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Responses of Western Hemlock, Western Redcedar, and Amabilis Fir to Fertilization

A Synthesis

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BRITISH COLUMBIA

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S.D. Addo-Danso, C.E. Prescott, and L. de Montigny

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ABSTRACT

In British Columbia, three tree species—western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), western redcedar (*Thuja plicata* Donn ex D. Don), and amabilis fir (*Abies amabilis* Dougl. ex Forbes)—dominate coastal forests. With concerns about the long-term supply of timber from coastal forests, attention has been focussed on management and productivity of regenerating natural stands and plantations. The British Columbia Ministry of Forests, Lands, Natural Resource Operations and Rural Development (FLNRORD) has been investing in fertilization as a strategy for increasing rates of growth and stand development in regenerating forests. This report synthesizes published data and analyzes responses by western hemlock, western redcedar, and amabilis fir to various fertilization applications in coastal British Columbia and northern Washington State. The results improve understanding of growth response to fertilizer applications and identify key information needs for current and future forest fertilization investments under two FLNRORD programs: Forests for Tomorrow (FFT) and Forest Carbon Initiative (FCI).

EXECUTIVE SUMMARY

Western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), western redcedar (*Thuja plicata* Donn ex D. Don), and amabilis fir (*Abies amabilis* Dougl. ex Forbes) dominate the forests of coastal British Columbia. The Forests for Tomorrow (FFT) Program of the British Columbia Ministry of Forests, Lands, Natural Resource Operations and Rural Development has been investing in fertilization to improve the mid-term timber supply. This report presents analysis and synthesis of the responses of these three tree species to fertilization in coastal British Columbia and northern Washington State, and identifies key information needs for the ongoing FFT fertilization programs. The effects of stand age, stand density, and site quality on response to fertilization are also discussed. Overall, additions of nitrogen (N) alone or combinations of N and phosphorus (P) increased growth of western hemlock, western redcedar, and amabilis fir, indicating that these species are generally responsive to fertilization in coastal British Columbia and Washington. For all three species, addition of N plus P (N+P) resulted in greater growth response than use of N-only fertilizer. Both N and P are needed to induce a significant growth response in western hemlock. The strongest and most consistent growth responses in both western hemlock and western redcedar resulted from N+P fertilization of cedar–hemlock (CH) and hemlock–amabilis fir (HA) sites on northern Vancouver Island. Western hemlock response to fertilization was inconsistent among sites (except CH and HA sites on northern Vancouver Island). Western redcedar growth responded to addition of N-only or of N+P on most sites. Addition of fertilizer occasionally had no effect on growth of western redcedar, which may be related to the effects of competing vegetation on some sites. Amabilis fir has been responsive to N+P fertilization in trials on Vancouver Island, and there is evidence that sufficient light and control of competing vegetation can improve growth response to fertilization in this species.

In the analysis in this study, there was some indication of younger stands responding better than older stands, but this comparison was confounded by the stands of different ages occurring on different sites, with many of the young stands being on CH and HA sites. There was some indication of greater response at intermediate stand densities (1000–3000 stems per hectare), and several studies have indicated greater responses of thinned stands of western hemlock and western redcedar to fertilization. Responses of western hemlock and western redcedar to fertilization do not appear to be related to the quality of the site. Foliar nutrient analyses appear to be the most reliable indicator of potential growth response to fertilization and should be employed prior to fertilization.

On the basis of the consistent and large responses in this study, N+P fertilization of both western hemlock and western redcedar on CH and HA sites can be expected to deliver the greatest return on investment in fertilization. Although growth responses of western redcedar are generally smaller than those of western hemlock, they are more consistent and warrant further consideration for fertilization.

Continued monitoring of established installations and fertilization trials are needed to assess the duration of fertilization responses and the most appropriate intervals for repeated fertilization. Additional fertilization trials of all three species are needed at sites outside of northern Vancouver Island. New field experiments should be designed to assess specifically how growth responses to addition of N-only or N+P fertilizers vary with stand age, stand density, and site quality. Potential influences of fertilization of coastal forests on carbon storage and fluxes of greenhouse gases need to be quantified. Finally, more information is needed with regard to fertilization effects on amabilis fir, for which data are lacking.

ACKNOWLEDGEMENTS

Most of the information available regarding fertilization responses of these important coastal tree species arose from the Salal Cedar Hemlock Integrated Research Program (SCHIRP). We acknowledge the particular contributions of John Barker, Paul Bavis, and Annette van Neijenhuis of Western Forest Products, and Gordon Weetman, Rod Negrave, Leandra Blevins, and Victor Nery of the University of British Columbia in the design, establishment, maintenance, re-measurement, and analysis of the long-term SCHIRP experiments.

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1 INTRODUCTION

Western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and western redcedar (*Thuja plicata* Donn ex D. Don) are ecologically and commercially important tree species in the coastal forests of the Pacific Northwest (Ruth and Harris 1979; Minore 1983). In the Coast Forest Region of British Columbia, western hemlock represented 34% of the log harvest volume in 2015 (B.C. Ministry of Forests, Lands and Natural Resource Operations 2016). Western hemlock is valued for its timber quality and is used for construction and pulp (Middleton and Munro 2001). Western redcedar, the only *Thuja* species native to western North America, is distributed along the Pacific coast from northern California to southeastern Alaska, and along the interior wet belt from McGregor River, B.C., to western Montana and northern Idaho (Minore 1983; Klinka and Brisco 2009). Western redcedar has a high commercial value and is used extensively for decorative and structural purposes (Klinka and Brisco 2009). First Nations peoples used western redcedar for their homes, canoes, and other purposes (Hebda and Mathewes 1984). Amabilis fir (*Abies amabilis* Dougl. ex Forbes) ranges from northwestern California to southwestern Alaska, including coastal British Columbia (Crawford and Oliver 1990). Amabilis fir is used for construction plywood and framing, veneer, and pulp (Crawford and Oliver 1990) and is also grown commercially for Christmas trees. In British Columbia, these three tree species dominate old-growth forests at low-to-medium elevations in the wetter subzones of the Coastal Western Hemlock (CWH) biogeoclimatic zone, as classified by Green and Klinka (1994).

Concerns over the long-term supply of timber from coastal forests have focussed attention on the management and productivity of young regenerating natural stands and plantations (Ruth and Harris 1979; Harrington and Wierman 1985; Omule and Britton 1991; Klinka and Brisco 2009). Fertilization has the potential to increase rates of growth and stand development in regenerating forests (Lee 1968; Debell 1975; B.C. Ministry of Forests, Lands and Natural Resource Operations 2017[1]), and fertilization trials have been established throughout the coast to provide information on responses of dominant tree species to various fertilizer blends and application rates (Debell 1975; Webster et al. 1976; Omule and Britton 1991; Prescott and Weetman 1994). Coastal Douglas-fir is by far the most studied species in this regard, but a smaller number of trials have examined the growth responses of western hemlock, western redcedar, and amabilis fir to fertilization. However, uncertainty remains regarding the magnitude and duration of growth response that can be expected from fertilization of these species in coastal British Columbia. It also remains unclear how site characteristics mediate the response to fertilization, and thus which site and species combinations will be most responsive to fertilization. An improved understanding of the growth response to fertilizer applications and the factors mediating responses is necessary to support current and future forest fertilization investment opportunities under the Forests for Tomorrow (FFT) program and the Forest Carbon Initiative (FCI).

1 British Columbia Ministry of Forests, Lands and Natural Resource Operations. 2017. Silviculture Funding Criteria. 2017/18 to 2020/21. Victoria, B.C., Unpubl. rep. www2.gov.bc.ca/assets/gov/environment/natural-resource-stewardship/land-based-investment/forests-for-tomorrow/201718_lbis_silviculture_funding_criteria_-_july_final.pdf (Accessed May 5, 2019).

One of the aims of the FFT program of the B.C. Ministry of Forests, Lands, Natural Resource Operations and Rural Development is to improve the future timber supply in British Columbia. Hence, the FFT program is investing in fertilization as a mitigation strategy to address mid-term timber supply challenges. Sound decision-making on future expansion of the fertilization program requires that we be able to predict the responses of commercially important coastal tree species to fertilizer application. This report synthesizes past and current data, and reviews studies to date to examine how western hemlock, western redcedar, and amabilis fir stands have responded to fertilization in British Columbia and northern Washington State. It also examines how growth response varies with stand age at fertilization, stand density, and site quality. Finally, it identifies knowledge gaps and information needs in support of fertilization decision-making and growth and yield (and carbon) modelling for forests in coastal British Columbia.

2 METHODS

Data were compiled through a literature search from published sources, including journal platforms (Google Scholar, ISI Web of Science, and CABI Forest Science Database). The search focussed on studies from British Columbia using terms and keywords such as "fertilization in British Columbia," "fertilization and tree growth in British Columbia," "growth response to nitrogen and phosphorus fertilizers in British Columbia," "fertilization of western hemlock," "fertilization of western redcedar," and "fertilization of amabilis fir." In addition, relevant literature and reports were identified using the Province of British Columbia's databases, as well as library sources. To complement data from British Columbia, a further search was conducted to identify literature on growth response of the three species to fertilization in Washington. A database was compiled using the following criteria modified from Reid et al. (2017): (1) the study was conducted in the field in natural stands or plantations in coastal British Columbia and northern Washington; (2) the study design included fertilized (treatment) and unfertilized (control) plots; (3) trees were 5 years old or older when fertilized; (4) at least one growth parameter (height, basal area, and volume) was measured; (5) growth response was assessed at least 3 years after initial fertilization; (6) fertilization response was not confounded by other silvicultural treatments such as scarification, herbicide application, or brushing; and (7) growth response was not predicted from regression models.

