# Growth limitations of planted conifers regenerating under Montane Alternative Silviculture Systems (MASS): Seven-year results

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As part of the Montane Alternative Silviculture Systems (MASS) project, this study investigates limits on the growth of montane conifers resulting from varying overstory retention under conventional and alternative silvicultural systems. After harvesting treatments were complete in 1993, *Abies amabilis* (amabilis fir) and *Tsuga heterophylla* (western hemlock) seedlings were spring planted in replicated blocks of shelterwood (SW), patch cut (PC), green tree retention (GT) and clearcut (CC) systems. In addition, sub-plots were established within each silvicultural system in which fertilization (at planting) and vegetation control post-planting treatments were applied alone and in combination to test the extent to which growth limitations are related to nutrient availability and vegetative competition. The impact of overstory retention was most pronounced in the reduced light environment of the SW where height growth after seven years was 26–30% lower in both species compared to the untreated CC, GT and PC systems. Although the effect on growth of both species in the SW was mitigated somewhat by fertilization and vegetation control treatments, amabilis fir did not attain free–to-grow height (1.3 m) regardless of post-planting treatment. Time to free-to-grow height in the more open silvicultural systems was reduced in both fir and hemlock with fertilization and vegetation control alone and in combination, except in the CC where the initial growth response to fertilization alone was diminished by the end of the seven-year study. In contrast to fertilization, the effects of vegetation control on height growth were not apparent until three to five years and seven years after planting in the CC and GT, PC, SW, respectively. Combining vegetation control and fertilization had an additive effect on growth in amabilis fir but not in western hemlock. The effect of silvicultural systems and post-planting treatments on the two species illustrate that both above- and below-ground resource availability (light and nutrients) availability was potentially limiting to growth, particularly in the shelterwood treatment.

**Key words:** MASS, silviculture systems, regeneration, *Tsuga heterophylla*, *Abies amabilis*, shelterwood, patch cut, green tree retention, clearcut, fertilizer, vegetation control

En tant qu'élément du projet sur les systèmes alternatifs de sylviculture dans la zone montagneuse, cette étude porte sur la réduction de la croissance des conifères alpins à la suite d'une rétention variable du couvert forestier selon des systèmes sylvicoles conventionnels et alternatifs. Suite aux travaux de récolte complétés en 1993, des semis d'*Abies amabilis* (sapin amabilis) et de *Tsuga heterophylla* (pruche de l'Ouest) ont été plantés au printemps dans des blocs d'une étude des régimes de jardinage, de coupe partielle, de coupe par troué, de coupe avec rétention d'arbres verts et de coupe à blanc. De plus, des sous-parcelles ont été établies dans chaque régime sylvicole pour lesquels des traitements de fertilisation (au moment de la plantation) et de contrôle de la végétation post-plantation avaient été réalisés seul ou en combinaison afin d'évaluer jusqu'à quel point la réduction de la croissance est reliée à la disponibilité des éléments nutritifs et à la compétition de la végétation. L'effet de la rétention du couvert forestier était le plus prononcé sous l'environnement réduit en lumière de la coupe de jardinage où la croissance en hauteur après sept ans était de 26 à 30 % inférieure pour les deux espèces comparativement aux régimes témoins, de coupe à blanc, de coupe avec rétention d'arbres verts et de coupe partielle. Même si l'effet sur la croissance des deux espèces selon la coupe de jardinage a été mitigé d'une certaine façon par les traitements de fertilisation et de contrôle de la végétation, le sapin amabilis n'a pas atteint une hauteur permettant une croissance sans compétition (1,3 m) peu importe le traitement post-plantation. L'âge de la hauteur permettant une croissance sans compétition pour les systèmes sylvicoles plus ouverts a été réduit tant pour le sapin que pour la pruche suite au traitement de fertilisation et de contrôle de la végétation, seul ou en combinaison, sauf pour la coupe à blanc où la réaction initiale de croissance suite à la fertilisation a été réduite à la fin de l'étude de sept ans. Contrairement à la fertilisation, les effets du contrôle de la végétation sur la croissance en hauteur n'ont pas été apparents avant trois à cinq ans et après sept ans suite à la plantation respectivement dans les coupes à blanc, les coupes à rétention d'arbres verts, les coupes partielles et les coupes de jardinage. La combinaison du contrôle de la végétation et de la fertilisation a eu un effet additionnel sur la croissance du sapin amabilis mais pas pour la pruche de l'Ouest. L'effet des régimes sylvicoles et des traitements post-plantation sur les deux espèces illustre que la disponibilité tant des ressources tirées au-dessus qu'en dessous du sol (la lumière et les éléments nutritifs) limitait potentiellement la croissance, particulièrement dans le cas des coupes progressives.

**Mots-clés :** MASS, régimes sylvicoles, régénération, *Tsuga heterophylla*, *Abies amabilis*, coupes progressives, coupe par trouée, rétention d'arbres verts, coupe à blanc, fertilisant, contrôle de la végétation

## Introduction

Montane forests contain a large part of the British Columbia potential coastal timber harvest for the next 25 years (Koppenaal and Mitchell 1992). Local and global demand to sustain non-timber values has raised concern with clearcut-based silviculture. Coastal forest managers need to know where alternatives to clearcutting are operationally feasible, and economically and ecologically sound. In response to these concerns, a multi-agency cooperative, the Montane Alternative Silvicultural Systems (MASS) Partnership (Arnott and Beese 1997) was established to test new approaches to timber harvesting and subsequent regen-

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eration in the Montane Moist Maritime Coastal Western Hemlock biogeoclimatic variant (CWHmm2) of east Vancouver Island (Green and Klinka 1994). Coastal montane climates are characterized by a short growing season, winter snow pack, and slow decomposition rates that place unique biological and physical demands on shade-tolerant regeneration (Koppenaal and Mitchell 1992).

