Significance was tested at $P < 0.05$ unless otherwise stated.

Results

Plot characteristics in 1989

Plots were established on a variety of sites with different ages of planted Douglas-fir trees (Table 1). The mean conditions in 1989 on the plots were 19.6% slope (range 0%–40%), 185 m elevation (range 50 – 500 m); 12.7 cm DBH (range 1.0–42.2 cm); and 27 years of age (range 6–45 years). The aspect of the plots varied with approximately equal representation of southerly and northerly exposures. Topography was undulating or smooth on all plots. Disturbances prior to planting included harvesting and typical site preparation (broadcast slash burning and, in two cases, mechanical removal of stumps for treatment of root disease) and disturbances after planting were mechanical or chemical weed control and thinning of stands 6 to 10 years prior to plot establishment. The range of stand stocking was 500–1900 stems/ha.

Disease incidence

Over the 11 years of the study, BSRD incidence varied among individual study plots. Incidence did not change on some plots, increased on others, and decreased on the remainder. Overall, the combined number of dead trees, trees infected with BSRD, and trees infected by other root diseases increased from 1989 to 2000 (Table 2).

In 1989, 34.6% of the 806 Douglas-fir on the 15 plots were dead or had signs or symptoms of BSRD (17.4%), unknown causes (9.0%), or other root diseases (1.0%). In 1994, 20.0% of the trees had BSRD; by 2000, disease incidence had not changed (20.4%), but mortality had increased by 67% (Table 2). The number of Douglas-fir trees killed by BSRD increased by 6.0% in 1994 and a further 1.5% died by 2000. The rate of disease increase was variable but did not vary with tree age or other factors. The increase in symptomatic living and dead trees was variable from 0% to 12.6% per year over the 15 plots. Trees with symptomatic crown conditions associated with any root disease decreased from 1989 to 2000, whereas those trees with symptomatic crown conditions due to unknown causes rose during the same period (Table 2). Mortality from all causes rose consistently during the study period.

Laminated root rot occurred on 14 trees in five plots (Butler, North Arm, EP 599.01, Lens Creek, and Cook Creek), but it was not a major factor in the death of trees or the occurrence of BSRD except at the North Arm plot. The North Arm plot appears to involve mainly *P. sulphurascens* infected trees with BSRD affecting the already stressed trees. Laminated root rot was not as evident in 1989 as it was in 1994 at the North Arm plot.

Armillaria root disease occurred occasionally at nine locations involving a total of 19 dead trees by 2000. There was no clear relationship between armillaria root disease and BSRD occurrence. Although trees with laminated root rot and those with armillaria root disease trees comprised only about 4% of the sample trees by 2000, the resultant mortality caused by these diseases steadily increased during the study.

Influence of site and tree factors on BSRD incidence

There was no significant change in root disease incidence in the three diameter classes over the 11 years nor was there a difference in incidence among size classes within a year (Table 3). Tree age and year of collection were not significantly related to BSRD incidence. Based on plot-level data, the incidence of BSRD increased ($P > 0.09$) with an increase in elevation and with an increase ($P > 0.08$) in plot slope.

Tree health status change over time

Tree health diagnosis provided a snapshot of how coastal Douglas-fir responds to BSRD over time. Of the 530 nonsymptomatic trees in 1989, 4.1% became BSRD trees, an unknown cause affected 15.9%, and 1.4% were affected by armillaria root disease or laminated root rot. Most trees affected by BSRD, unknown causes, armillaria root disease, or laminated root rot remained in those same categories throughout the study. Overall, 77% of trees nonsymptomatic in 1989 remained that way over the study period. Well over 80% of trees symptomatic due to an identified root disease (BSRD and others) died within the 11 years, but only about 11% of the trees symptomatic for unknown reasons died by 2000. About one-half of the initial symptomatic (slightly yellow) trees remained that way, whereas nearly one-third recovered to nonsymptomatic status.

Foliar symptoms and future tree condition

Crown condition symptoms changed over the 11 years for some trees (Table 4). Only 77% of healthy trees remained so, whereas 14.1% had foliar symptoms in 2000 ranging from slightly yellow to >50% defoliated, and 8.5% of the trees had died. Trees with crown condition classes of slightly yellow foliage, moderately yellow foliage, totally yellow foliage, and >50% defoliated in 1989 died at higher rates by 2000: 26%, 45%, 64%, and 77% tree mortality, respectively. Compared with healthy trees, deaths of slightly

Table 1. Black stain root disease monitoring plot information on coastal Douglas-fir in British Columbia in 1989.

