Five-year growth response of western red cedar, western hemlock, and amabilis fir to chemical and organic fertilizers

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Abstract: The hypothesis that growth responses of conifers to application of organic fertilizers are of longer duration than responses to chemical fertilizers was tested in two trials on northern Vancouver Island. Both trials were in 10-year-old plantations of conifers on a salal-dominated cutover known to have poor N supply. In Trial 1, western red cedar (*Thuja plicata* Donn ex D. Don), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), and amabilis fir (*Abies amabilis* (Dougl.) Forbes) were treated with municipal biosolids at 542 kg $N \cdot ha^{-1}$ and 162 kg $P \cdot ha^{-1}$ or ammonium nitrate and triple superphosphate at 225 kg $N \cdot ha^{-1}$ and 75 kg $P \cdot ha^{-1}$. Height increments in the 5 years following applications were two to five times greater in plots treated with either biosolids or fertilizer than in untreated plots. In Trial 2, western red cedar was treated with fertilizer at 225 kg $N \cdot ha^{-1}$ and 75 kg $P \cdot ha^{-1}$ or the following organic amendments at 504–610 kg $N \cdot ha^{-1}$: biosolids, biosolids and pulp and paper sludge, fish silage and wood ash, fish silage with wood ash and pulp and paper sludge, and wood ash alone. Height increments in the 5 years following applications were similar in all treated plots (except wood ash alone). These experiments provided no evidence for sustained growth responses in plots treated with organic fertilizers compared with those treated with chemical fertilizer.

Résumé : L'hypothèse selon laquelle l'effet des fertilisants organiques sur la croissance des conifères dure plus longtemps que celui des fertilisants chimiques a été testée dans deux essais effectués dans la partie nord de l'île de Vancouver. Les deux essais ont eu lieu dans des plantations de conifères âgées de 10 ans et situées sur un site dominé par la gaultherie et coupé à blanc, réputé pour sa déficience en azote. Dans le premier essai, le cèdre de l'Ouest (*Thuja plicata* Donn ex D. Don), la pruche de l'Ouest (*Tsuga heterophylla* (Raf.) Sarg.) et le sapin gracieux (*Abies amabilis* (Dougl.) Forbes) furent traités avec un fertilisant organique (boues des eaux usées municipales) contenant 542 kg $N \cdot ha^{-1}$ et 162 kg $P \cdot ha^{-1}$ ou avec du nitrate d'ammonium et du triple superphosphate aux taux de 225 kg $N \cdot ha^{-1}$ et de 75 kg $P \cdot ha^{-1}$. Au cours des 5 années suivant les applications, la croissance en hauteur était deux à cinq fois plus élevée dans les parcelles traitées avec le fertilisant organique ou les fertilisants chimiques que dans les parcelles témoins. Dans le deuxième essai, le cèdre de l'Ouest a été traité avec les fertilisants chimiques à raison de 225 kg $N \cdot ha^{-1}$ et de 75 kg $P \cdot ha^{-1}$ ou avec les amendements organiques suivants à raison de 504–610 kg $N \cdot ha^{-1}$: des boues des eaux usées municipales, des boues des eaux usées municipales avec des boues d'une usine de pâtes et papiers, des déchets de poisson avec de la cendre de bois, des déchets de poisson avec de la cendre de bois et des boues d'une usine de pâtes et papiers et avec de la cendre de bois seule. Au cours des 5 années suivant les applications, la croissance en hauteur était semblable dans toutes les parcelles traitées, excepté dans les parcelles traitées avec de la cendre de bois seule. Ces expériences ne fournissent aucun indice d'une réponse soutenue en croissance dans les parcelles traitées avec des fertilisants organiques comparativement aux parcelles traitées avec des fertilisants chimiques conventionnels.