Studies investigating the relationship between the size of forest opening and growth of conifer regeneration in British Columbia have found that growth response and survival is influenced by regional climate (Wright *et al.* 1998b), species shade tolerance (Mitchell and Arnott 1995, Chen 1997, Kobe and Coates 1997), soil moisture (Carter and Klinka 1992), substrate (Wright *et al.* 1998a), nutrition (Koppenaal *et al.* 1995) and temperature (Minore 1986). The present study examines the relationship between opening size and growth of amabilis fir (*Abies amabilis* Dougl. ex Forbes) and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) seedlings in a coastal montane climate, particularly as it relates to above-ground (light) and below-ground (nutrients) resource limitations on growth in alternative silvicultural systems.

In accordance with the influence of residual overstory trees on regeneration microclimate we expected that differences in the size of forest opening and amount and distribution of retained trees among the silvicultural systems [Clearcut (CC), Green tree (GT), Patch cut (PC), and Shelterwood (SW)] would provide a wide range of light, temperature, evaporative demand, and moisture. Reductions of solar energy input through shade provided by the retained overstory trees can cause changes in light quality and quantity, soil and air temperature, vapour pressure deficit, and precipitation patterns (Franklin 1963, Seidel and Cooley 1974, Larcher 1983, Kaufmann 1985). Availability of nutrients, particularly nitrogen, can be affected by both microclimatic conditions in the post-harvest environment through changes in decomposition and mineralization rates, and by nutrient uptake from competing vegetation (Binkley 1984, Edmonds *et al.* 1989, Vogt *et al.* 1989, Vogt 1991, Prescott and Zabek 1999). Thus, the only remaining factor that we could influence experimentally was edaphic, although alteration of overstory structure was expected to have a less dramatic effect on the edaphic environment than on the photosynthetic environment. To assess below-ground resources as a primary limiting factor to seedling growth in the four silvicultural systems, we conducted fertilization and vegetation control treatments (Carlson 1981, Arnott and Burdett 1988, Dunsworth 1990, and Dunsworth and DeYoe 1990). Thus, the null being tested is that differences in above-ground (light) and below-ground (nutrient availability) resources were not limiting conifer growth in any of the silvicultural systems.

Using planted container-grown amabilis fir and western hemlock seedlings, the objectives of this study were to determine the effects of (1) varying amounts and configuration of overstory retention on seedling growth, (2) competing vegetation on seedling growth, and (3) soil nutrient availability on seedling growth within each of the silvicultural systems.

## Methods

### Study site

The site is located on Eastern Vancouver Island (latitude 49°50′N; longitude 125°25′E) south of Campbell River on private land (Weyerhaeuser Canada Ltd.) in the Montane Moist Maritime Coastal Western Hemlock biogeoclimatic variant (CWHmm2) (Green and Klinka 1994). The elevation ranges from 740 to 850 m on a northerly aspect. The site is characterized by cool temperatures (5.4°C annual mean), a short growing season (150 frost-free days) and snow cover (up to 130 cm) for five months of the year. Soils are predominantly Orthic and Gleyed Ferro-humic Podzols over one meter deep, with some shallow areas over sandstone, shale or conglomerate rock. Well-drained to moderately well-drained soils occur on the middle to upper slopes and hummocks with moderately well-drained to imperfectly drained soils occurring on the lower slopes and in depressions. Although the forest floor varies widely over short distances, a typical Mor humus form includes a thin (0.5 to 1.0 cm) litter layer, a 3- to 5-cm matted "F" layer and a well-decomposed "H" layer 5 to 15 cm thick. Decomposed wood is a predominant component of deeper humus layers (Arnott and Beese 1997).

The stand is a multi-storied uneven-aged old-growth forest (overstory 200–800 years old) with gross merchantable (> 17.5 cm dbh) volumes of 975–1038 $m^3$ $ha^{-1}$ dominated by western hemlock (44% of total basal area, b.a.) and amabilis fir (24% of total b.a.), with varying amounts of western redcedar (*Thuja plicata* Donn Ex D. Don) (24% to 28% of total b.a.) and yellow cedar (*Chamaecyparis nootkatensis* (D. Don) Spach) (4% to5% total b.a.) (Arnott and Beese 1997). Canopy heights of amabilis fir and western hemlock were 24–32 m, and those of western redcedar and yellow cedar were 34–42 m (Beese *et al.* 1995).

### Silviculture systems

Arnott and Beese (1997) describe these in detail. A brief summary of the silvicultural systems is provided here. The trial includes four silvicultural systems treatments applied in 1993, each of which was randomly assigned (with some restrictions in the case of the clearcut—see below) to three 9-ha treatment blocks as illustrated in Fig. 1. The four treatments were as follows:

- Clearcut: Conventional clearcutting included for comparison to alternative systems. Owing to operational constraints, which precluded unrestricted randomization of the clearcut treatment, all three 9-ha treatment "blocks" were located within a single 69-ha clearcut opening but, for the purposes of analysis, the randomization was considered unrestricted (i.e., variation in growing conditions among the three blocks within the 69-ha clearcut was assumed to be comparable to variation among the blocks assigned to the other three treatments).
- Patch Cut: Three 1.5-ha openings (120 m × 125 m) created within each of the 9-ha treatment blocks.
- Green Tree: A minimum of 25 trees/ha kept within the 9-ha treatment blocks. The residual trees were selected for relatively even distribution and windfirmness, representing the entire stand profile.
- Shelterwood: A total of 200 trees/ha, or approximately 30% of the original stand basal area, was retained within each of the 9-ha treatment blocks. The residual trees represented the entire stand profile and were selected for yarding feasibility, safety, windfirmness and residual stand structure.

