Growth and foliar nutrition of western red cedar fertilized with sewage sludge, pulp sludge, fish silage, and wood ash on northern Vancouver Island

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The fertilizer efficacy of a variety of organic wastes was tested in a 9-year-old plantation of western red cedar (*Thuja plicata* Donn ex D. Don) growing on a cutover of cedar–hemlock (*Tsuga heterophylla* (Raf.) Sarg.) forest on northern Vancouver Island. Seven treatments were compared: municipal sewage sludge, sewage sludge plus pulp sludge, fish silage and wood ash, silage and ash plus pulp sludge, wood ash alone, ammonium nitrate with triple super phosphate, and control (untreated). Each treatment was replicated three times. Rates of application were 225 kg $N \cdot ha^{-1}$ in the inorganic fertilizer and about 500 kg $N \cdot ha^{-1}$ in the organic wastes (except wood ash). The height and diameter of the cedar trees 2 years after fertilization were greatest in the plots treated with inorganic fertilizer (average height was 274 cm, vs. 211 cm in control plots; average diameter at 30 cm was 49 mm, vs. 34 mm in control plots). Smaller but significant growth responses were achieved with sewage sludge and fish silage plus ash. Mixtures of sewage sludge or silage with pulp sludge produced smaller height growth responses, but did not affect diameter growth. Wood ash alone had no effect on tree growth. All treatments except wood ash increased the concentrations of macronutrients in foliage. Foliar N concentrations were greatest in trees treated with fish silage or inorganic fertilizer. Stagnated plantations of western red cedar appear to provide an opportunity for recycling these organic wastes.

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L'efficacité fertilisante d'une variété de déchets organiques a été évaluée dans des plantations de thuja géant (*Thuja plicata* Donn ex D. Don) âgées de 9 ans et croissant dans une forêt de thuya et de pruche (*Tsuga heterophylla* (Raf.) Sarg.) coupée à blanc dans le nord de l'île de Vancouver. Sept traitements ont été comparés : des boues d'égouts municipaux, des boues d'égouts avec des boues de pulpe, un ensilage de poisson et de la cendre de bois, de l'ensilage et de la cendre avec des boues de pulpe, de la cendre de bois seule, du nitrate d'ammonium avec du super phosphate triple et le témoin (non traité). Chaque traitement a été répété trois fois. Le taux d'application allait de 225 kg $N \cdot ha^{-1}$ pour le fertilisant inorganique à environ 500 kg $N \cdot ha^{-1}$ pour les déchets organiques, à l'exception de la cendre de bois. La hauteur et le diamètre des thuyas 2 ans après fertilisation étaient le plus élevés dans les parcelles traitées avec le fertilisant inorganique (hauteur moyenne de 274 cm, vs 211 cm dans les parcelles témoins; diamètre moyen à 30 cm de 49 mm, vs 34 mm dans les parcelles témoins). Des réponses de croissance plus faibles mais significatives ont été obtenues avec les boues d'égouts et l'ensilage de poisson plus la cendre. Des mélanges de boues d'égouts ou d'ensilage avec les boues de pulpe ont produit des réponses en croissance en hauteur plus faibles mais n'ont pas affecté la croissance en diamètre. La cendre seule n'a pas eu d'effet sur la croissance des arbres. À l'exception de la cendre de bois, tous les traitements ont augmenté les concentrations en éléments majeurs dans le feuillage. Les concentrations foliaires en N ont été le plus élevées dans les arbres traités avec l'ensilage de poisson ou le fertilisant inorganique. Les plantations stagnantes de thuya géant offrent une opportunité pour le recyclage de ces déchets organiques.

[Traduit par la rédaction]

Introduction

Organic waste recycling in forests offers the dual benefits of waste disposal and potential improvements in the productivity of forests resulting from the fertilizing effects of the nutrients in the wastes. Impressive growth responses have been reported following the application of municipal sewage sludge to forests of coastal Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) (Cole et al. 1984), white spuce (*Picea glauca* (Moench) Voss) (Gagnon 1973), loblolly pine (*Pinus taeda* L.) (McKee et al. 1986), Corsican pine (*Pinus nigra* var. *maritima* (Ait.) Melville) (Moffat et al. 1991), and Sitka spruce (*Picea sitchensis* (Bong.) Carr.) (Bayes et al. 1987). High rates of nitrate leaching from sludge-amended forests (Reikerk 1978) prompted trials with sewage sludge mixed with wood wastes such as sawdust or pulp and paper sludges to raise the C/N ratio of the sludge. Mixtures of

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these wastes in appropriate proportions have been effective at reducing nitrate losses and promoting tree growth (Henry 1986; Vogt et al. 1980).