[Traduit par la rédaction]

Introduction

Municipal biosolids and other organic residuals contain all essential plant nutrients and organic matter, and should therefore be effective as a fertilizer and soil conditioner in forests. Indeed, substantial growth responses have been reported in many species of conifers fertilized experimentally with municipal biosolids (Henry et al. 1993; McDonald et al. 1994). It has further been suggested that additions of biosolids, unlike chemical fertilizers, may lead to substantial improvement in site quality and sustained increases in productivity through permanently higher organic matter and nutrients (Brockway et al. 1986; Henry 1990). Biosolids might promote a longer growth response than chemical fertilizers because: (*i*) the nutrients in the organic matrix will be mineralized over time, prolonging the increase in nutrient availability; (*ii*) several nutrients are added, so they may be retained in the ecosystem through increased growth and cycling (Cole et al. 1982); and (*iii*) trees may also benefit from improvements in soil structure and moisture retention afforded by biosolids (Khaleel et al. 1981). Although tree growth response to biosolids is purported to be typically

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greater and longer lasting than chemical fertilization (Henry et al. 1993), there have not been sufficient direct comparisons of the magnitude and duration of tree growth responses to biosolids with that achieved with conventional chemical fertilizers. This information is essential for decisions regarding the inclusion of organic fertilizers in forest fertilization programs.

Plantations of western red cedar (*Thuja plicata* Donn ex D. Don), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), and amabilis fir (*Abies amabilis* (Dougl.) Forbes) on cedar–hemlock sites on northern Vancouver Island demonstrated substantial growth responses following applications of municipal biosolids (Weetman et al. 1993). During the first two growing seasons after applications, conifer growth was enhanced in plots treated with biosolids, similar to that observed in plots that received chemical fertilizer (ammonium nitrate and triple superphosphate). Growth responses to chemical fertilizers on these sites are substantial, but have been shown to decline about three years after fertilization (Weetman et al. 1989*a*, 1989*b*). We hypothesized that this decline in growth response after 3 years would not be as great in trees treated with municipal biosolids, which would continue to mineralize nutrients in subsequent years. This hypothesis was tested by comparing height increments of trees during the fourth and fifth years after application of each of the fertilizer treatments. The hypothesis of extended growth response was also tested in a second trial in which western red cedar was amended with municipal biosolids, ensiled fish waste, and mixtures of these materials with pulp sludge (McDonald et al. 1994). It was hypothesized that the higher C/N ratios in the pulp sludge mixtures would immobilize excess N from the biosolids (Henry 1986), which would further slow N mineralization and extend the growth response period.

Methods

The study area is in the wetter Coastal Western Hemlock biogeoclimatic zone (CWHb) (Pojar et al. 1987) between the towns of Port McNeill and Port Hardy, B.C. (50°60′N, 127°35′W). Annual average precipitation is 1700 mm and mean daily temperatures range from 3.0°C in January to 13.7°C in July (data from Atmospheric Environment Service station in Port Hardy). Topography is gently undulating, and elevations are all less than 300 m. Soils are well-drained to imperfectly drained ferro-humic podzols of sandy loam texture on deep unconsolidated morainal and fluvial outwash material. Cedar–hemlock sites have deep humus accumulations prior to harvesting and variable amounts thereafter. Both trials were on a single cutover of a cedar–hemlock site that was clearcut and burned in 1981 and planted with conifers in 1982. The ericaceous shrub, salal (*Gaultheria shallon* Pursh), was abundant throughout the cutover.

Trial 1

Municipal biosolids or chemical fertilizer (ammonium nitrate and triple superphosphate) were applied to 9-year-old plantations of cedar, hemlock, and fir in December 1990. There were three blocks; each block received one treatment. Each block contained four randomly distributed 15 × 15 m plots of each tree species. There were 36 plots in total, including 12 control (unfertilized) plots. Dewatered, anaerobically digested biosolids from the Greater Vancouver Regional District was rewatered on site and manually sprayed onto the plots. The application rate was 69 $Mg \cdot ha^{-1}$ dry mass, which supplied about 542 kg $N \cdot ha^{-1}$ and 162 kg $P \cdot ha^{-1}$. The biosolids were 26% solids and 2.4% N, with a C/N ratio of 10. About 15% of the N was in inorganic forms. Ammonium nitrate and triple superphosphate were applied by hand at rates of 225 kg $N \cdot ha^{-1}$ and 75 kg $P \cdot ha^{-1}$, which is the standard operational treatment for these sites. The higher loading of N in the biosolids was designed to compensate for the lower inorganic N content.