### Regeneration experimental design

The study was designed as a split-plot experiment with each of the four silvicultural systems (Clearcut, Patch Cut, Green

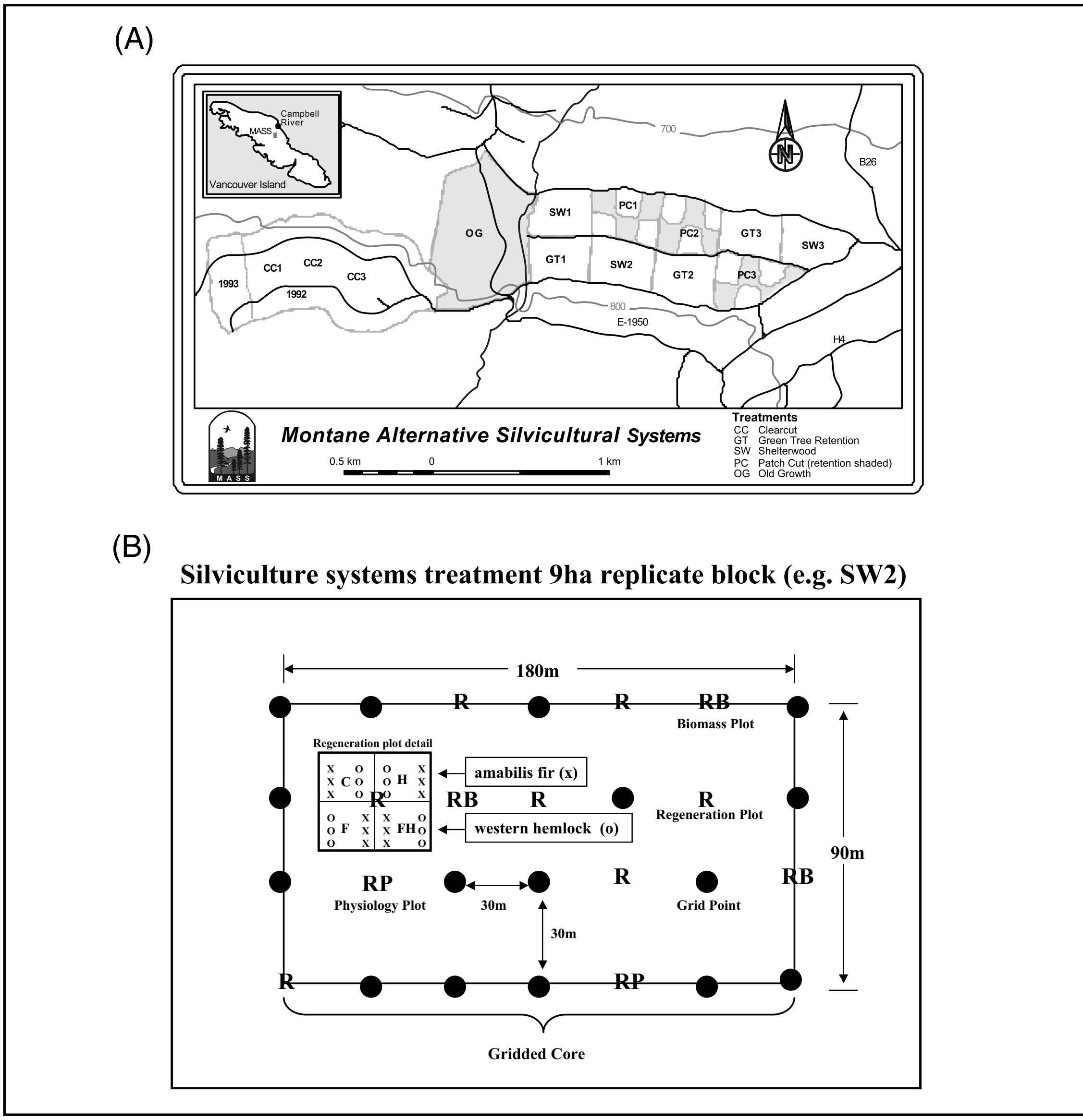


**Fig. 1.** Montane Alternative Silviculture Systems (MASS) Project (A) layout of silvicultural treatments and (B) example layout of regeneration plots. R, regeneration sub-plot; RB, Biomass sampling regeneration sub-plot, RP, Physiology sampling regeneration sub-plot. Regeneration plot detail: C, untreated; F, fertilized; H, vegetation control; FH, fertilized + vegetation control.

Tree, Shelterwood) assigned to three whole plots (i.e., 9-ha blocks). Within each of the replicated whole plots, points were randomly selected from a 30 m × 30 m permanent grid and used to locate, inside a 1.0-ha (PC, cut area only) or 1.6-ha (CC, GT, SW) central "core" area, 12 sub-plots (12 m × 16 m). Each sub-plot was divided into four quadrants (split-plots) to which each was randomly assigned one of four, post-planting treatments: control (C), fertilization (F), vegetation control (H), and vegetation control with fertilization (FH). Within each quadrant (6 m × 8 m), three seedlings each of amabilis fir and western hemlock (i.e., a total of six seedlings per quadrant) were assigned to six randomly located planting spots 2 m from each other and 2 m from the edges of the quadrant (Fig. 1B). As two of the sub-plots within each replicated whole plot were dedicated to destructive physiological sampling in 1996, and a further three were dedicated to destructive sampling for seedling dry weights in the spring of 1997, measurement and analyses for seedling height and stem volume in year 4, 5 and 7 were based on a total of seven sub-plots per replicated whole plot.

## Seedling culture and planting

The PSB 415B (Beaver Plastics Ltd., Edmonton, Alta.) plug seedlings were grown using conventional cultural techniques (Van Eerden and Gates 1990) at the Pacific Regeneration Technology Nuu-chah-nulth Nursery at Port Alberni, B.C., in 1993. Seedlings were held in cold storage (–2°C) at that company's facility at Campbell River, B.C., until required for planting in early May 1994. Planting took place between May 3 and May 12, and was done using planting "spears" (a blade measuring 24 cm in length and a width tapering from 10 cm at the top to 6 cm at the tip). A total of 25 trees of each species were sampled from the boxes containing each planted species to characterize initial height and root collar diameter and shoot and root dry weight (mean ± standard error, s.e.).