The raw data presented for control and fertilized plots were extracted from tables and figures. When data were presented for plots under different fertilizer combinations (e.g., N alone, P alone, N+P, or a blend of N+P+other nutrients), they were treated as independent. If data were presented for multiple years after initial or single application at the same site, the longest-term data were used. When data were available for initial and repeated fertilization at the same site, the oldest measurements before and after refertilization were used. Background information was also collected, including site location, climate, biogeoclimatic (BEC) zone and subzones, stand type (natural stand or plantation), and site index (m at 50-year breast-height age). Additional information collected included installation date, fertilizer types and rates applied, stand

density (stems per hectare), and stand age at fertilization, as well as the period (years) during which growth parameters were measured following fertilizer application.

To evaluate the growth response to fertilization, the relative response from each study was calculated as:

Relative response = (Treatment value – Control value)/Control value – 100%

The relative response presents growth rates (height, basal area, and volume) following fertilization relative to growth rates in control (unfertilized) plots in each study. Absolute growth responses were also calculated by subtracting mean values for growth (e.g., volume) of control trees from mean values for growth of fertilized trees (Reid et al. 2017). Several site factors, including stand age, initial stand density, and site quality, can influence the magnitude and direction of the response to fertilization (Debell 1975; Chappell et al. 1992; Weetman and Prescott 2001; Brown 2003), so the influences of these site characteristics on growth responses to fertilization were also assessed. Data from western hemlock stands on nutrient-poor western redcedar–western hemlock (CH) cutovers on northern Vancouver Island were analyzed separately, as previous studies had shown extremely high relative responses of western hemlock to fertilization on these sites (e.g., Negrave et al. 2007; Prescott et al. 2013).

Relationships between stand age and growth response to fertilization were assessed from the data available in the database. Initial stand densities in the database ranged from 270 to 7195 stems per hectare. To assess how stand density affected responses to fertilization, the stand density data were arbitrarily grouped into three categories: low density (< 1000 stems per hectare), medium density (1000–3000 stems per hectare), and high density (> 3000 stems per hectare). The findings from this analysis were supplemented with information on fertilization responses in thinned and unthinned stands from the literature. Relationships between growth responses and site quality were assessed using site index as a proxy for site quality (Kayahara et al. 1995; B.C. Ministry of Forests 1999). Site index is defined based on the average height or height increment that unsuppressed, undamaged top-height trees of a species can attain in 50 years of growth above breast height (Wang et al. 1994; B.C. Ministry of Forests 1999) and is often used to predict stand growth and yield (B.C. Ministry of Forests 1999; Stearns-Smith 2001). Despite its usefulness, site index does not easily relate to ecological measures of site quality (Wang 1998).

2.1 Database

The database encompasses studies from different sites where fertilizer trials have been established in coastal British Columbia (Appendices 1–4). Data were collected from installations located in subzones of the Coastal Western Hemlock (CWH) biogeoclimatic zone including the Very Wet Maritime subzone (vm1 and vm2 variants), Wet Hypermaritime subzone (wh1 variant), and Very Wet Hypermaritime subzone (vh2 variant) (Green and Klinka 1994). The majority of relevant studies from British Columbia were collected from fertilization trials established in naturally regenerated stands and plantations on Vancouver Island, including the Salal Cedar Hemlock Integrated Research Program (SCHIRP) and the Montane Alternative Silvicultural Systems (MASS) field trials (e.g., Weetman et al. 1993; Dunsworth and Arnott 1996[2]; Prescott et al. 1996; van Niejenhuis 2004; Negrave et al. 2007). The SCHIRP silvicultural

2 Dunsworth, B.G. and J.T. Arnott. 1996. Growth limitations of regenerating montane conifers in field environments. Unpubl. Progr. Rep. (72/31F). Prepared for Science Council of British Columbia by MacMillan Bloedel Ltd. and Pac. For. Cent., Can. For. Serv., Victoria, B.C.

trials were initiated in the early 1980s with the objectives of understanding the causes of poor regeneration of coastal conifers on sites dominated by ericaceous shrubs, and recommending best practices to improve tree growth on these sites (Prescott and Weetman 1994). The MASS trials were established in 1992 on Vancouver Island to test the operational, ecological, and economic impacts of three retention silvicultural systems, including clearcutting, aggregated retention, and dispersed retention (Arnott and Beese 1997). Other studies reporting results of fertilization trials in coastal British Columbia included in the database are de Montigny and de Jong (1998), Carter et al. (2001), van Niejenhuis (2004), Kranabetter et al. (2013), and Reynolds and de Montigny (2015).

Data from stands in Washington were collected from fertilization trials managed by the Regional Forest Nutrition Research Project (RFNRP) (now the Stand Management Cooperative) and other trials initiated in natural stands in coastal Washington and Oregon (e.g., Radwan et al. 1984; Harrington and Wierman 1985). The University of Washington initiated the RFNRP in 1969, establishing 25 permanent fertilization installations in natural stands of western hemlock and Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) in coastal Washington, coastal Oregon, and the Washington Cascades (Olson et al. 1981; Radwan et al. 1984). The data also included other trials established on the Olympic Peninsula in Washington (e.g., Harrington and Wierman 1985). Growth data for western redcedar accounted for the largest number of observations in the database (57%), followed by western hemlock (39%) and amabilis fir (4%). Several additional fertilization studies, particularly with western hemlock, did not meet the criteria used in this study (e.g., Omule and Britton 1991), but the results of such studies are used in the Discussion section to supplement the analyses from this study.

For western hemlock, data were available from fertilization trials in both naturally regenerated stands and plantations, but the majority of data was from plantations. Fertilizers applied included N alone, combinations of N and P, and blends. Nitrogen was added as urea or ammonium nitrate at rates ranging from 100 to 300 kg N/ha. Phosphorus was applied as triple superphosphate in most cases at rates from 75 to 300 kg P/ha. Fertilizer blends contained additional macronutrients (e.g., K and S) and micronutrients (e.g., Ca, B, and Cu). Some stands were repeatedly fertilized; for example, in a SCHIRP experiment (Prescott et al. 2013) on northern Vancouver Island, fertilizer was applied at the time of planting (60 g of slow-release Nutricote per seedling, providing 10 g of N, 2.5 g of P, and 5 g of K), after five growing seasons (225 kg N/ha as urea and 75 kg P/ha as triple superphosphate), and after 11 growing seasons (225 kg N/ha as urea). Stand ages at fertilization ranged from 6 to 28 years, and site index at the 50-year breast-height age ranged from 17 to 35 m.

Data for western redcedar came from natural stands and plantations. Combinations of N and P fertilizers were used in the majority of studies, but some studies included N alone, fertilizer blends, and/or P alone. Fertilizer sources were similar to those used in western hemlock trials. Nitrogen application rate ranged from 75 to 300 kg N/ha, while P ranged from 50 to 100 kg P/ha. Stand ages ranged from 6 to 20 years, and site index from 18 to 25 m. A few western redcedar stands were fertilized multiple times, with cumulative rates ranging from 450 to 600 kg N/ha (Harrington and Devine 2010; Prescott et al. 2013).

Three studies reported on the response of amabilis fir to fertilizer application. Nitrogen and P fertilizers were applied at rates of 225 kg N/ha and 75 kg P/ha. Stand ages ranged from 9 to 45 years.

3.1 Magnitude of Growth Response

3.1.1 Western hemlock For the analyses of western hemlock responses, the data from cedar–hemlock (CH) sites on northern Vancouver Island are presented separately from those from other sites, because the extremely high responses on CH sites (relative to unfertilized plots, expressed as %) made it difficult to discern responses on other sites in the figures, and strongly affected mean response values.

Relative growth responses of western hemlock to a single application of N-only or N+P fertilizer were consistently positive but highly variable (Table 1). Relative height and basal-area growth responses to addition of N-alone ranged from 18 to 80% and 17 to 50%, respectively. Relative height growth response to addition of N+P ranged from 7 to 65%. Basal-area and volume growth responses to addition of N+P ranged from 0 to 176% (absolute basal area, 0 to 22 m^2/ha) and 6 to 264% (absolute volume, 20 to 129 m^3/ha). Growth responses by geographic location are shown in Figure 1. The most responsive western hemlock stands were on hemlock–amabilis fir (HA) sites on northern Vancouver Island; here basal-area and volume responses to addition of N+P were >100%. Hemlock stands in Washington responded positively to addition of N (Figure 1). In contrast, the stands on Haida Gwaii did not respond to N+P addition (Figure 1).

TABLE 1 *Summary of growth response (% difference relative to controls) of western hemlock, western redcedar, and amabilis fir to single fertilization in coastal British Columbia and northern Washington. Values are mean and range. For each species, the fertilizer treatment (with number of observations in brackets) and rates are provided. Data for hemlock stands on cedar–hemlock (CH) sites on northern Vancouver Island, B.C., were excluded.*

Species	Fertilizer applied	N rate applied (kg N/ha)	P rate applied (kg P/ha)	Height (%)	Basal area (%)	Volume (%)
Western hemlock	N (4)	224	–	40 (18–80)	32 (17–50)	–
	N+P (4)	231 (225–250)	100	41 (7–65)	105 (0–176)	146 (6–264)
Western redcedar	N (5)	210 (75–300)	–	36 (19–54)	37 (26–48)	–
	P (1)	–	75	7	–	–
	N+P (16)	225 (75–300)	86 (50–150)	37 (2–72)	160 (29–249)	201 (94–289)
	Blend (9)	188 (75–300)	69 (50–75)	26 (1–60)	–	–
Amabilis fir	N+P (2)	225	75	78 (75–80)	–	300

Hemlock stands on CH sites on northern Vancouver Island showed exceptionally high growth responses to a single application of N+P fertilizer (expressed as %; Figure 2). Average growth responses in height, basal area, and volume to addition of N+P were 258%, 914%, and 1432%, respectively (relative to unfertilized controls). On CH sites, a three-fold difference in stand volume between western hemlock fertilized with N+P (32 m^3/ha) and unfertilized western hemlock (11 m^3/ha) was reported 11 years after fertilization (Prescott and Blevins 2005).