The heights of the 50–84 trees in each plot were measured in December of 1990 through 1993 and in December 1995. Height increments of each tree during 1992 and 1993 (2 and 3 years after treatment) and during 1994 and 1995 (3 and 4 years after treatment) were calculated and the means were compared among treatments by univariate analysis of repeated measures using SPSS. Height increments during the first growing season after fertilization (1992) were not assessed because growth of fir is determinant and therefore responses would not occur until the second growing season.

Trial 2

Municipal biosolids, municipal biosolids mixed with pulp sludge, fish silage mixed with wood ash, silage and ash mixed with pulp sludge, wood ash alone, and chemical fertilizer (ammonium nitrate and triple super phosphate) were applied to a 9-year-old plantation of western red cedar in December 1990. The trial was replicated in three blocks, each containing six treatment plots and one control (untreated) plot which were randomly distributed within each block. As in Trial 1, biosolids were applied at 542 kg $N \cdot ha^{-1}$, and inorganic fertilizer was applied at 225 kg $N \cdot ha^{-1}$ and 75 kg $P \cdot ha^{-1}$. Ensiled fish waste (2.0% N) was mixed with wood ash (3:1 by mass) on site and sprayed onto plots at a rate of 25 $Mg \cdot ha^{-1}$, which supplied about 504 kg $N \cdot ha^{-1}$. Wood ash has very low N concentrations (0.08%) but contains many micronutrients and has a high pH, which increased the pH of the silage. Fish silage and ash (25 $Mg \cdot ha^{-1}$) were mixed with an equivalent mass of pulp sludge and sprayed onto plots at a rate of 540 kg $N \cdot ha^{-1}$. Wood ash was applied by hand at 5 $Mg \cdot ha^{-1}$. Pulp mill clarifier sludge was added to the biosolids and to the silage to increase the C/N ratio of the fertilizers. The N content of the primary pulp sludge was 0.16% and the C/N was 275. Biosolids (69 $Mg \cdot ha^{-1}$) were mixed with an equivalent mass of pulp sludge and sprayed onto plots at a rate of 610 kg $N \cdot ha^{-1}$. As in Trial 1, the higher N loadings in the organic treatments were designed to compensate for less of the N being in available forms.

Heights of the 22–38 trees in each plot were measured at the same times as in Trial 1. The height increments during 1992 and 1993 (2 and 3 years after treatment) and during 1994 and 1995 (3 and 4 years after treatment) were calculated for all trees in each plot and the means were compared among treatments by univariate analysis of repeated measures using SPSS. The mean values were adjusted for original tree height (1990) before fertilizer application. The accepted level of significance was $p < 0.05$.

Results

Trial 1

Both biosolids and N + P fertilizer significantly increased the height growth of all three species (Figs. 1*a*, 2*a*, and 3*a*), and there were no significant differences between the two treatments. Height increments of all three species in fertilized and biosolids-amended plots during years 4 and 5 were much reduced from those during years 2 and 3, but were still significantly greater than in control plots (Figs. 1*b*, 2*b*, and 3*b*). There were no significant differences in height growth during the second interval between trees treated with biosolids and those treated with chemical fertilizer. In control

Fig. 1. (*a*) Height growth of western red cedar following application of chemical (N + P) fertilizer or biosolids. Each value is the mean of four plots of each treatment. For each year, different letters signify significant differences between treatments based on analysis of variance. (*b*) Height increments during years 2 and 3 (black bars) and during years 4 and 5 (white bars) after fertilizer application. The mean and SE of the four plots of each treatment are shown. For each interval, different letters indicate significant differences between treatments.