**Table 1. Least-square means (± s.e., standard error) of seven-year growth parameters in amabilis fir by silvicultural system and post-planting treatment. (n is the number of live seedlings)**

| Growth parameter | Silvicultural System | Post-planting treatment: Control | Fertilized | Herbicide | Fertilizer & herbicide | n | *p*-value |
|---|---|---|---|---|---|---|---|
| Height (cm) | Clearcut | 112.9 (10.1)a/z | 136.9 (9.9)a/y | 165.3 (10.1)b/z | 196.9 (10.0)c/z | 226 | *<.0001* |
| | Green tree | 114.5 (10.0)a/z | 145.0 (9.9)b/y | 145.8 (10.0)b/z | 175.0 (10.1)c/z | 234 | *<.0006* |
| | Patch cut | 109.9 (9.9)a/z | 140.2 (9.9)b/y | 153.8 (10.2)b/z | 187.4 (9.9)c/z | 236 | *<.0001* |
| | Shelterwood | 79.9 (10.8)a/y | 113.9 (10.1)b/y | 103.0 (10.3)ab/y | 124.8 (10.3)b/y | 205 | *<.0124* |
| | *p* value | *0.0808* | *NS* | *0.0005* | *<.0001* | | |
| Diameter (mm) | Clearcut | 23.24 (2.08)a/z | 27.64 (2.06)a/z | 39.78 (2.09)b/z | 45.00 (2.07)c/z | 226 | *<.0001* |
| | Green tree | 22.20 (2.06)a/z | 28.70 (2.05)b/z | 31.19 (2.06)b/y | 38.69 (2.08)c/y | 234 | *<.0001* |
| | Patch cut | 20.40 (2.05) a/yz | 27.71 (2.05)b/z | 33.80 (2.09)c/yz | 38.99 (2.05)d/yz | 236 | *<.0001* |
| | Shelterwood | 15.07 (2.19)a/y | 20.56 (2.07)b/y | 20.72 (2.11)b/x | 25.04 (2.12)b/x | 205 | *0.0045* |
| | *p* value | *0.0599* | *0.0394* | *<.0001* | *<.0001* | | |
| Stem volume ($cm^3$) | Clearcut | 254.5 (95.3)a/y | 364.8 (94.1)a/y | 830.7 (95.4)b/z | 1240.7 (94.6)c/z | 226 | *<.0001* |
| | Green tree | 211.4 (94.4)a/y | 370.2 (93.8)ab/y | 522.7 (94.3)b/y | 857.7 (94.8)c/y | 234 | *0.0002* |
| | Patch cut | 160.0 (93.6)a/y | 358.2 (93.8)ab/y | 532.3 (95.7)b/y | 855.7 (93.8)c/y | 236 | *<.0001* |
| | Shelterwood | 101.4 (99.8)a/y | 234.4 (94.9)a/y | 226.4 (96.3)a/x | 396.1 (96.8)a/x | 205 | *NS* |
| | *p* value | *NS* | *NS* | *0.0014* | *<.0001* | | |
| Height:diameter ratio | Clearcut | 48.31 (1.63)b/y | 50.52 (1.59)b/y | 42.18 (1.63)a/y | 43.11 (1.61)a/y | 226 | *<.0016* |
| | Green tree | 53.27 (1.60)c/z | 50.85 (1.58)bc/y | 47.30 (1.60)ab/z | 45.52 (1.60)a/yz | 234 | *<.0070* |
| | Patch cut | 54.44 (1.57)c/z | 52.53 (1.58)bc/y | 45.86 (1.64)a/yz | 48.46 (1.58)ab/z | 236 | *<.0024* |
| | Shelterwood | 51.79 (1.70)ab/yz | 54.77 (1.62)b/y | 49.32 (1.67)a/z | 49.45 (1.68)a/z | 205 | *<.0733* |
| | *p* value | *0.0598* | *NS* | *0.0302* | *0.0389* | | |

Least-square mean comparisons of post-planting treatments (rows) are indicated by a,b,c,d and silvicultural systems (columns) are indicated by x,y,z.
Means followed by the same letter are not significantly different (p>0.05) using Fisher's LSD test (p-values adjusted for multiple comparisons by Tukey's method).

### Post-planting treatments

For those trees in the fertilizer treatments, a one-time application (at planting) of 24 g of slow-release fertilizer (Nutricote 16-10-10, 180-day formulation) was placed in a speared slot within 10 cm of the seedling at the time of planting.

Vegetation control was applied on the H and FH post-planting treatment plots from 1994 to 1997. Prior to treatment with Vision® (glyphosate, 35.6% active ingredient, a.i.) herbicide, a mechanical cleaning of the taller vegetation, principally *Vaccinium spp.* and fireweed (*Epilobium angustifolium)* was done in mid-July 1994. Herbicide was applied as follows: 1994 1st application – 2.34L/ha (0.83 kg/ha a.i.), 1995 2nd application – 3.05 L/ha (1.09 kg/ha a.i.), 1996 – 3rd application 3.05 L/ha (1.09 kg/ha a.i.), 1997 – 4th application (2.1 L/ha (0.75 kg/ha a.i.), 1998 5th application – 2.5 L/ha (0.89 kg/ha a.i.) bringing the total application of the active ingredient to 4.65 kg/ha. Seedlings in the FH post-planting treatment plots received both fertilizer and vegetation control treatments as described above. Control seedlings were not treated.

### Seedling assessment

All live planted seedlings were assessed for height (± 5 mm), and soil surface diameter (± 0.5 mm) following planting and at the end of the first (October 11 to 14, 1994), second (October 16 to 19, 1995), third (October 21 to 25, 1996), fourth (October 6 to 7, 1997), fifth (October 15 to 20, 1998) and seventh (October 4 to 7, 2000) growing seasons. Volume was calculated assuming a conical shape.

### Data analyses

Differences in seedling growth were analysed by analysis of variance (ANOVA) using restricted maximum likelihood (REML) estimation (SAS Version 8.2, Proc Mixed procedure, SAS Institute Inc. 1992). Each year and species was analysed separately (i.e., for each combination of species and year, the ANOVA was based on a split-plot model with silviculture and post-planting treatments corresponding respectively to whole plots and split-plots). Planned contrasts of least-square means were used to test for main effects of silviculture systems (for each post-planting treatment) and post-planting treatments (for each silviculture system). Fisher's LSD test was used to compare pairs of least-square means with individual p-values adjusted for multiple comparisons by Tukey's method.

## Results

### Survival

Survival of western hemlock and amabilis fir seedlings after seven years was highest in the GT (fir: 93%; hemlock: 92%) and PC (fir: 94%; hemlock: 93%), slightly lower in the CC (fir: 90%; hemlock: 87%) and lowest in the SW (fir: 82%; hemlock: 82%). Most of the mortality occurred within the first three years after planting. Post-planting treatments had little effect on survival in any of the silvicultural systems.