Repeated fertilization with N+P increased growth of western hemlock on HA sites on northern Vancouver Island and sites on the Olympic Peninsula, Washington (Table 2; Figure 3). Relative basal-area and volume growth responses of western hemlock to repeated N addition on the Olympic Peninsula were 11% and 20%, respectively. Relative basal-area and volume growth responses

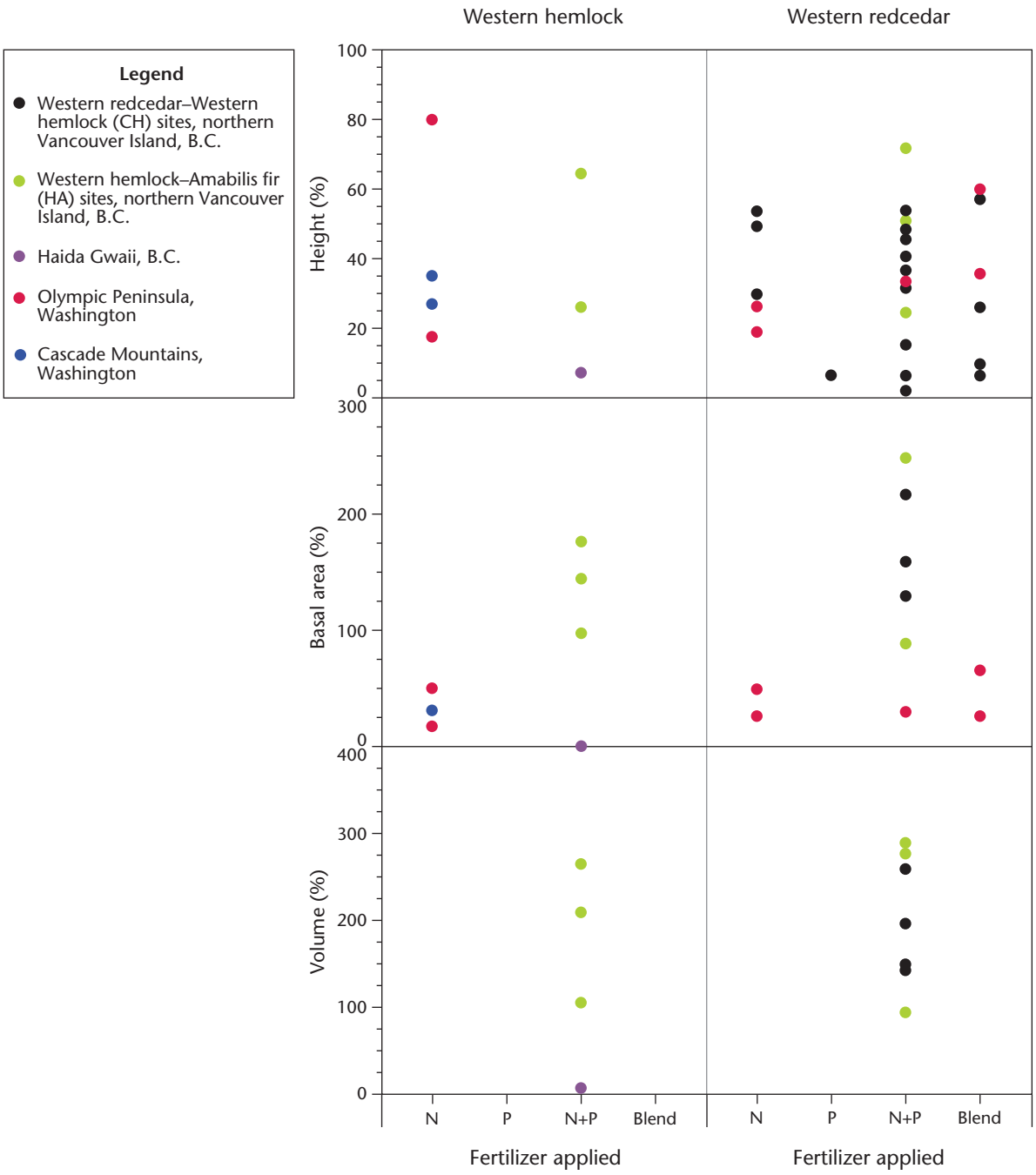

FIGURE 1 *Relative height, basal-area, and volume growth responses (% difference from control plots) to initial or single fertilization treatment for western hemlock and western redcedar in British Columbia and northern Washington. Each point represents a treatment mean.*

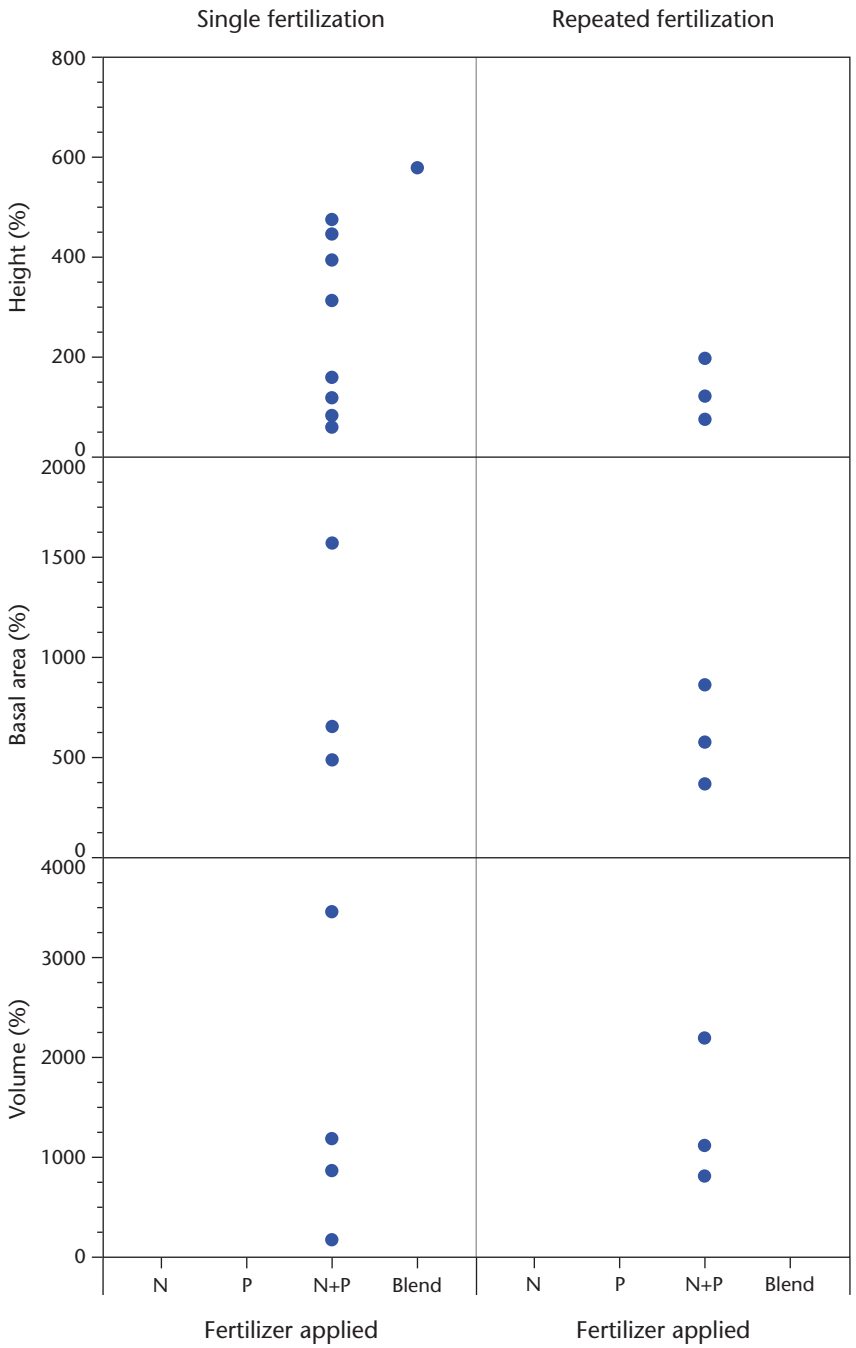

FIGURE 2 *Relative height, basal-area, and volume growth responses (% difference from control plots) to single and repeated fertilization treatments for western hemlock on nutrient-poor western redcedar–hemlock (CH) sites on Northern Vancouver Island, B.C. Each point represents a treatment mean.*

TABLE 2 *Summary of growth response (% difference relative to controls) of western hemlock and western redcedar on cedar–hemlock (CH) sites on northern Vancouver Island, B.C., to repeated fertilization. Values are mean and range. For each species, the fertilizer treatment (with number of observations in brackets) and cumulative rates are provided.*

Species	Fertilizer applied	Cumulative N rate applied (kg N/ha)	Cumulative P rate applied (kg P/ha)	Number of repeated fertilization	Height (%)	Basal area (%)	Volume (%)
Western hemlock	N (1)	600	–	1	–	11	20
	N+P (5)	560 (500–600)	160 (100–200)	1.6 (1–2)	54 (29–69)	93 (9–154)	142 (20–243)
Western redcedar	N (1)	600	–	1	22	49	66
	N+P (8)	525 (500–600)	125 (100–200)	1.8 (1–2)	46 (19–80)	173 (58–248)	209 (78–351)

of western hemlock on HA sites to N+P fertilization (fertilizer mix at planting, N+P at 5 years, and N at 15 years) ranged from 90 to >200% (Figure 3). Hemlock in similarly fertilized HA plots produced an extra 250 m^3/ha of western hemlock after 22 years (at 2500 stems per hectare) (Prescott et al. 2013). On CH sites, western hemlock basal-area and volume responses to repeated N+P fertilization were >200% (Figure 2), and fertilized western hemlock produced an extra 100 m^3/ha relative to unfertilized plots 22 years after initial fertilization.