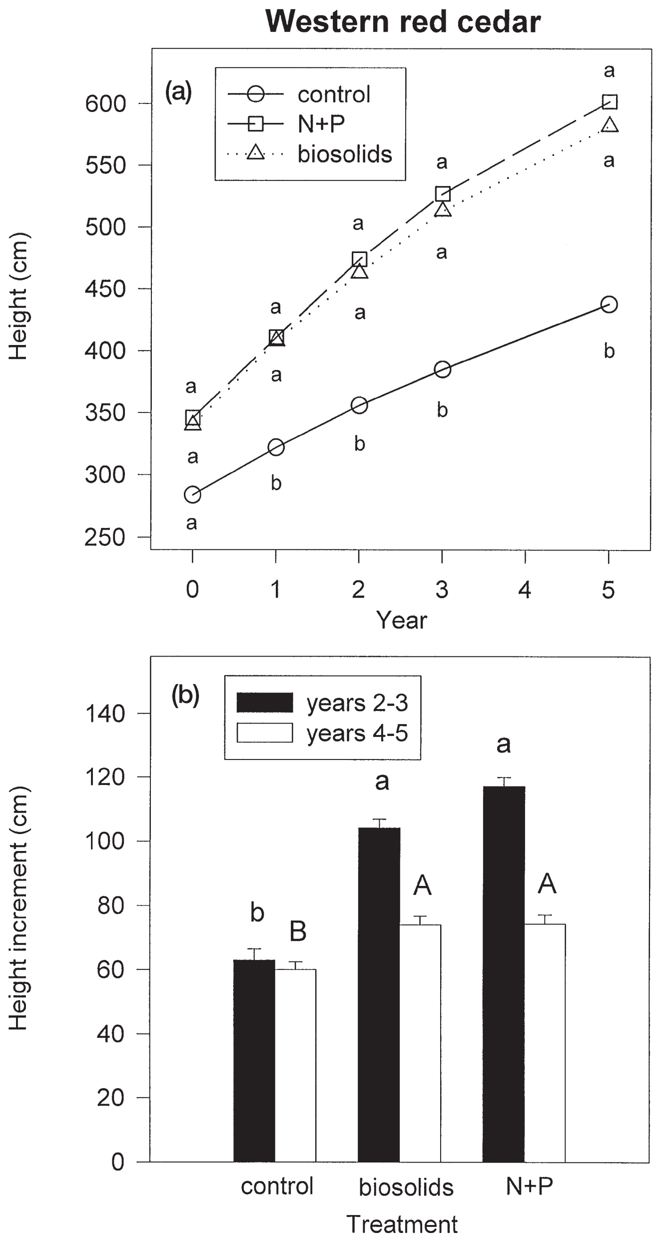
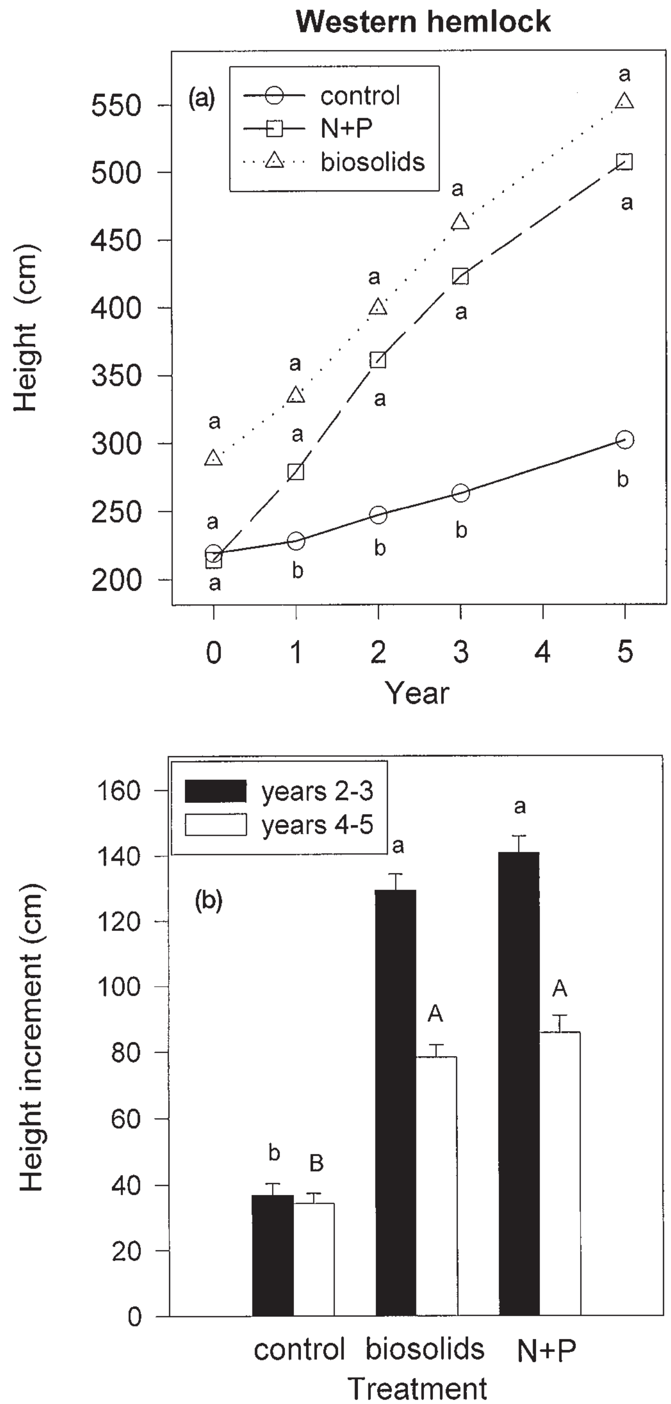