In coastal British Columbia, substantial amounts of municipal sewage sludge and wood wastes are produced, from the Greater Vancouver Regional District and pulp and paper mills, respectively. Another waste product of concern in coastal British Columbia is dead fish ("morts") from fish farms. Currently, morts are ground and preserved in acid (formic, propionic, or citric) and stored in drums. The resulting silage is acidic (pH 3.8), but could be neutralized with wood ash (pH 12–13; Unger and Fernandez 1990). Large amounts of wood ash are produced in coastal British Columbia by burning waste wood from pulp mills and sawmills. Wood ash is high in P, K, and base cations (Erich 1991; Unger and Fernandez 1990), and, especially in combination with a nitrogen-rich material such as fish silage, could be an effective fertilizer. In this study, we address the possibility of using these wastes to fertilize nutrient-deficient conifer plantations.

Stagnated plantations of western red cedar (*Thuja plicata* Donn ex D. Don) and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) on northern Vancouver Island responded to the addition of N and P in inorganic fertilizers (Weetman et al. 1989). Growth responses equal to those achieved with inorganic fertilizers were reported 1 year after the application of municipal sewage sludge to nearby plantations of western red cedar, western hemlock, and Pacific silver fir (*Abies amabilis* (Dougl.) Forbes) (Weetman et al. 1993). We established another trial in an adjacent 9-year-old cedar plantation to compare the fertilization efficacy of a variety of organic wastes and inorganic fertilizer. Sewage sludge was applied alone and mixed with pulp sludge. A mixture of fish silage and wood ash was applied alone and in combination with pulp sludge. Wood ash alone, and a conventional inorganic fertilizer (ammonium nitrate with triple super phosphate), were also applied. Here we present the effects of each of these treatments on the growth and foliar nutrition of cedar trees one and two growing seasons after fertilization.

Methods

The study site was in the wetter Coastal Western Hemlock biogeoclimatic zone (CWHb) (Pojar et al. 1987), at 300 m, between the towns of Port McNeill and Port Hardy, B.C. (50°60′N, 127°35′W). The climate is very wet maritime with an average annual precipitation of 1700 mm, and mean daily temperatures range from 3.0°C in January to 13.7°C in July. The topography is gently rolling, and the soils are well to poorly drained Ferro-Humic Podzols on unconsolidated morainal and fluvial outwash material (Weetman et al. 1993). The soil in CH cutovers is described as a sandy loam with a thin (4 cm) grey-brown Ae horizon over a yellowish red to yellowish brown Bf horizon (Germain 1985). Average chemical properties of soils in CH cutovers are as follows: pH 4.2, 0.18% N, 0.03% P, and C/N 45 (Germain 1985). The plantation of western red cedar was established in 1982 after clearcutting and slash-burning an old-growth cedar–hemlock forest with a salal (*Gaultheria shallon* Pursh) understorey. Salal was abundant in the cutover. At the beginning of the experiment, the density of the cedar plantation was 665 stems/ha, the average height was 175 cm (range 35–404 cm), and the average diameter (at 30 cm) was 29 mm (range 1–95 mm). The trial was replicated in three blocks, each containing seven plots. Each plot ranged in size from 15 × 15m to 15 × 35m and enclosed at least 12 cedar trees. The seven plots were randomized within each block. There were no buffer strips, but all sampled trees were at least 5 m from the edge of the plot. Each of the seven plots in each block received one of the seven treatments listed in Table 1. Inorganic fertilizer and sewage sludge were applied in December 1990, and the remaining four treatments in March 1991.

TABLE 1. Amounts of each organic waste mixture applied in each treatment, and the resulting rates of N addition

Treatment	$Mg \cdot ha^{-1}$	$kg\ N \cdot ha^{-1}$
Control	0	0
Inorganic fertilizer	—	225
Sewage sludge	69	542
Sewage sludge + pulp sludge	69[a]	610
Fish silage + ash + pulp sludge	25[b]	540
Fish silage + ash	25[c]	504
Ash	5	0

[a]There was 69 $Mg \cdot ha^{-1}$ of sewage sludge and 69 $Mg \cdot ha^{-1}$ of pulp sludge.
[b]There was 25 $Mg \cdot ha^{-1}$ of fish silage – ash and 25 $Mg \cdot ha^{-1}$ of pulp sludge.
[c]There was 18.75 $Mg \cdot ha^{-1}$ of fish silage and 6.25 $Mg \cdot ha^{-1}$ of wood ash.