3.1.2 Western redcedar Relative growth responses of western redcedar to fertilizer application were consistently positive (Table 1; Figure 1). Addition of N alone or N+P increased height growth response of western redcedar on all sites. Average relative height growth response to N fertilization was 36% (range of 19 to 54%). Relative height growth response to addition of N+P and to a fertilizer blend ranged from 2 to 72% (absolute height, 0.2 to 0.9 m) and 1 to 60% (absolute height, 0.01 to 1.05 m), respectively (Table 1). Basal-area growth response to addition of N ranged from 26 to 48% (absolute basal area, 1.6 to 3 m^2/ha). Although the average relative basal-area response to N+P fertilization was positive (160%) (Table 1), the range of values was wide. Average relative volume growth response to addition of N+P was 201% (range of 94 to 289%). On northern Vancouver Island, on both CH and HA sites, basal-area responses of western redcedar to N+P fertilization were usually >100%, as were volume responses (Figures 1 and 2).

Western redcedar stands responded similarly to second and third applications of N or N+P (Table 2; Figure 3). Following the second application of 300 kg N/ha, relative height, basal-area, and volume growth responses increased by 22%, 49%, and 66%, respectively, over control plots (Table 2). Growth response of western redcedar to repeated N or N+P fertilization ranged from 19 to 80% for height, 58 to 248% for stand basal area, and 78 to 351% for stand volume. The greatest responses occurred on both CH and HA sites on northern Vancouver Island (Figure 3), where responses in basal area and volume were >100%. Western redcedar on CH sites fertilized with a fertilizer mix at planting, N+P at 5 years, and N at 15 years produced an extra 100 m^3/ha relative to unfertilized plots 22 years following initial fertilization, while western redcedar in similarly fertilized plots on HA sites produced an extra 180 m^3/ha of western hemlock after 22 years (at 2500 stems per hectare) (Prescott et al. 2013).

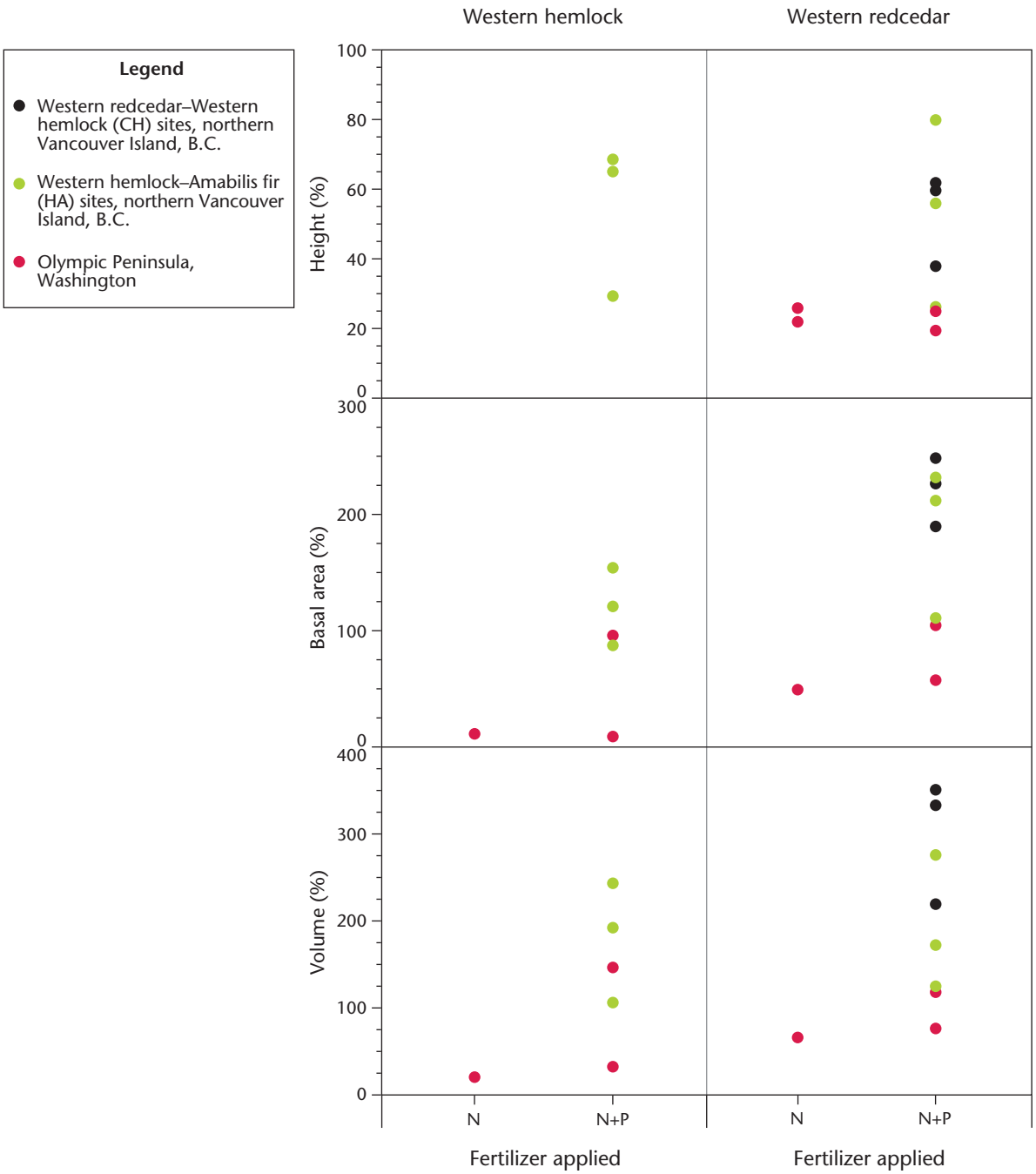

FIGURE 3 *Relative height, basal-area, and volume growth responses (% difference from control plots) to repeated fertilization treatments for western hemlock and western redcedar in coastal British Columbia and northern Washington. Each point represents a treatment mean.*

3.1.3 Amabilis fir Addition of N+P increased height and volume growth of amabilis fir (Table 1). Relative basal-area growth response ranged from 75 to 80% (absolute basal area, 1.2 to 1.5 m^2/ha). Relative volume growth response to the addition of N+P was 100%. Relative height-increment response ranged from 19 to 51% (absolute height increment, 0.37 to 0.74 m/yr) following the application of 225 kg N/ha on naturally regenerated amabilis fir stands on central Vancouver Island (van Niejenhuis 2004).

3.2 Stand Age and Growth Response to Fertilization

Most of the data was for young stands, with very limited information from older stands. Stand age at fertilization (in years) ranged from 6 to 28 years for western hemlock, 6 to 20 years for western redcedar, and 9 to 45 years for amabilis fir. For western hemlock, the young stands were typically plantations (6–9 years), while the older stands were naturally regenerated mid-rotation stands. All were predominantly western hemlock except those on Haida Gwaii, which were mixed western hemlock and Sitka spruce. In the case of western redcedar, young stands consisted of both plantations and naturally regenerated stands.

Young (6- to 9-year-old) stands appeared to have greater basal-area and volume growth responses to N+P fertilizer than did older (18- to 28-year-old) stands (Figure 4). However, the young stands were all on CH or HA sites on northern Vancouver Island, while the older stands were from other locations. It is therefore not possible to distinguish an age effect because of the confounding influence of site differences. For western hemlock stands on CH sites on northern Vancouver Island, response was lower in the 9-year-old stand than the 6- and 8-year-old stands (Figure 5), but this is based on a single data point from a separate experiment and so is not strong evidence of an age influence on fertilizer response. There are insufficient data with which to assess the relationship between stand age and response to fertilization in amabilis fir; however, on central Vancouver Island, there was a tendency for periodic annual increment of height response to increase as stand age increased (van Niejenhuis 2004).

3.3 Stand Density and Growth Response to Fertilization

Initial stand density in the database for western hemlock ranged from 270 to 7195 stems per hectare, and for western redcedar stand density ranged from 500 to 5570 stems per hectare. For amabilis fir, stand density ranged from 892 to 3300 stems per hectare. Stand densities were arbitrarily grouped into low density (<1000 stems per hectare), medium density (1000–3000 stems per hectare), and high density (>3000 stems per hectare). For the three species, the different stand-density categories contained data obtained from both natural stands and plantations.

For western hemlock (Figure 6), growth responses at low and medium density were greater than those at high density; however, the lone high-density plots were in the Haida Gwaii trial. It therefore cannot be ascertained if the poor response on Haida Gwaii was due to the high density or to other factors. Some of the highest basal-area and volume growth responses to addition of N+P fertilizers occurred in the medium-density plots (Figure 6). For CH sites on northern Vancouver Island (Figure 7), some of the highest height growth responses occurred in high-density fertilized plots. On the other hand, the highest basal-area and volume growth responses occurred in the medium-density fertilized plots.