### Seedling growth (cumulative to year 7)

Silvicultural system and post-planting treatment main effects were significant for seven-year height, diameter and volume of both amabilis fir (Table 1) and western hemlock (Table 2) seedlings.

**Silvicultural Systems** – In both amabilis fir (Table 1) and western hemlock (Table 2), seven-year seedling height and diameter was less in the SW, which had the most canopy retention, than in the CC, GT and PC silvicultural systems (as indicated by the least squares means). An exception was the fertilized-only seedlings of both species in which silvicultural system had no significant effect on height after seven years. While untreated fir and hemlock in the SW showed a similar proportional reduction in height (26–30%) compared to the more open systems, diameter was reduced more in hemlock (38.4%) than fir (31.1%). Fertilizer and herbicide treatments alone and in combination resulted in heights and diameters in the SW comparable to those found in the untreated control of the

**Table 2. Least-square means (± s.e., standard error) of seven-year growth parameters in western hemlock by silvicultural system and post-planting treatment. (n is the number of live seedlings)**

| Growth parameter | Silvicultural System | Control | Fertilized | Herbicide | Fertilizer & herbicide | n | *p*-value |
|---|---|---|---|---|---|---|---|
| | | Post-planting treatment | | | | | |
| Height (cm) | Clearcut | 203.5 (13.7)a/z | 216.1 (13.8)a/y | 278.7 (14.1)b/z | 272.9 (14.1)b/z | 219 | *<.0001* |
| | Green tree | 210.8 (13.8)a/z | 244.0 (13.6)b/y | 244.7 (13.9)b/z | 254.5 (13.8)b/z | 230 | *0.0162* |
| | Patch cut | 209.5 (13.6)a/z | 249.8 (13.7)b/y | 238.6 (13.7)b/z | 255.2 (13.9)b/z | 234 | *0.0072* |
| | Shelterwood | 150.4 (14.1)a/y | 205.8 (14.3)b/y | 187.0 (14.8)b/y | 208.5 (13.9)b/y | 206 | *0.0003* |
| | *p* value | *0.0158* | *NS* | *0.0017* | *0.0215* | | |
| Diameter (mm) | Clearcut | 41.05 (3.11)a/z | 45.06 (3.13)a/z | 62.13 (3.19)b/z | 64.47 (3.18)b/z | 219 | <.0001 |
| | Green tree | 38.45 (3.12)a/z | 44.51 (3.09)b/z | 51.52 (3.15)c/y | 57.90 (3.13)d/z | 230 | <.0001 |
| | Patch cut | 36.82 (3.09)a/z | 48.70 (3.11)b/z | 52.76 (3.11)bc/y | 56.49 (3.15)c/z | 234 | <.0001 |
| | Shelterwood | 23.83 (3.18)a/y | 34.73 (3.24)b/y | 34.20 (3.32)b/x | 37.92 (3.14)b/y | 206 | <.0001 |
| | *p* value | *0.0051* | *0.0353* | *<.0001* | *<.0001* | | |
| Stem volume (cm$^3$) | Clearcut | 1179 (262)a/y | 1508 (263)a/y | 3191 (270)b/z | 3497 (269)b/z | 219 | <.0001 |
| | Green tree | 1069 (263)a/y | 1484 (260)a/y | 2305 (265)b/y | 2675 (263)b/y | 230 | <.0001 |
| | Patch cut | 908 (260)a/y | 1846 (261)b/y | 2031 (261)bc/y | 2365 (266)c/y | 234 | <.0001 |
| | Shelterwood | 543 (268)a/y | 1189 (273)b/y | 1077 (279)ab/x | 1217 (265)b/x | 206 | *0.0486* |
| | *p* value | *NS* | *NS* | *0.0002* | *<.0001* | | |
| Height:diameter ratio | Clearcut | 50.04 (1.87)b/x | 50.29 (1.88)b/x | 45.44 (1.95)a/y | 42.75 (1.94)a/y | 219 | *0.0013* |
| | Green tree | 58.04 (1.88)b/y | 56.84 (1.84)b/y | 49.57 (1.90)a/y | 45.18 (1.88)a/y | 230 | *<.0001* |
| | Patch cut | 58.32 (1.84)c/y | 53.08 (1.86)b/y | 46.08 (1.86)a/y | 46.53 (1.91)a/y | 234 | *<.0001* |
| | Shelterwood | 69.18 (1.94)b/z | 65.40 (1.98)b/z | 59.34 (2.05)a/z | 57.70 (1.90)a/z | 206 | *<.0001* |
| | *p* value | *<.0001* | *<.0001* | *<.0001* | *<.0001* | | |

Least-square mean comparisons of post-planting treatments (rows) are indicated by a,b,c,d and silvicultural systems (columns) are indicated by x,y,z.
Means followed by the same letter are not significantly different (p>0.05) using Fisher's LSD test (p-values adjusted for multiple comparisons by Tukey's method).

more open silvicultural systems. There were no significant differences in the height of either hemlock or fir among the more open silvicultural systems (CC, GT, PC) in any of the planting treatments. Differences in diameter among the open silvicultural systems was restricted to the H and FH treatments where diameter growth was greater in the CC compared to the GT in fir and compared to the PC and GT in hemlock.

In terms of standing volume after seven years, differences among the open silvicultural systems in both fir and hemlock were only significant in the H and FH treatments where volume was greater in the CC than the PC and GT. In these two treatments (H and FH), stem volume of fir and hemlock in the SW was approximately one-half that in the GT and PC, and one-third that in the CC. Although differences in stem volume among silvicultural systems were not significant in the untreated control for either fir or hemlock, mean seedling volume in the SW was reduced by 37% to 60% compared to the more open silvicultural systems. Hemlock standing volume was 3.5- to 4-fold higher than fir after seven years across all silvicultural systems.

Differences in height:diameter ratio (HDR) were most pronounced in western hemlock and were highest in the SW in all planting treatments and lowest in the CC (Table 2). Amabilis fir HDR was also lowest in the clearcut with the exception of the fertilized seedlings, which showed no significant differences among silvicultural systems (Table 1). In contrast to hemlock, HDR of fir in the SW were not significantly lower than their counterparts in the GT and PC.