Anaerobically digested sewage sludge from the Greater Vancouver Regional District was dewatered, transported by truck to the site, and rewatered in a 27-m^3 open-topped metal tank equipped with a manure agitator. The sewage sludge contained 3.0% N. The sludge was sprayed onto plots using a trash pump and a 4 cm diameter hose. The application rate was 69 $Mg \cdot ha^{-1}$ (26% solids), which supplied about 542 kg $N \cdot ha^{-1}$ and 162 kg $P \cdot ha^{-1}$. Fish silage from IBEC Aquaculture Corp. in Port Hardy, B.C., and wood ash from the Western Pulp Ltd. mill in Port Alice, B.C., were transported to the site in trucks. The N concentrations were 2.0% in the silage and 0.08% in the wood ash. Wood ash was added to fish silage (3:1 silage–ash by weight) in the tank, mixed with the manure agitator, and sprayed onto plots at a rate of 25 $Mg \cdot ha^{-1}$, which supplied about 504 kg $N \cdot ha^{-1}$. Pulp mill clarifier sludge from Western Pulp Ltd. in Port Alice was transported to the site in trucks and mixed with sewage sludge and with fish silage–ash in tanks. The pulp sludge was 44.0% C and 0.16% N (C/N = 275). Sewage sludge (69 $Mg \cdot ha^{-1}$) was mixed with equivalent weights of pulp sludge and sprayed onto plots at a rate of 610 kg $N \cdot ha^{-1}$ and 30 Mg $C \cdot ha^{-1}$. Fish silage and ash (25 $Mg \cdot ha^{-1}$) was mixed with an equivalent amount of pulp sludge and sprayed onto plots at a rate of 540 kg $N \cdot ha^{-1}$ and 11 Mg $C \cdot ha^{-1}$. Wood ash was applied by hand at a rate of 5 $Mg \cdot ha^{-1}$, which was the same amount added with the silage. Inorganic fertilizer in the form of ammonium nitrate and triple superphosphate was applied by hand at a rate of 225 kg $N \cdot ha^{-1}$ and 75 kg $P \cdot ha^{-1}$. The seven treatments are summarized in Table 1. The higher loadings of N in the organic fertilizers were designed to compensate for N being less available than in inorganic fertilizers.

The height and diameter (at 30 cm) of all cedar trees in each plot were measured in August 1990 (prior to treatment) and again in August 1991 and 1992 . The sizes of trees in 1991 and 1992 were compared among plots by analysis of covariance and Duncan's multiple range test (SAS Institute Inc. 1988). The mean values were adjusted for the covariate (original 1990 height or diameter). Inclusion of the covariate increased the precision in determining the effects of the treatments on tree growth.

In December 1991 and 1992, one branchlet was taken from the midcrown of five trees in each plot, and bulked into one sample from each plot. Current-year foliage was separated as described by Radwan and Harrington (1986), oven-dried at 70°C, and ground in a Wiley mill. Samples were digested in sulphuric acid and hydrogen peroxide using a modification of the method of Parkinson and Allen (1975). Concentrations of N and P in each sample were measured with an AutoAnalyzer, and concentrations of K, Mg, and Ca were measured by atomic absorption. All analyses were done at the MacMillan Bloedel Lab,

TABLE 2. Height and diameter of western red cedar trees one and two growing seasons after application of organic and inorganic fertilizers

Treatment	Height (cm)		Diameter (mm)	
	Year 1	Year 2	Year 1	Year 2
Control	187.1 (1.7)*d*	210.9 (3.2)*d*	30.7 (0.7)*c*	34.3 (0.8)*d*
Inorganic fertilizer	208.2 (1.6)*a*	273.9 (2.9)*a*	35.0 (0.7)*a*	49.3 (0.7)*a*
Sewage sludge	202.0 (1.8)*b*	259.8 (3.3)*b*	35.9 (0.7)*a*	42.4 (0.8)*c*
Sewage sludge + pulp sludge	199.4 (1.7)*b*	252.6 (3.2)*bc*	29.8 (0.7)*bc*	43.5 (0.8)*c*
Fish silage + ash + pulp sludge	193.6 (1.9)*c*	243.9 (3.5)*c*	34.9 (0.8)*a*	46.0 (0.9)*b*
Fish silage + ash	203.0 (1.6)*b*	260.4 (2.7)*b*	31.7 (0.6)*b*	46.6 (0.7)*b*
Ash	179.7 (1.6)*e*	201.8 (2.9)*d*	28.8 (0.7)*c*	32.3 (0.7)*d*