Plot location	No. of trees[a]	BGC subzone[b]	Most recent spacing[c]	Stocking level (stems/ha)[d]	Mean tree age (years)[e]	Mean tree diameter (cm)[e]
Butler Main Line	103	CWHxm2	1979*	na	18	3.7
North Arm Experiment Station[f]	66	CWHxm2	—	1940	14	13.6
Provenance Trial (EP 599.01)	239	CWHmm1	1983	1280	20	15.5
Lens Creek-6300-5	43	CWHmm1	1983	na	25	24.5
Lens Creek 6300-6	7	CWHmm1	1983	na	30	25.5
Lens Creek 6300-7	107	CWHmm1	1983	na	26	24.8
Lens Creek 6300-8	76	CWHmm1	—	na	8	6.6
Cook Creek-1	25	CWHxm1	1983	892	45	15.2
Cook Creek-2	25	CWHxm1	1983	892	43	13.1
Cook Creek-3	13	CWHxm1	1980	510	44	15.1
Firvale-1	37	CWHds2	1977	810	24	19.1
Firvale-2	25	CWHds2	1977	810	24	19.5
Firvale-3	31	CWHds2	1977	810	22	11.7
Firvale-4	62	CWHds2	1977	810	20	11.8
Lost Lake[f]	30	CWHxm1	—	1500	6	1.1

[a]All species.
[b]Biogeoclimatic subzone classification based on Green and Klinka (1994).
[c]Most recent year of thinning. Rows without values indicate that there was no discernable thinning. *, estimated year.
[d]Stocking level in 1989. na, not available.
[e]Tree ages were determined using increment cores at 1.3 m as were diameters of all Douglas-fir trees. Values are least square means.
[f]The site had stumps removed for root disease management prior to planting.

Table 2. Change in crown condition and occurrence of root disease on Douglas-fir in black stain root disease monitoring plots, British Columbia (n = 806 for each year).

Tree crown condition and root disease occurrence[a]	Incidence (%)[b]			
	1989	1994	2000	Change 1989–2000 (%)
Healthy	65.4	53.2	53.2	–18.5
Symptomatic, black stain present	6	2.5	1.4	–76.7
Symptomatic, other root diseases	1	1.1	0.6	–40
Symptomatic, unknown cause	9	15.6	12.8	42.2
Dead, black stain present	11.4	17.5	19	66.7
Dead, other root diseases	1	1.7	7.5	650
Dead, unknown cause	6.2	7.5	15.6	151.6

[a]Symptomatic trees had crown health classes including slightly yellow needles, moderately yellow, totally yellow, and 50%–100% defoliated; dead trees had died ≥1 year prior to the year of monitoring; black stain present includes trees with just black stain root disease, trees with black stain root disease and armillaria root disease, and trees with black stain root disease and laminated root rot; other root diseases were armillaria root disease or laminated root rot.
[b]Percentage of trees in each category. The values do not add up to 100% because of rounding.

yellow trees, moderately yellow trees, totally yellow trees, and trees with >50% defoliated were 3.1, 5.3, 7.5, and 9.1 times more likely, respectively (Table 4). Crown health improved by 2000 at a decreasing rate with increase in severity of rating in 1989. Trees that improved in crown health were all originally trees with unknown causes, and crown health of 33%, 41%, 27%, and 23% of the trees improved among the slightly yellow trees, moderately yellow trees, totally yellow trees and >50% defoliated crowns, respectively (Table 4). No trees diagnosed with BSRD became nonsymptomatic, but the corown condition of some of the trees remained consistent or improved slightly over the period of monitoring. Four trees with confirmed BSRD in 1989 had an improvement in crown condition by 2000. These trees exhibited branch dieback and with new green adventitious foliage in 2000.

Discussion

The rate of BSRD mortality and the relationship of symptoms to future mortality on sites with active BSRD can be assessed from results of these permanent plots. However, one cannot determine how much damage is associated with this disease on a region-wide basis, because no random sample of the Douglas-fir population exists. The permanent plots also did not help determine the effect of tree size on the occurrence and intensification of BSRD over time, because there was inadequate tree size distribution among the 15 plots, and there was a large variation in BSRD incidence among plots. The range of site features such as slope, aspect, elevation, and soil types were not represented well within our plots. Thus, the positive relationship we found of elevation and slope with an increase in disease incidence is not strong.