Fig. 2. (*a*) Height growth of western hemlock following application of chemical (N + P) fertilizer or biosolids. Each value is the mean of four plots of each treatment. For each year, different letters signify significant differences between treatments based on analysis of variance. (*b*) Height increments during years 2 and 3 (black bars) and during years 4 and 5 (white bars) after fertilizer application. The mean and SE of the four plots of each treatment are shown. For each interval, different letters indicate significant differences between treatments.

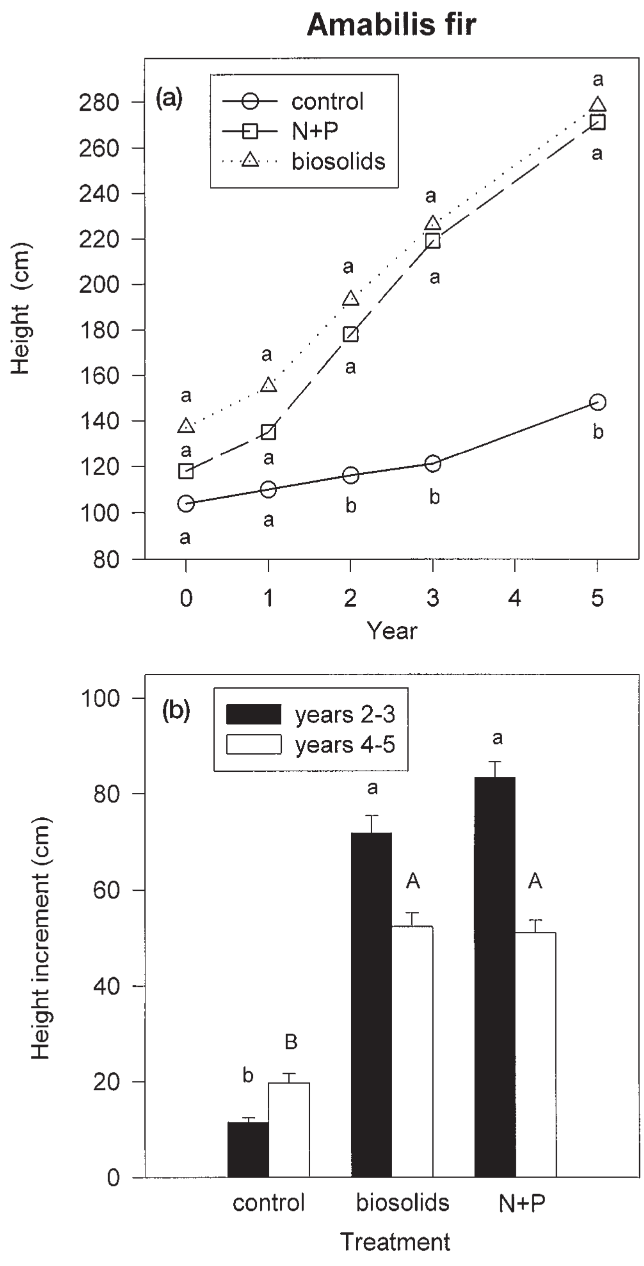


plots, height increments during years 4 and 5 were either similar or slightly greater than in years 2 and 3.