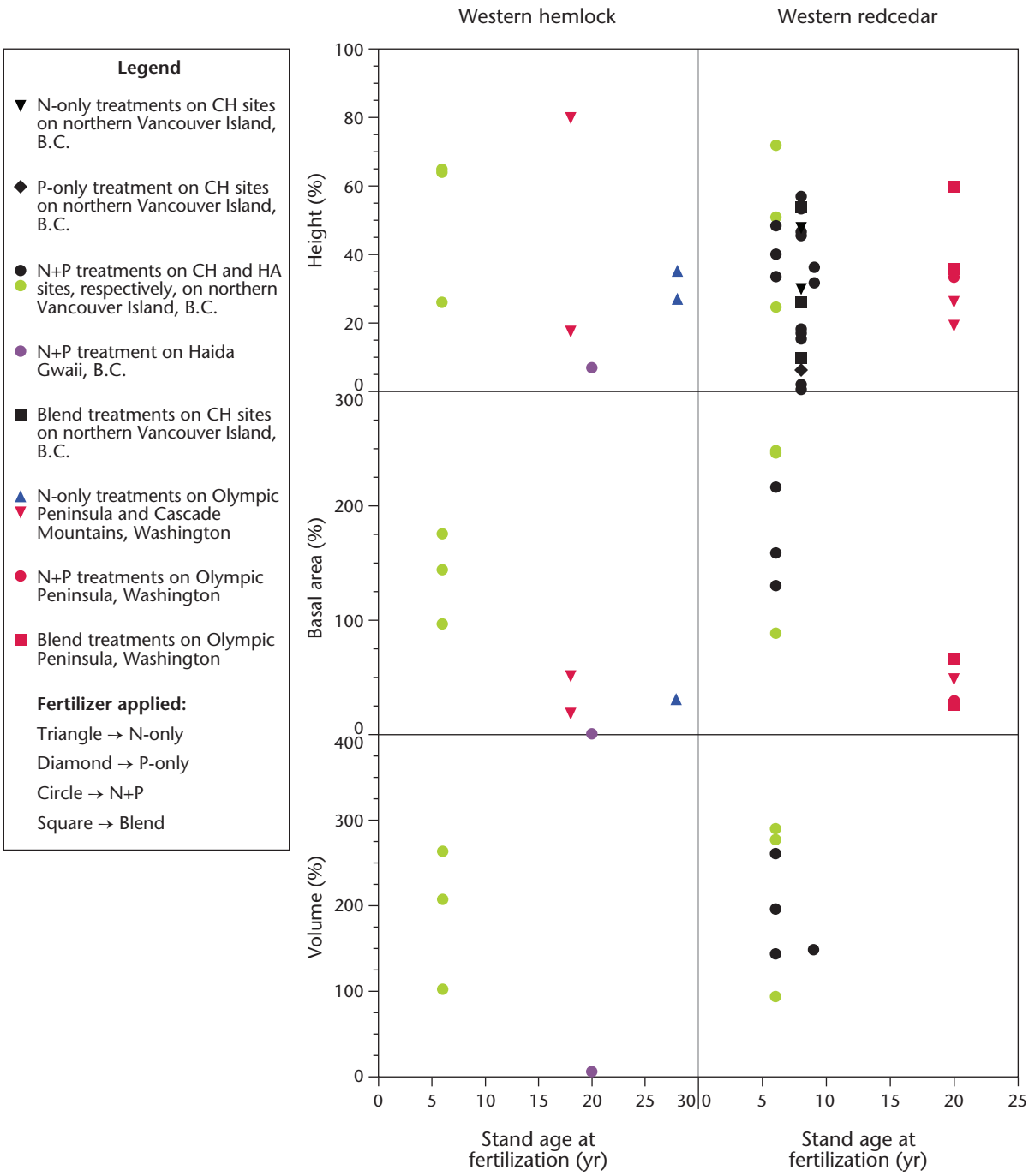

FIGURE 4 *Relative height, basal-area, and volume growth responses (% difference from control plots) as a function of stand age at fertilization for western hemlock and western redcedar in coastal British Columbia and northern Washington. Each point represents a treatment mean.*

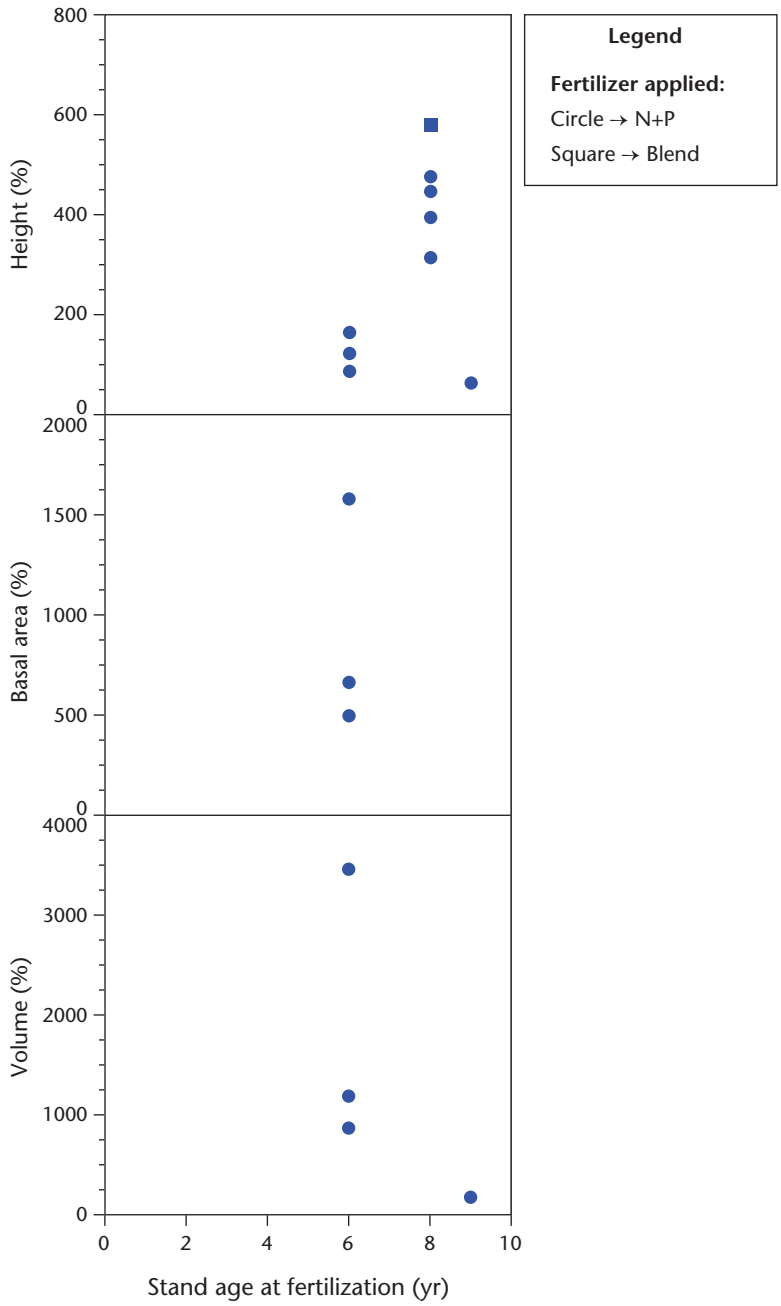

FIGURE 5 *Relative height, basal-area, and volume growth responses (% difference from control plots) as a function of stand age at fertilization for western hemlock on cedar–hemlock (CH) sites on northern Vancouver Island, B.C. Each point represents a treatment mean.*

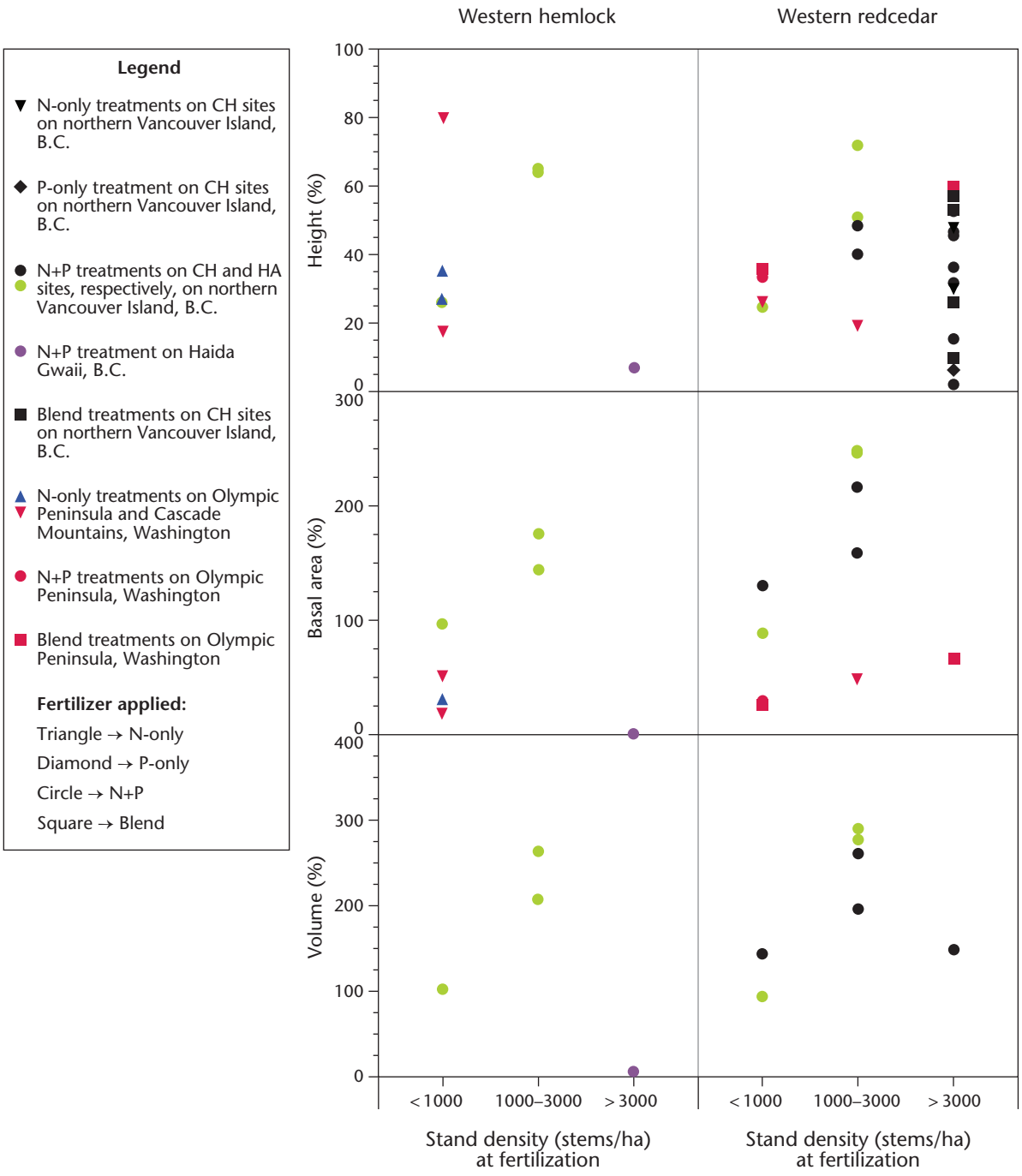

FIGURE 6 *Relative height, basal-area, and volume growth responses (% difference from control plots) as a function of stand density at fertilization for western hemlock and western redcedar in coastal British Columbia and northern Washington. Each point represents a treatment mean.*