Table 3. Black stain root disease incidence in Douglas-fir by diameter class between 1989 and 2000.

Diameter class in 1989 (cm)	No. of trees[a]	Mean diameter in 1989 (cm)	Black stain incidence (%)		
			1989 (%)	1994 (%)	2000 (%)
1.0–12.0	347	7.5	21.2	26.0	28.2
12.1–22.0	361	15.8	17.8	19.8	20.0
>22.0	83	26.4	15.8	17.9	17.9

Note: Percent incidences are least square means and are not significantly different among years nor among diameter classes.

[a]Fifteen trees were excluded because of incomplete diameter data.

Table 4. Crown condition of Douglas-fir trees in 2000 in relation to crown condition in 1989.

Crown condition in 1989	Crown condition in 2000: *N*	Healthy or green foliage (%)	Slightly yellow foliage (%)	Moderately yellow foliage (%)	Yellow foliage (%)	>50% defoliated (%)	Dead (%)[a]
Healthy	530	76.6	10.4	2.1	0.2	1.3	8.7 a
Slightly yellow foliage	69	33.3	30.4	4.4	1.4	0	26.1 b
Moderately yellow foliage	29	6.9	34.5	10.3	0	0	44.8 bc
Yellow foliage	11	0	9.1	18.2	0	9.1	63.6 cd
>50% defoliated	22	4.6	9.1	9.1	0	0	77.3 d
Dead	145	0	0	0	0	0	100

[a]Values followed by same letter are not significantly different among the 1989 crown conditions (chi square, $P \geq 0.05$, $n = 812$).

The rate of new BSRD affected trees on individual plots varied from a doubling to almost no change after 5 years. This variation could be due to environmental factors, such as drought or microsite conditions. Similar unexplained variation in BSRD incidence and mortality was seen in a larger monitoring program of BSRD on Douglas-fir in Oregon and Washington states (Hansen and Goheen 1988). Hansen and Goheen (1988) found mortality increased 3.1 times in the first 5 years but only 1.4 times in the second 5 years of the 10-year study. In our study, tree mortality increased overall, but the rate was erratic by plot and over time. We could not show a reduced mortality rate in larger or older trees as seen by other researchers (Hansen et al. 1988; Morrison and Hunt 1988). Our disease incidence and mortality rates were variable and dependent on plot variation rather than tree size. Elevation and slope were slightly related to disease incidence suggesting a potential relationship with soil moisture or some other site factor.

In all the assessments, many dead trees that were assigned the unknown cause disease code were likely killed by BSRD because they were surrounded by BSRD trees and signs of other root disease pathogens were not found. Black stain root disease signs and symptoms, including staining in root tissue do not remain in roots for many months before other insect and fungal activity obscures these symptoms. Additionally, in 1989, we did not assign a causal disease to many of the trees with the crown class of slightly yellow. Detecting BSRD when living trees exhibit initial symptoms is not easy because the fungus may not appear within 1 m of the root collar where detection was attempted. Living trees with symptoms that had no discernible cause in 1989 mostly stayed that way (64.4%); however, 8.1% died from unknown but, likely, natural competition causes; these casualties were understory trees <10 cm in diameter. Annual monitoring would have provided a clearer picture of the causes of mortality.

Crown condition was a reasonable predictor of future tree condition. The ability to predict mortality over 11 years was relatively linear. Totally yellow foliage or partial defoliation of trees strongly indicated that most of these trees would be dead after 11 years. These simple symptom classes will allow managers to predict the progression of BSRD. Possible predisposing effects of potential climate change may increase the impact of BSRD on young stands in the region and affect the crown condition and mortality relationship. A random survey of tree health in young stands over the entire region that was repeated after 5–10 years could shed more light on the impact of BSRD on Douglas-fir forests, and what site and tree factors might be related to incidence and mortality rates of BSRD.

For forest managers, our advice is to moderate as much as practical any disturbance to Douglas-fir stands, especially those in areas where previous occurrences of BSRD have been observed. In most cases, some mortality is inevitable within 5 years of disturbance, but this will gradually decline as the stand recovers and the vector population decreases or becomes too dispersed to mount lethal attacks on individual trees. Managers should also delay thinning treatments on stands that are experiencing mortality because of BSRD until the risk has passed.

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