Trial 2

All of the organic amendments (except wood ash alone) stimulated height growth of western red cedar (Fig. 4*a*). Height increments during years 2 and 3 were significantly greater in plots treated with chemical fertilizer, biosolids, or fish silage (alone or amended with pulp sludge) than in control plots or plots treated with wood ash (Fig. 4*b*). Height growth during years 4 and 5 declined in all plots treated with chemical fertilizer or organic amendments. There were

Fig. 3. (*a*) Height growth of amabilis fir following application of chemical (N + P) fertilizer or biosolids. Each value is the mean of four plots of each treatment. For each year, different letters signify significant differences between treatments based on analysis of variance. (*b*) Height increments during years 2 and 3 (black bars) and during years 4 and 5 (white bars) after fertilizer application. The mean and SE of the four plots of each treatment are shown. For each interval, different letters indicate significant differences between treatments.



no significant differences in responses to the various organic and inorganic treatments during years 4 and 5. In control trees and in trees treated with wood ash, height growth in years 4 and 5 increased relative to years 2 and 3.

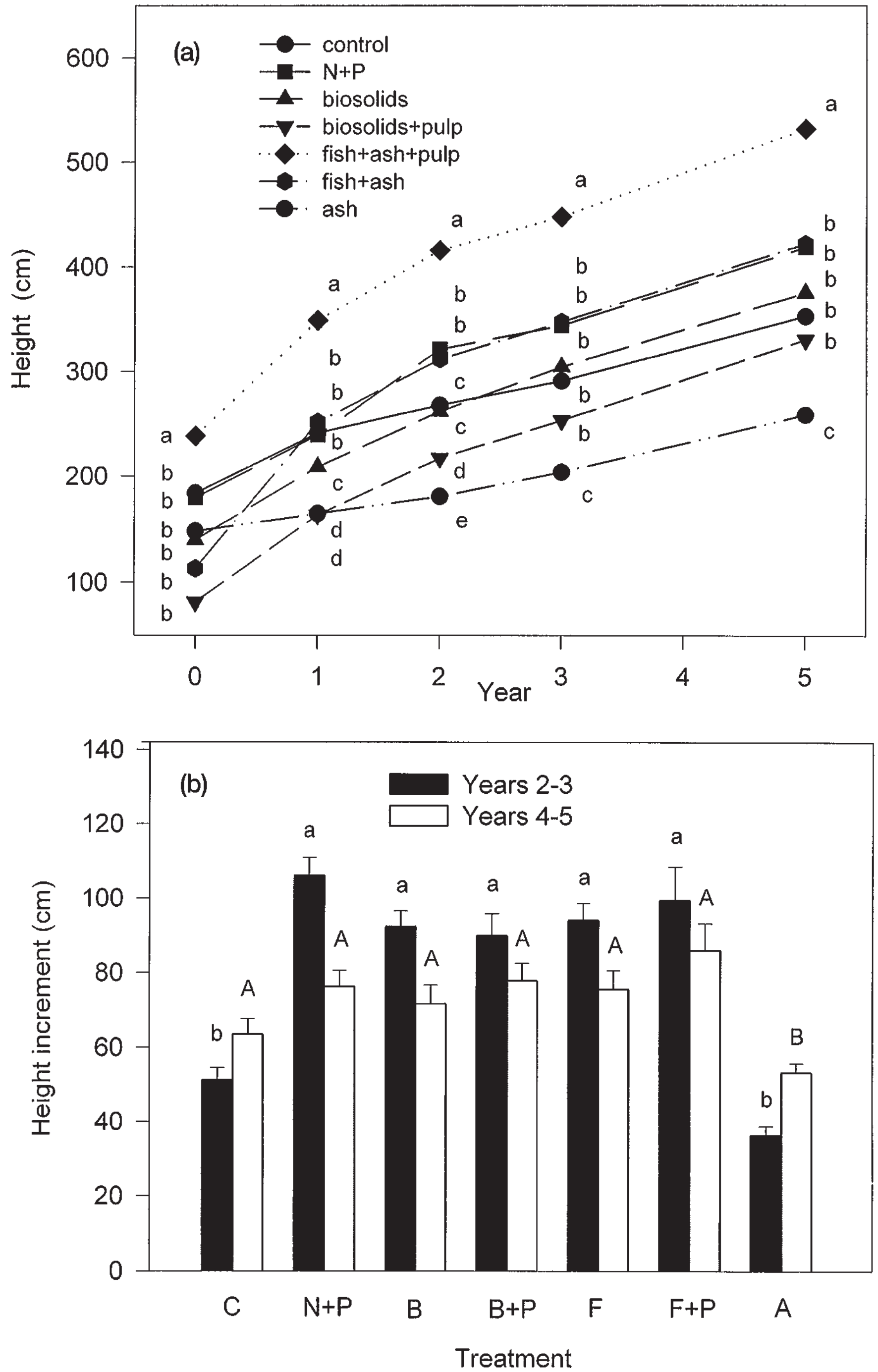
Discussion

All of the organic amendments (except wood ash) used in these trials increased growth of conifers in these nutrient-deficient plantations. However, the growth responses to the organic amendments were similar to those achieved with chemical N + P fertilizer, both in magnitude and duration. We had hypothesized that the municipal biosolids would provide a longer growth response because N is mineralized over a longer period of time compared with chemical fertilizers, which release all of the N during the first growing season. However, the declines in height increments during the third and fourth years after treatment indicate that release of N from the biosolids was mostly confined to the first one or two growing seasons after application. This was also indicated by foliar N concentrations that declined to pretreatment levels by the third growing season after fertilization (C. Prescott, unpublished data). There were also visual indications that N supply was diminishing by year 5 in both fertilized and biosolids-amended plots. In amabilis fir, leader growth and needle size and colour were maintained in the upper whorls, but were much diminished in lower whorls relative to controls, suggesting that there was translocation of N and sacrificing of needles on lower branches in response to reduced N supply. Growth responses to biosolids in this trial were therefore very similar to those achieved with the conventional practice of chemical fertilization of these sites. Although more than twice as much N was added in the biosolids, the response was the same as that achieved with 225 kg $N \cdot ha^{-1}$ in ammonium nitrate.