**Post-Planting Treatments** – Western hemlock and amabilis fir both responded to fertilization and vegetation control alone and in combination under all silvicultural systems. After seven years, height, diameter and volume of amabilis fir in the more open silvicultural systems was generally lowest in the C (untreated), intermediate in the H and highest in the combined FH (Table 1). Growth of fertilized fir was either less than or equivalent to the vegetation control treatment depending on silvicultural system. Notably, in the CC, fir seedlings that received fertilizer alone seven years earlier did not differ significantly in height, diameter and volume from the control treatment. Height and diameter differences in fir were least pronounced in the SW where planting treatments were only significantly different from the control. Standing volume of amabilis fir seedlings in the more open silvicultural systems increased approximately three-fold with herbicide alone and four- to five-fold when combined with fertilizer. Fertilization alone had no significant effect on seven-year volume of fir seedlings in any silvicultural system.

In western hemlock differences in growth among post-planting treatments were less pronounced than in fir and were generally only significant in comparison to the untreated control, with the exception of diameter growth in the GT which increased in order of C<F<H<FH (Table 2). Stem volume of hemlock seedlings increased by two- to three-fold in all silvicultural systems with the application of herbicide alone and combined with fertilizer. Fertilization alone only had a significant effect on volume of hemlock in the PC and SW where it increased volume two-fold. Hemlock and fir HDR was lowest in the H and FH treatments and generally highest in the C and F treatments in all silvicultural systems.

### Seedling growth (Years 1–7)

In the first season after planting, a height response to post-planting treatments was observed in both fir (Fig. 2) and hemlock (Fig. 3) under all silvicultural systems except for fir in the SW where a response occurred after two seasons. The greatest initial effect on the height growth of both species was from fertilization alone and combined with herbicide. However, by the end of the seven-year study, the response to fertilization alone, which consisted of a single application at the time of planting, was diminished in the CC where there was no significant difference in height compared to the control seedlings after five and seven years in hemlock and fir respectively. The fertilization

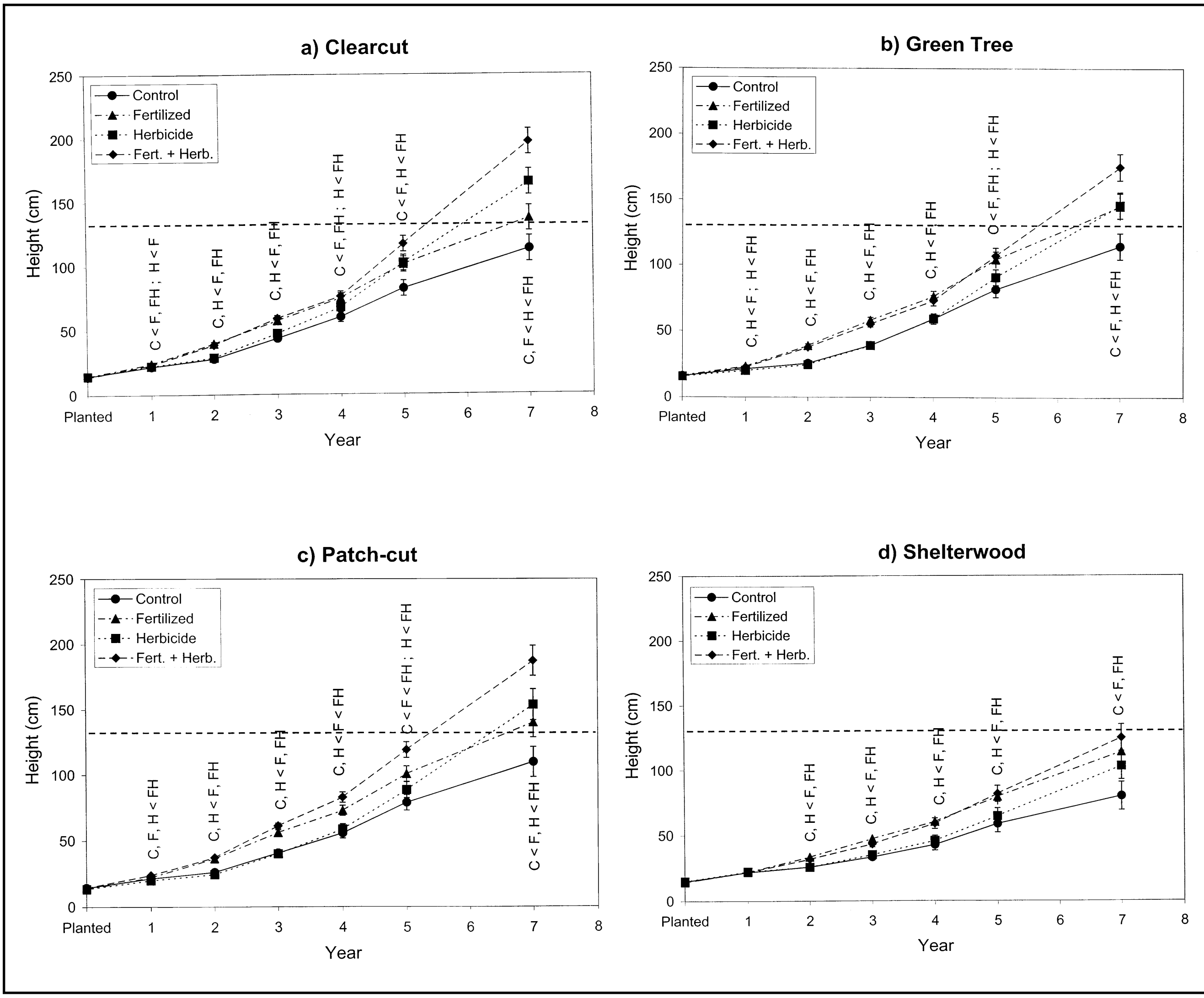


**Fig. 2.** Height (least-square means) of amabilis fir (Ba) in years 0 to 7 after planting in each of the post-planting treatments (Control, C; Fertilized, F; Herbicide, H; Herbicide and Fertilizer, FH) in a) Clearcut, b) Green Tree, c) Patch cut and d) Shelterwood systems. Dashed line represents 1.3 m free-to-grow height. Comparisons among post planting treatments in each year (e.g., C, F, H < FH) indicate significant differences ($p < 0.05$, Fisher's LSD, adjusted for multiple comparisons by Tukey's method).

response was also diminished to a lesser extent in the PC and GT in fir only. Conversely, herbicide alone had no significant effect on height growth until seven years after planting, except in the CC where the effect of herbicide was evident after three and five years in western hemlock and amabilis fir respectively. In amabilis fir, the combination of fertilizer and herbicide in the open silvicultural systems resulted in height growth which outpaced that of either treatment alone, the divergence becoming more pronounced with time. No similar additive effect on growth was observed in western hemlock.