NOTE: Each value is the mean (with standard errors given in parentheses) of 3 plots. Within years, means followed by the same letter are not significantly different ($p > 0.05$), based on analysis of covariance and Duncan's multiple range test.

TABLE 3. Nutrient concentrations in western red cedar foliage one and two growing seasons after application of organic and inorganic fertilizers

Treatment	%N	%P	%K	%Ca	%Mg	%S
Year 1						
Control	1.01 (0.03)*c*	0.18 (0.01)*c*	0.75 (0.03)*c*	0.56 (0.01)*c*	0.18 (0.02)*b*	nm
Inorganic fertilizer	2.47 (0.15)*a*	0.30 (0.01)*a*	1.11 (0.06)*b*	0.77 (0.03)*a*	0.21 (0.03)*a*	nm
Sewage sludge	1.60 (0.17)*b*	0.25 (0.02)*b*	1.12 (0.09)*b*	0.62 (0.04)*bc*	0.20 (0.02)*b*	nm
Sewage sludge + pulp sludge	1.52 (0.11)*b*	0.26 (0.02)*b*	0.99 (0.08)*b*	0.64 (0.02)*bc*	0.19 (0.02)*b*	nm
Fish silage + ash + pulp sludge	2.60 (0.12)*a*	0.32 (0.01)*a*	1.40 (0.08)*a*	0.66 (0.02)*b*	0.22 (0.02)*a*	nm
Fish silage + ash	2.61 (0.11)*a*	0.33 (0.01)*a*	1.38 (0.04)*a*	0.72 (0.03)*ab*	0.21 (0.02)*a*	nm
Ash	0.88 (0.05)*c*	0.16 (0.01)*c*	0.77 (0.05)*c*	0.58 (0.02)*bc*	0.20 (0.02)*b*	nm
Year 2						
Control	1.07 (0.10)*c*	0.17 (0.02)*b*	0.57 (0.05)*a*	0.50 (0.06)*a*	0.17 (0.02)*a*	0.10 (0.01)*b*
Inorganic fertilizer	1.50 (0.07)*a*	0.28 (0.04)*a*	0.55 (0.13)*a*	0.64 (0.12)*a*	0.13 (0.01)*a*	0.13 (0.01)*a*
Sewage sludge	1.29 (0.13)*b*	0.24 (0.04)*a*	0.59 (0.07)*a*	0.64 (0.11)*a*	0.15 (0.03)*a*	0.12 (0.01)*ab*
Sewage sludge + pulp sludge	1.37 (0.12)*b*	0.25 (0.01)*a*	0.49 (0.04)*a*	0.60 (0.08)*a*	0.16 (0.01)*a*	0.13 (0.02)*a*
Fish silage + ash + pulp sludge	1.64 (0.05)*a*	0.28 (0.02)*a*	0.58 (0.11)*a*	0.67 (0.16)*a*	0.15 (0.01)*a*	0.13 (0.01)*a*
Fish silage + ash	1.57 (0.13)*a*	0.29 (0.06)*a*	0.69 (0.22)*a*	0.60 (0.01)*a*	0.16 (0.03)*a*	0.14 (0.02)*a*
Ash	1.06 (0.04)*c*	0.17 (0.01)*b*	0.57 (0.03)*a*	0.57 (0.03)*a*	0.17 (0.01)*a*	0.11 (0.01)*b*

NOTE: Each value is the mean and (standard error) of 3 plots. Within each nutrient and year, means followed by the same letter are not significantly different ($p > 0.05$), based on analysis of covariance and Duncan's multiple range test. nm, not measured.

Nanaimo, B.C. Differences in concentrations of each element between treatments were compared by analysis of variance and Duncan's multiple range test (SPSS Inc. 1988).