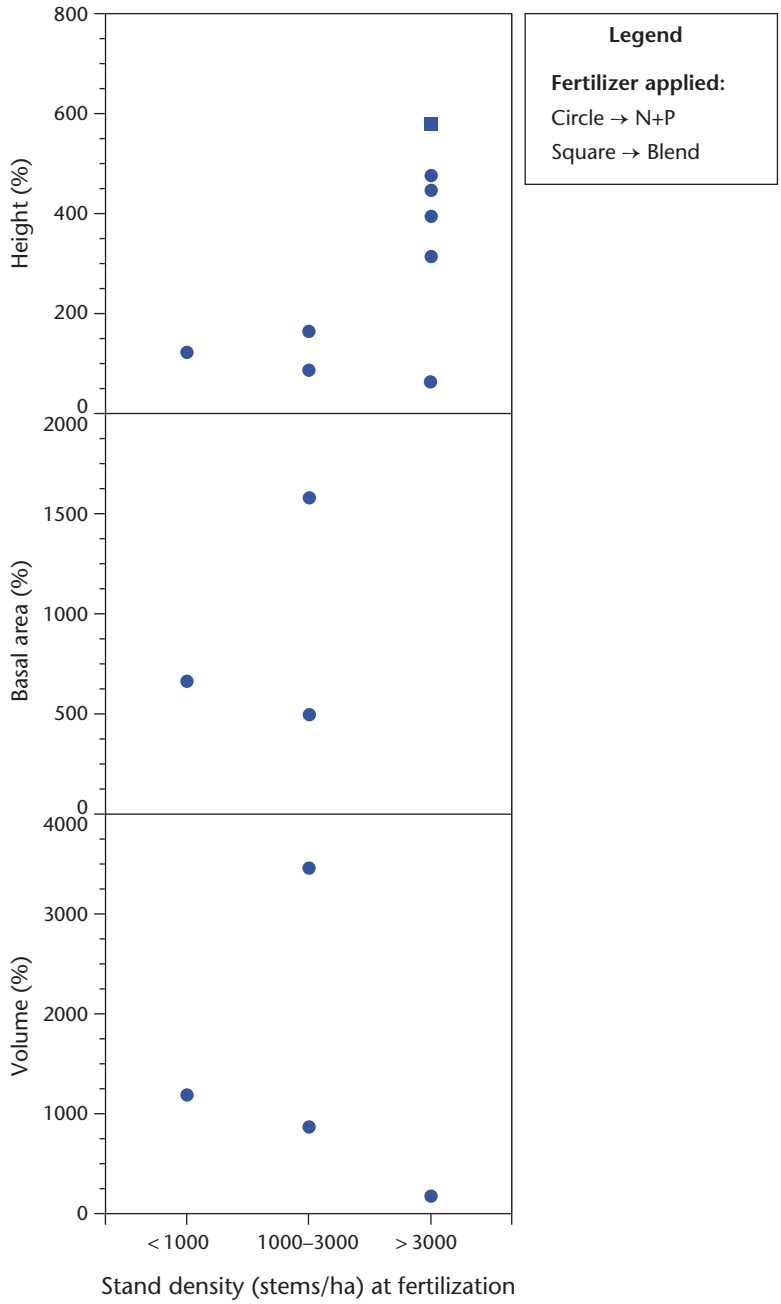

FIGURE 7 *Relative height, basal-area, and volume growth responses (% difference from control plots) as a function of stand density at fertilization for western hemlock on cedar–hemlock (CH) sites on northern Vancouver Island, B.C. Each point represents a treatment mean.*

There was no clear association between the response of western redcedar to fertilization and stand density (Figure 6). One discernable trend was that some of the largest growth responses occurred in medium-density plots. In particular, trees in the medium-density plots had greater relative basal-area and volume growth responses than those in the other density categories (Figure 6). This effect was largely driven by the smaller fertilization responses of western redcedar on CH sites when planted at 2500 stems per hectare than at 1500 stems per hectare (Negrave et al. 2007).

Periodic annual height increment response of amabilis fir to N-only fertilization decreased as the number of trees increased (van Niejenhuis 2004). For example, relative periodic annual height increment growth responses were 51%, 27%, and 17% for 892, 1029, and 1417 stems-per-hectare treatments, respectively. This observation is based on a single study, so no conclusion can be made about the influence of initial stand density on growth response to fertilization in amabilis fir stands.

3.4 Site Quality and Growth Response to Fertilization

Site index was used as an indicator of site quality (B.C. Ministry of Forests 1999). In the database, western hemlock fertilization trials occurred on sites with indices ranging from 17 to 35 m. There was no apparent relationship between relative height growth response to fertilization and site quality (Figure 8). Hemlock stands on CH sites on northern Vancouver Island all occurred on sites with an index < 20 m, so it was not possible to assess the relationship between site index and growth responses to fertilization on CH sites (Figure 9).

For western redcedar, fertilization trials occurred on sites with indices ranging from < 18 to 25 m. There was no clear relationship between site index and relative growth response of western redcedar to fertilization (Figure 8).

Amabilis fir data were too limited to analyze growth response to fertilization in relation to site quality.

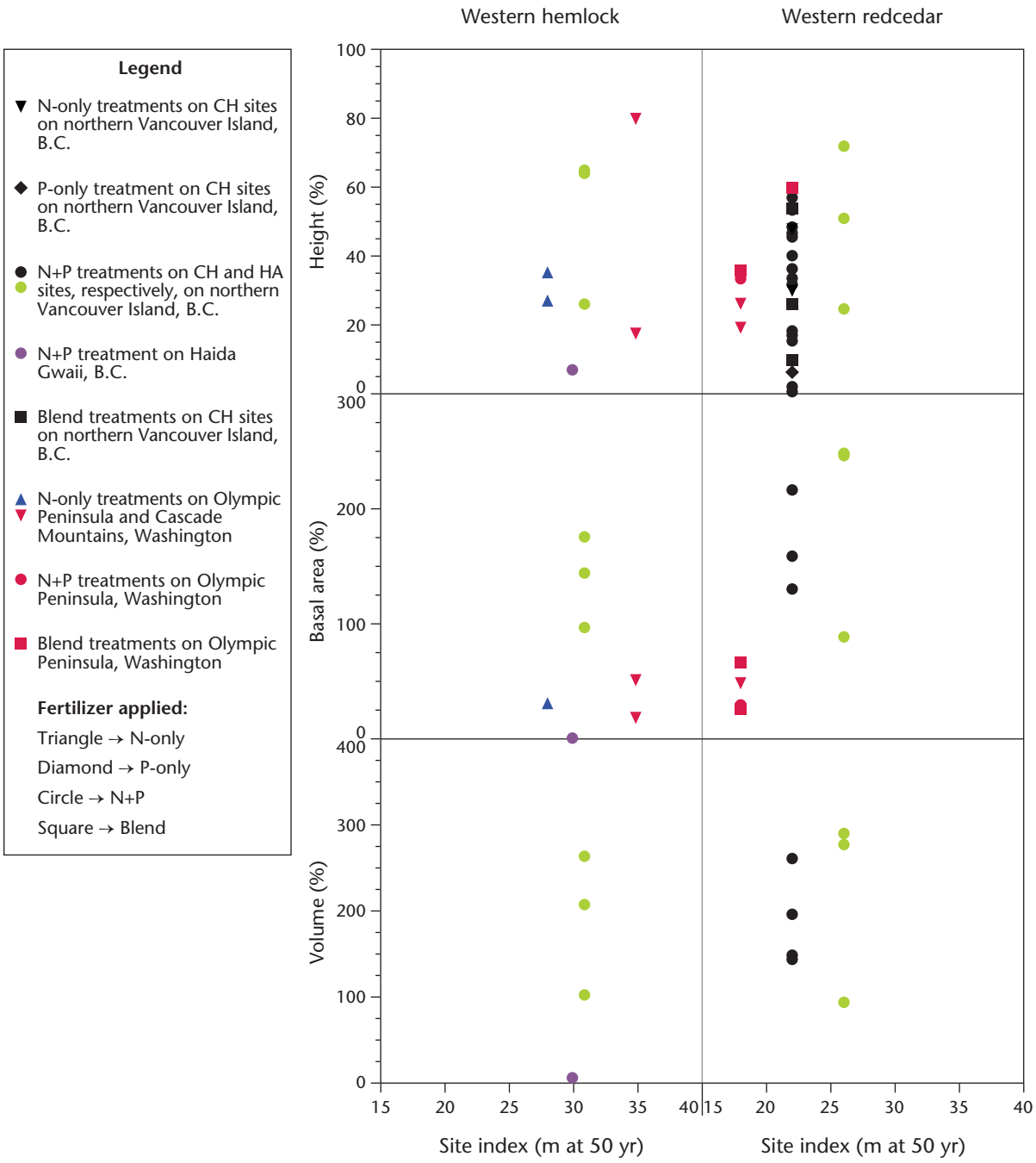

FIGURE 8 *Relative height, basal-area, and volume growth responses (% difference from control plots) as a function of site index at fertilization for western hemlock and western redcedar in British Columbia (B.C.) and northern Washington. Each point represents a treatment mean.*