## Discussion

Despite the high shade tolerance of amabilis fir and western hemlock (Minore 1979, Krajina *et al.* 1982), seven-year survival and growth of planted seedlings in the SW was less than in the more open systems across all planting treatments. Slower growth in the SW is likely related to above-ground limitations, specifically low light in the understory environment since there were only small differences among silvicultural systems in soil water deficits and soil and air temperatures (Mitchell 2001). On the MASS site, rates of N mineralization and nitrification were greatest on the CC, but did not differ between the SW, GT and PC (Prescott 1997), so it is unlikely that N availability accounts for the difference in growth between the SW and the other alternative silvicultural systems.

These results are consistent with other studies from several coastal sites in British Columbia that found the maximum growth potential for amabilis fir and western hemlock occurs when canopy light transmittance is greater than 75% (Carter and Klinka 1992, Klinka *et al.* 1992) a level that occurred in less than half of the SW microsites (Beese *et al.* 2004). Gaps in the dispersed SW were variable in size, most being under one

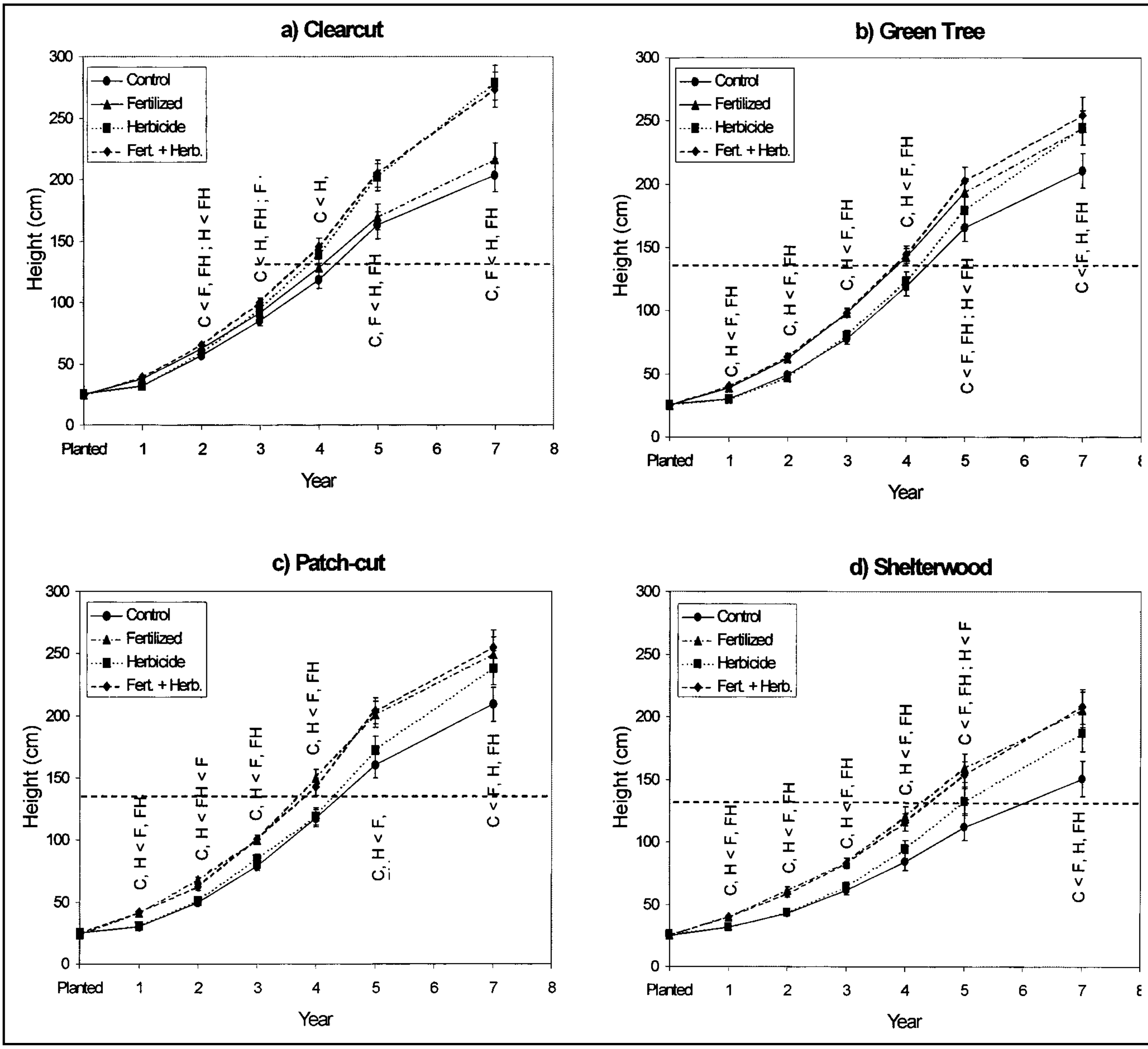


**Fig. 3.** Height (least-square means) of western hemlock (Hw) in years 0 to 7 after planting in each of the post-planting treatments (Control, C; Fertilized, F; Herbicide, H; Herbicide and Fertilizer, FH) in a) Clearcut, b) Green Tree, c) Patch cut and d) Shelterwood systems.

tree height in diameter (approximately 0.1 ha), a gap size below which growth declines have been reported in both western hemlock and amabilis fir (Gray and Spies 1996, Coates 2000).