Results and discussion

The growth of western red cedar trees in this plantation was improved by each of the fertilization treatments, except wood ash (Table 2). The greatest height after 1 and 2 years occurred in plots treated with inorganic fertilizer. Greater height was achieved with fish silage and sewage sludge alone, than in mixtures with pulp sludge. The height of trees treated with wood ash was slightly ($p > 0.05$) less than control trees after 1 and 2 years. The diameter of trees after 1 year was greatest in the plots treated with inorganic fertilizer, sewage sludge, and fish silage plus pulp. After 2 years, the trees in plots treated with inorganic fertilizers had the largest mean diameter, followed by those in plots that received fish silage (with or without pulp sludge), and then those that received sewage sludge (with or without pulp sludge).

In all covariance analyses, treatment, block, and the covariate (initial height or diameter) all significantly ($p < 0.0001$) influenced tree growth. Both height and diameter varied significantly between the three blocks, because trees in the third block grew more than those in the other blocks. In all analyses there was a significant ($p < 0.001$) block × treatment interaction, due to variation in the responses to treatments among the blocks. This did not change the ranking of the treatments.

All treatments except wood ash increased the foliar concentrations of N, P, K, Ca, and Mg one growing season after fertilization (Table 3); fish silage (with and without pulp sludge) and inorganic fertilizer were the most effective treatments. After two growing seasons, treatment differences were smaller, but concentrations of N and P were still significantly higher in all treated plots, except wood ash. Foliar S concentrations were measured after the second growing season, at which time they were higher in treated plots (except wood ash). It is surprising that the fish silage treatments raised the foliar concentrations of N, P, and K above those of trees treated with inorganic fertilizer, but produced a smaller growth response. Foliar concentrations of N, P, and K in trees treated with inorganic fertilizer or fish silage were above the "adequate" values of 1.65, 0.16, and 0.85%, respectively, for western red cedar (Ballard and Carter 1985). This may explain why silage-treated trees did not grow faster than fertilized trees, but it is not clear why they grew more slowly. There were no indications of any fertilization-induced deficiencies of macronutrients in the cedar foliage in any of the treatments. The lower foliar concentrations of N and P in trees treated with sewage sludge suggest that less N and P was released from the sewage sludge during 1 year than from equivalent amounts of N and P in fish silage, and smaller amounts of N and P in inorganic fertilizer. Concentrations of all nutrients in ash-treated plots were similar to those in control plots, suggesting that the trees did not take up the nutrients that were added in the ash. Wood ash is a suitable fertilizer for these forests only in combination with a N-rich fertilizer such as fish silage.

The effects of these fertilization treatments on competing vegetation, although not quantified, is of interest. Cedar–hemlock cutovers in this area are dominated by the ericaceous shrub, salal, which contributes to the nutrient supply problem in these plantations (Messier and Kimmins 1992). Bayes et al. (1987) reported the elimination of the ericaceous shrub, heather (*Calluna vulgaris* L.), in a Sitka spruce plantation in northern Scotland, after application of municipal sewage sludge. Reductions in salal cover were reported in Douglas-fir forests fertilized with N (Prescott et al. 1993). In this trial, however, the growth of salal was particularly luxuriant in the plots treated with the organic wastes, except wood ash. We observed that the plots in the third block, which had the greatest tree growth response, also had the most luxuriant growth of salal and fireweed (*Epilobium angustifolium* L.). The growth responses of the cedar trees cannot, therefore, be attributed to reductions in competing vegetation.

We expected western red cedar on this site to respond to fertilization, since responses to inorganic fertilizers and sewage sludge have already been documented (Weetman et al. 1989, 1993). Nitrogen concentrations in cedar foliage in the control plots (1.01% N) are in the range considered to be indicative of a very severe deficiency (Ballard and Carter 1986). Similar concentrations of N and P were measured in young stands of western red cedar in coastal Washington (Radwan and Harrington 1986), as were growth responses to N and P fertilization (Harrington and Wierman 1990). Nutrient-deficient plantations of western red cedar could provide a beneficial end use for organic wastes. Weetman et al. (1993) found that western hemlock and Pacific silver fir trees responded even more favourably to sewage sludge and inorganic fertilizers than did western red cedar trees. The growth of coastal Douglas-fir has also been improved by applications of sewage sludge in several trials (Archie and Smith 1980; Cole et al. 1984). Regenerating forests of these species in coastal British Columbia could provide a viable means of recycling a variety of organic "wastes".

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