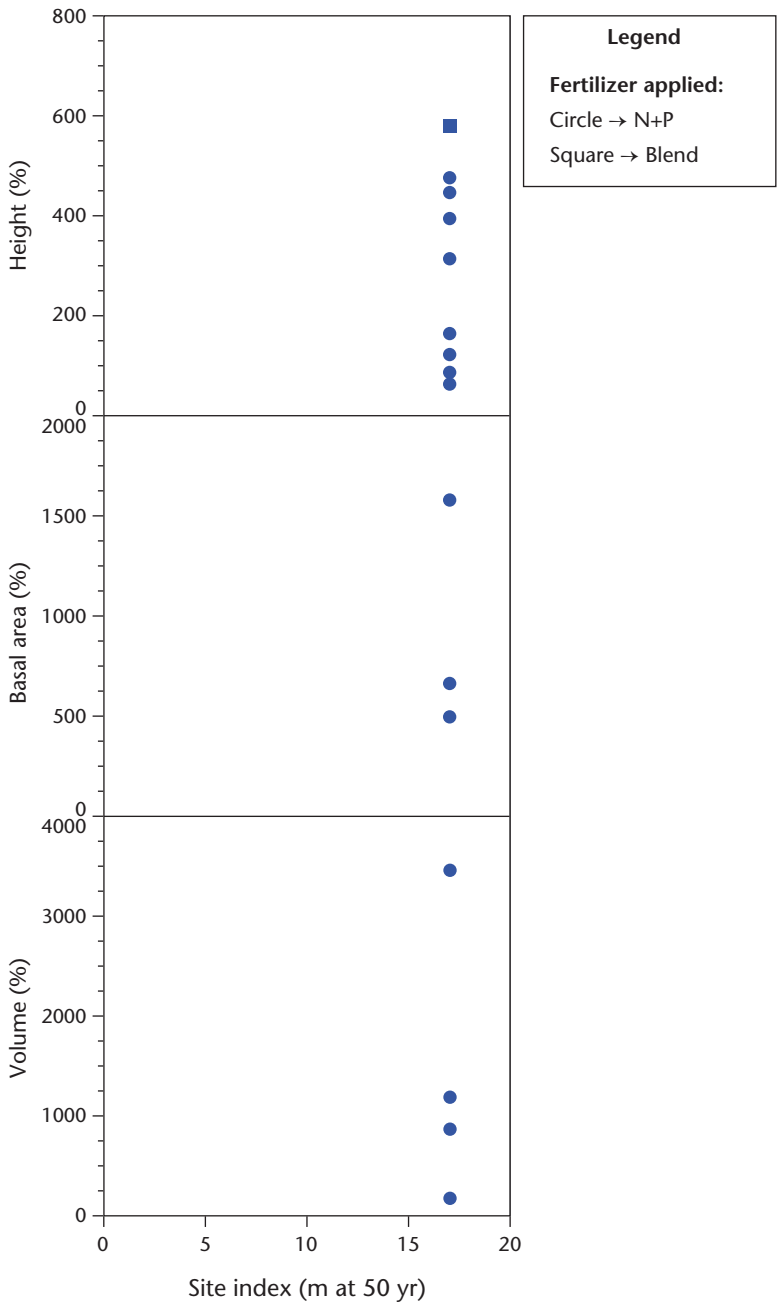

FIGURE 9 *Relative height, basal-area, and volume growth responses (% difference from control plots) as a function of site index at fertilization for western hemlock on nutrient-poor western redcedar–western hemlock (CH) sites on northern Vancouver Island, B.C. Each point represents a treatment mean.*

4.1 Magnitude of Growth Response

4.1.1 Western hemlock Large growth responses of western hemlock to repeated N+P fertilization have been reported from experiments on both CH and HA sites on northern Vancouver Island. While proportional responses are greater on CH sites, absolute-volume responses are greatest on HA sites. On some CH sites, there was a three-fold difference in stand volume between western hemlock fertilized with N+P (32 m^3/ha) and unfertilized western hemlock (11 m^3/ha) (Prescott and Blevins 2005). After 15 years, western hemlock stands on CH sites that were fertilized at planting, fertilized with N+P at 5 years, and refertilized with N at 10 years had an additional 19.5, 20.0, and 35.7 m^3/ha (at 500, 1500, and 2500 stems per hectare) relative to unfertilized stands, while those on HA sites had an additional 20.3, 107.9, and 128.7 m^3/ha (Negrave et al. 2007). Twenty-two years following initial fertilization, repeated fertilization increased volumes of western hemlock on CH sites (at 2500 stems per hectare) by about 100 m^3/ha relative to unfertilized plots, while on HA sites, western hemlock in fertilized plots had produced an extra 250 m^3/ha (at 2500 stems per hectare) (Prescott et al. 2013).

The wide variation in western hemlock response to fertilization on sites other than CH and HA agrees with observations from previous large-scale regional studies on the species (Debell 1975; Webster et al. 1976; Olson et al. 1981; Chappell et al. 1992; Brix 1993; Brown 2003). Summarizing results of N fertilization installations of western hemlock across a network of 1000 plots in British Columbia, Oregon, and Washington, Debell (1975) reported high variability in basal-area growth response, ranging from −20 to +47% in the period 2–6 years after N fertilization. In natural stands of western hemlock in western Oregon and Washington, radial growth response to 227 or 455 kg N/ha ranged from −25 to +38% and −33 to +54% respectively 7 years after treatment (Olson et al. 1981). Negative effects of fertilization on western hemlock growth have been observed in other trials (e.g., Strand 1968; Omule and Britton 1991). In a literature review of fertilization in coastal Pacific Northwest forests, Chappell et al. (1992) characterized western hemlock growth responses as "inconsistent, highly variable, and possibly negative on some sites" and noted that site index had little relation to western hemlock growth response in field trials.

DeBell (1975) speculated that the variability in growth response could be due to factors such as the inability of mensurational techniques to capture responses, N toxicity on roots, and genetic differences in the ability of western hemlock trees to absorb and utilize mineral nutrients, as well as other limiting factors, including soil moisture availability. Olson et al. (1981) attributed the high variability in growth responses to factors such as changes in stand structure, disease incidence, N availability, and deficiencies in other nutrients. Other authors have attributed the erratic response of western hemlock to N fertilization to differences in experimental designs and treatments, adverse effects of nutrients on root growth and mycorrhizae, different nutritional requirements during different stages of stand development, and other growth-limiting factors (e.g., light and physical properties of soil) (Gill and Lavender 1983; Weetman et al. 1992; Brown 2003; Wright et al. 2009).

Carter et al. (2001) attempted to tease out the site factors governing western hemlock response to fertilization in 44 western hemlock stands across the full

range of growing conditions for western hemlock in six regional climates (site index 26–35 m) in British Columbia. Only 12 stands showed a significant basal-area response to N+P fertilization and these stands were found across a wide range of site indices and ecological site qualities. The only factors significantly correlated with growth response were foliar concentrations of P (pre-treatment) and SO_4-S (post-treatment). Foliar P concentrations ranged from 0.10 to 0.27% across the 44 sites. Sites with a significant absolute basal-area response had an average foliar P concentration of 0.14%, while non-responding sites had an average concentration of 0.165%. Foliar P concentrations < 0.15% are thought to represent a moderate-to-severe P deficiency (Brown 2003). Foliar P concentrations in young western hemlock trees in unfertilized plots on CH and HA sites on northern Vancouver Island were both 0.10% (range of 0.09–0.11%) (Negrave et al. 2007); western hemlock trees with foliar P concentrations < 0.11% are considered to be very severely deficient in P (Brown 2003). Foliar N concentrations were 0.76–0.79% on CH sites and 0.86–0.92% on HA sites (Negrave et al. 2007); N concentrations < 1.0% indicate a very severe N deficiency in western hemlock (Brown 2003). In contrast, average foliar P concentrations of western hemlock in the non-responsive stands on Haida Gwaii were 0.14%, and average foliar N concentration was 1.1% (L. de Montigny, unpublished data). These observations indicate that critical foliar nutrient concentrations are currently the most promising means of predicting western hemlock response to fertilization. Further assessment and refinement of critical nutrient concentrations for N and P, as well as exploration of the potential utility of foliar N:P ratios for predicting growth responses to fertilization, are needed.

The physiological response of western hemlock to fertilization was studied by White (2000). He assessed the growth response of 5-year-old western hemlock stands to addition of N-only (225 kg/ha), N+P (100 and 500 kg/ha), and blend (225 kg N/ha, 100 kg P/ha, 60 kg K/ha, 100 kg S/ha, 40 kg Mg/ha, 10 kg Cu/ha, 20 kg Zn/ha, 2.5 kg B/ha) fertilizers, and their relationships to photosynthetic rates and photosynthetic parameters. The addition of N alone resulted in a nearly two-fold increase in photosynthetic rate during the first and second growing seasons. The addition of P at a rate of 300 kg/ha further increased the photosynthetic rate during the fall season. At the end of the second growing season, trees fertilized with N-only or N+P had about six times the foliar biomass of the unfertilized trees. Moreover, fertilization resulted in a two-fold increase in chlorophyll a and b concentrations in foliage, and thylakoid membranes per granum stack increased from 2.4 to 4.3 (White 2000). Concentrations of arginine (the primary form of N stored in many plants) in foliage increased about 160-fold over control levels when fertilized with N alone, which suggests that much of the added N could not be used for growth without additional P. This is consistent with other evidence that both N and P are needed to induce a significant growth response in western hemlock.