In the SW, where western hemlock height/diameter ratio (HDR) was highest, height growth was at the expense of diameter growth while both height and diameter growth were reduced more proportionately in amabilis fir (i.e., HDR did not differ between the GT, PC and SW). Higher HDR of hemlock in the SW reflects a growth allocation pattern that favours vertical extension towards the canopy. Although HDR of amabilis fir was relatively unchanged in the SW, crown morphological acclimation in advance amabilis fir regeneration in the SW reported in a related study (Beese *et al.* 2004) is consistent with the allocation of reserves to lateral extension for available light capture in understory environments, and is a characteristic of greater shade tolerance in conifers (Klinka *et al.* 1992, Chen 1997). Foliar morphological [specific leaf area (SLA)] and physiological (photochemical efficiency) acclimation to overstory shading in the SW has also been shown to differ for fir and hemlock in another related study (Mitchell 2001). In particular, higher SW SLA in hemlock but not fir seems to confirm above-ground limitations as the driving factor for changes in the growth allocation (HDR) of hemlock observed in the present study.

While differences in the size of opening and residual trees among the more open silvicultural systems (CC, GT and PC) had no effect on volume growth after seven years in seedlings that were untreated or only fertilized, vegetation control alone and in combination with fertilizer resulted in greater stem volume than untreated seedlings in the CC than in the PC or GT for both fir and hemlock. This suggests that above and below ground resource availability was more favourable for seedling growth in the CC once vegetation limitations to growth were reduced. While differences in soil and air temperatures were negligible among the silvicultural systems at the MASS site, light levels at seedling height were highest in the CC (Mitchell 2001) and may have resulted in higher daily photosynthate production. Similar findings of clearcut openings producing the greatest growth response have been reported for western hemlock in the Interior Cedar-Hemlock zone (Coates 2000) and the Coastal Western Hemlock (CWH) zone (Mailly and Kimmins 1997) and amabilis fir in the CWH (Hawkins *et al*. 2002) and the Pacific Silver Fir zone in Washington State (Murray *et al* 1991).

Post-harvest conifer stagnation, defined here as variable periodic annual growth, has been found on large high-elevation clearcuts (Herring and Etheridge 1976, Wagner 1980, Koppenaal and Mitchell 1992), often in association with dense ericaceous shrub competition on nutrient poor sites (Husted 1982). Conifer stagnation was not observed on the MASS study site, possibly because the seven-year post-harvest term of the study was not long enough to observe the onset of stagnation, which often occurs ten or more years following release. Alternatively, above- and below-ground climatic and nutritional limitations on the study site may not have been severe enough to elicit growth stagnation. It should be emphasized that the MASS study was situated on a north-facing site and that seedlings were not exposed to severe summer water deficits or lethal temperatures that have been reported to affect the survival of shade-tolerant conifers on south-facing clearcuts in the Pacific Northwest (Minore 1986, Livingston and Black 1987).

The growth response of both western hemlock and amabilis fir to fertilization (F and FH) supports the view that nitrogen is limiting on many montane sites in British Columbia (Prescott and Zabek 1999). Because the fertilizer was applied only once, at the time of planting, the response to fertilizer alone was diminished by the end of the trial, particularly in amabilis fir in the CC, GT and PC and western hemlock in the CC. The response to vegetation control was probably an effect of increased nutrient availability and more light at seedling height, the relative contribution of each effect varying with microsite differences in competition for below- and above-ground resources. Overall, in the open silvicultural systems with competing vegetation intact (control) incoming solar radiation was 20–30% less compared to vegetation control , but was probably still well above the saturation point for fir and hemlock (Mitchell and Arnott 1995), causing little if any reduction in photosynthetic rates. In the SW, the overall increase in light penetrating to the seedling layer due to vegetation control was probably marginal since the growth of both fir and hemlock remained depressed compared to their counterparts in the more open silvicultural systems. The delayed response to vegetation control alone in all silvicultural systems (three to five years in CC and seven years in GT, PC and SW) seems to be more consistent with the small cumulative increases in the uptake of available nutrients that might be expected following reduced uptake by competing vegetation. Competing vegetation became more vigorous with time from harvest in the CC, GT and PC, resulting in increased competition for available nutrients and possibly light, which would explain at least some of the delay in response to vegetation control. This would also explain the persistent growth response of both species in the FH despite diminishing returns from the fertilizer treatment.

In amabilis fir there was an additive effect on height and diameter growth of applying both fertilizer and vegetation control (i.e., FH > F, H) in all systems except the SW, which is probably a cumulative response to the initial fertilizer treatment and the longer-term increase in nutrient and light availability from vegetation control. In western hemlock no additive effect of the FH treatment on growth was observed after seven years (i.e., FH = F and/or H), reflecting differences in growth rate and nutritional requirements between the two species (Mitchell and Arnott 1995, Wright *et al*. 1998b).

## Summary

Although amabilis fir and western hemlock are shade-tolerant and can persist in a suppressed state in low understory light environments, maximum growth potential of both species was realized under the more open silvicultural systems (CC, GT, PC). In the SW, where 25% of the basal area was retained, above-ground limitations (low understory light) seemed to be the overriding factor responsible for lower growth and resulted in growth allocation that favoured stem extension at the expense of diameter growth in hemlock. It must be emphasized that these results cannot be extrapolated to harsh sites or sites where stocking objectives rely on natural regeneration, for which retention of an overstory influence may be more favourable for seedfall and emergence of shade-tolerant species compared to open sites with full sun exposure.

Alleviating below- and above-ground limitations to growth has operational implications in the time to reach free-to-grow height (1.3 m) for meeting adjacency standards in coastal British Columbia. In amabilis fir, while tree height in the untreated control was still below the 1.3 m free-to-grow height after seven years, it was exceeded with fertilization or herbicide alone and in combination in the more open silvicultural systems. In western hemlock, the free–to-grow height was exceeded after four years with combined fertilization and herbicide, one year earlier than the untreated control. When resource limitations were reduced with vegetation control alone and in combination with fertilizer, seven-year volume growth of fir and hemlock was greatest in the CC. Combined vegetation control and N fertilization elicited an additive growth response from amabilis fir but not western hemlock in all silvicultural systems except the SW, reflecting differences in growth rate and nutritional requirements between the two species.

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