Several processes may account for the lack of additional response with the larger loading of N in biosolids. First, several studies have shown that much of the mineralized N in biosolids can be lost through volatilization or denitrification (Zasoski et al. 1984). Second, much of the organic N in biosolids may be mineralized so slowly that it may be insignificant as a fertilizer. A number of laboratory studies of N mineralization from biosolids have indicated that there are basically two pools of organic N in biosolids; a rapid pool consisting of labile organic forms and a slow pool consisting of more recalcitrant organic forms (Boyle and Paul 1989; Lerch et al. 1992; Gilmour et al. 1996*a*). The labile pool generally accounts for between 10 and 50% of the organic N and is generally lower in anaerobically digested sludges (Serna and Pomares 1992, Parker and Sommers 1983). The remaining biosolids appear to be converted to humuslike material (Gilmour et al. 1996*b*) and may in fact be more recalcitrant than native soil organic matter (Boyle and Paul 1989). The implications for this experiment are that less than half of the 500 kg $N \cdot ha^{-1}$ applied in the biosolids would have been mineralized at an appreciable rate and that this would probably have all occurred during the first growing season. The fertilization effect of the biosolids application would therefore have closely resembled the addition of 225 kg $N \cdot ha^{-1}$ in chemical fertilizer.

In the fish silage treatments, the organic material had been ground and ensiled in formic acid for several weeks prior to application, so it would have been largely broken down prior to application. Therefore, most of the N in the silage was also probably available immediately after application. NMR spectra of the fish silage indicated that much of the organic material in the silage was in the form of oils, which would be expected to be rapidly decomposed after application, leading to rapid N release (C. Preston, personal communication). Foliar N concentrations were greater in the fish silage

Fig. 4. (*a*) Height growth of western red cedar following application of fertilizers. For each year, different letters signify significant differences between treatments based on analysis of variance. (*b*) Height increments during years 2 and 3 (black bars) and during years 4 and 5 (white bars) after fertilizer application. C, control; N + P, chemical fertilizer; B, municipal biosolids; B + P, biosolids + pulp sludge; F, fish silage; FP, fish silage + pulp sludge; A, wood ash. The mean and SE of three plots per treatment are shown. For each interval, different letters indicate significant differences between treatments.



treatments than any other treatment during the first 2 years after application, despite similar application rates (McDonald et al. 1994), indicating that silage supplied more mineral N than biosolids in the first year or two after application. However, the additional N released from silage did not result in significantly greater height growth, suggesting that the cedar on these sites do not respond more to N additions greater than 250 kg·ha^{-1}.

Pulp sludge was added to the biosolids and fish silage to increase the C/N ratio of the mixture, which should cause some of the N to be immobilized and thus released more gradually. However, there was little evidence of significant N immobilization in the pulp sludge since foliar N concentrations and growth increments during the first two growing seasons were similar in biosolids or fish silage with and without pulp sludge (McDonald et al. 1994). There was also no evidence of prolonged release since rates of tree growth during the fourth and fifth year after application were similar in sludge amended and unamended biosolids and silage treatments. The materials in this study were crudely mixed compared with the intimate mixing of C and N in natural litters and residues, in which a relationship between C/N and N mineralization is often observed. This degree of mixing of the carbon and nutrients would not have been on a scale that makes them both accessible to the microorganisms that would degrade the materials and immobilize N. The nature of the carbon source would also play a role in determining the degree of microbial immobilization of N during decomposition. Pulp sludge may be too recalcitrant to stimulate sufficient microbial activity soon enough to retain the highly available N in microbial biomass. Substrates such as straw that have more labile C might be more effective at retaining N from biosolids and promoting a longer period of N release.

The apparent lack of long-term response to application of organic materials to these plantations may also be related to (*i*) the fairly low rates of addition and (*ii*) unique characteristics of this site such as deep organic layers, high precipitation, and competing vegetation. Improved site quality and permanent increases in productivity are only expected when very large amounts of nutrients are added relative to the site capital (Miller 1981), which was not the case in this study. Other studies in the Pacific Northwest that have demonstrated large and sustained productivity responses have involved addition of N in biosolids an order of magnitude greater than the 500 kg $N \cdot ha^{-1}$ applied in this study (Henry et al. 1993). Because of the associated risk of nitrate leaching from such high loadings, repeated smaller applications of biosolids would be preferable for sustaining productivity increases. The cedar–hemlock forests from which these cutovers originated have among the highest accumulations of organic matter recorded (Keenan et al. 1993), and slashburns on these sites are kept relatively cool such that much of the surface organic layer persists in the regenerating plantations. Such sites would therefore not benefit from the improved aggregation, water holding capacity, and bulk density afforded by organic matter additions (Khaleel et al. 1981). Improved moisture retention from organic matter additions would also be of little benefit on these sites because they receive about 1700 mm of rain annually and do not experience summer drought. Some of the growth response of Sitka spruce (*Picea sitchensis* (Bong.) Carr.) in Scotland to municipal biosolids was attributed to a reduction in the cover of *Calluna* on the site (Dutch and Wolstenholme 1994). In contrast, salal appeared to be stimulated by all of the fertilizer treatments, so there was no additional effect of vegetation control. Although reductions in salal cover have been observed after repeated fertilization with N alone (Prescott et al. 1993), it usually responds favourably to fertilization with N and P and, in these trials, organic fertilizers. The poor N supply on cedar–hemlock cutovers is at least partly attributable to binding of N by tannins released from salal (Preston 1996). This problem would still exist and might tie up some of the N that was released from the biosolids after the initial postapplication flush. A prolonged response to biosolids might occur on sites that do not have these characteristics. Tree heights will be remeasured 10 years after fertilization to determine if responses to fertilizers diverge after 5 years.

In summary, these trials demonstrated that large growth responses can be achieved with organic fertilizers on these cedar–hemlock cutovers. There was, however, no evidence of sustained growth response or prolonged elevation of N availability in plots treated with organic fertilizers. Responses to municipal biosolids and fish silage were similar in both magnitude and duration to responses from inorganic fertilizers. Increasing the C/N ratio of the material by mixing sewage sludge or fish silage with pulp sludge also did not extend the response period.

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