4.1.2 Western redcedar Large growth responses of western redcedar to repeated N+P fertilization have been previously reported from experiments on both CH and HA sites on northern Vancouver Island. While proportional responses are greater on CH sites, absolute-volume responses are greatest on HA sites. After 15 years, fertilized western redcedar stands on CH sites (relative to unfertilized stands) had an additional 14.9, 39.3, and 34.3 m^3/ha (at 500, 1500, and 2500 stems per hectare), while those on HA sites had an additional 13.0, 63.6, and 83.9 m^3/ha (Negrave et al. 2007). Twenty-two years following initial

fertilization, repeated fertilization increased volumes of western redcedar on CH sites (at 2500 stems per hectare) by about 100 m^3/ha relative to unfertilized plots, while on HA sites, western redcedar in fertilized plots had produced an extra 180 m^3/ha (at 2500 stems per hectare) (Prescott et al. 2013).

For western redcedar, the results showed that for most sites the response to fertilization was positive. The results concur with findings from previous ancillary studies where both planted and natural stands of western redcedar have been shown to be responsive to addition of N, N+P, or a fertilizer blend (Harrington and Wierman 1985; Weetman et al. 1993; McDonald et al. 1994; Fraser et al. 1995; van Niejenhuis 2004; Blevins et al. 2006; Brodie and Harrington 2010). Harrington and Wierman (1985) examined fertilization (N-only, N+P, N+P+Ca, or N+P+K+Ca+S) effects on a thinned 20-year-old natural western redcedar stand on a poor site in coastal Washington. They reported that 2-year diameter growth was almost two times greater in an unthinned fertilized treatment and three times greater in thinned and fertilized treatments than in the control. Height growth was also significantly greater in unthinned fertilized and thinned fertilized treatments relative to the control. Furthermore, basal-area growth in an unthinned fertilized treatment was more than double that of the control (Harrington and Wierman 1985). Percent diameter at breast height of western redcedar increased significantly in response to addition of 200 kg N/ha every year for 3 years following fertilization, with the greatest effect in the first growing season after application in a natural, mixed-species stand near Olympia, Washington (Brodie and Harrington 2010).

In a 9-year-old western redcedar plantation on a CH site on northern Vancouver Island, McDonald et al. (1994) reported greater diameter and height of trees in plots treated with 225 kg/ha of ammonium nitrate than in control plots. Three-year height and volume increments were significantly higher in western redcedar trees fertilized with urea (225 kg N/ha) in the SCHIRP Installation on northern Vancouver Island (van Niejenhuis 2004). Stand volume growth of planted western redcedar more than doubled 15 years after initial addition of ammonium nitrate (100–300 kg N/ha) on CH sites on northern Vancouver Island (Blevins et al. 2006), but there was no additional effect of P fertilization on growth of western redcedar.

In some few cases, addition of fertilizer has had no effect on growth of western redcedar. On CH sites on northern Vancouver Island, Bennett et al. (2003) reported that addition of N+P (250 kg N/ha and 100 kg P/ha) did not increase the height of western redcedar 10–13 years after application. However, western redcedar seedlings grown on the forest floor from plots fertilized 10 years earlier were significantly larger than those on the forest floor from unfertilized plots, and growth of western redcedar was improved in plots in which salal was controlled. The lack of fertilization response in western redcedar was attributed to competition or interference from salal. Three-year height increment of naturally regenerated western redcedar saplings on central Vancouver Island did not differ in plots fertilized with N or N+P and unfertilized plots (van Niejenhuis 2004), which was attributed to the stands being 23–36 years old. Finally, Kranabetter et al. (2013) assessed the influence of fertilization and salal control on western redcedar plantations in an operational trial on Porcher Island, near Oona River, B.C. They reported no gains in soil fertility or growth 12 years following the addition of 75 kg P/ha as triple superphosphate. The authors concluded that fertilization and salal control

stimulated the natural establishment of red alder (*Alnus rubra*), which competed with western redcedar (Kranabetter et al. 2013).

4.1.3 Amabilis fir The results from this analysis, and findings of a few other studies, indicate that amabilis fir responds positively to fertilization on some low- and high-elevation coastal sites in British Columbia. Weetman et al. (1993) assessed responses of coastal conifers, including amabilis fir, to organic and inorganic fertilizers on CH sites on northern Vancouver Island. Addition of ammonium nitrate (225 kg N/ha) and triple superphosphate (75 kg P/ha) significantly increased growth of planted amabilis fir at the end of the first growing season. During the first two growing seasons, addition of 24 g per seedling of slow-release Nutricote (16-10-10) fertilizer to planted amabilis fir resulted in higher stem-volume increment than in unfertilized seedlings, even without control of competing vegetation on the MASS field trial site on eastern Vancouver Island (Arnott and Beese 1997). On an experimental trial site near Holberg, northwestern Vancouver Island, Titus et al. (2006) reported that root collar diameter of amabilis fir seedlings increased 5 years after the addition of 10 g per seedling of Schirp-Pak 1-2 fertilizer (equivalent to 2.6 and 0.9 g of N and P per pack). Total height and stem-volume growth did not respond to fertilization.

Mitchell et al. (2004) reported that basal-diameter and height growth were greater in amabilis fir trees fertilized at planting with 24 g of Nutricote (4 g N, 1 g P, and 2 g K) than in unfertilized plots on the MASS sites on eastern Vancouver Island. These studies indicate that fertilizing amabilis fir may be successful on some sites.

Although amabilis fir responds positively to fertilization in some situations, the addition of N or P does not always lead to increased growth of both natural and planted stands (Hawkins and Moran 2003; Titus et al. 2006). Hawkins and Moran (2003) examined potential factors limiting growth of advanced regeneration of amabilis fir on 72 experimental plots on a montane site on eastern Vancouver Island. They reported that addition of three levels of N (0, 100, and 250 kg/ha) had no effect on diameter and height growth and on biomass production of naturally regenerated amabilis fir seedlings 5 years after treatments. Moreover, amabilis fir seedlings showed no growth response to the addition of 100 kg P/ha as triple superphosphate on 24 plots (Hawkins and Moran 2003). Fertilization resulted in increased uptake of nutrients, but this did not lead to improved seedling growth. Likewise, amabilis fir plantations near Jordan River, southwestern Vancouver Island, did not respond to one-time application of 10g of Schirp-Pak 1-2 fertilizer 5 years after treatment (Titus et al. 2006).

The lack of response to fertilization may be partly attributable to the presence of competing vegetation and life history of the species (Crawford and Oliver 1990; Klinka et al. 1992; Hawkins and Moran 2003). Previous studies have shown that amabilis fir responds better to fertilization when competing vegetation is controlled (Hawkins and Moran 2003; Mitchell et al. 2007). Height growth of amabilis fir on Vancouver Island almost doubled from 93–148 m at 3 years after fertilization and control of *Vaccinium* spp. to 216–334 m after 10 years (Mitchell et al. 2007). Shrubs such as huckleberry (*Vaccinium* spp.), salal, and fireweed (*Epilobium angustifolium*) are commonly associated with post-harvest natural regeneration of amabilis fir (Crawford and Oliver 1990; Weetman and Prescott 2001; Mitchell et al. 2007). *Vaccinium* spp. and *E. angustifolium*

suppress growth of amabilis fir by competing for nutrients, particularly N, and light (Hawkins and Moran 2003; Titus et al. 2006; Mitchell et al. 2007). Thus, combining fertilization and vegetation control is suggested to have a greater effect on growth of amabilis fir (Mitchell et al. 2007). Amabilis fir has been found to have high nutrient-use efficiency compared with other conifers in the Pacific Northwest (Radwan and Debell 1989) and so may meet its nutrient requirements through efficient internal nutrient redistribution (Meier et al. 1985; Crawford and Oliver 1990; Hawkins et al. 1999).

4.2 Stand Age and Growth Response to Fertilization

Results from the current analysis do not show a clear relationship between growth responses of western hemlock to fertilization and stand age. There are some indications from trials in the Pacific Northwest that hemlock stands less than about 25 years old are more responsive than older stands. In a regional analysis of western hemlock stands in the Pacific Northwest, Debell (1975) found that basal-area growth response to N was similar across stand age classes, but some of the largest growth responses occurred in young (15- to 30-year-old) western hemlock stands that were thinned. In 26 installations in natural western hemlock stands in Washington and Oregon, radial growth response to N fertilization in thinned stands was greater in 10- to 20-year-old stands than in 21- to 40-year-old stands (Olson et al. 1981). In unthinned stands, N fertilization induced greater radial growth in 15- to 24-year-old stands compared with younger (<15 years) and older stands (>25 years) (Olson et al. 1981). In RFNRP trials in Washington, growth response to N fertilizer application was better in 12- to 23-year-old western hemlock stands than in 24- to 35-year-old stands (Peterson 1982). In naturally regenerated 35- to 65-year-old western hemlock stands on northern Vancouver Island, no significant relationships were detected between initial stand age and net basal-area responses to fertilization, thinning, and combined fertilization and thinning (Omule and Britton 1991); however, these stands were between 35 and 65 years old. Basal-area growth response to 225 kg N/ha was not related to stand age in 11- to 35-year-old western hemlock plantations at 44 sites in coastal British Columbia (Carter et al. 2001).

For western redcedar, van Niejenhuis (2004) attributed the lack of fertilization response of some stands on northern Vancouver Island to them being 23–36 years old, as younger western redcedar stands in the same area were responsive to fertilization.

Some operational fertilization programs target younger stands with the expectation of greater response, because young stands are likely to be in a period of crown expansion when nutrient requirements and uptake rates are high (Olson et al. 1981; Brix 1993). Young stands may also have more efficient crowns and are likely to take advantage of the added nutrients (Chappell et al. 1992). In contrast, older stands generally have lower live-crown ratios due to competition, and their response to added nutrients may be limited by room for crown expansion (Chappell et al. 1992). Nevertheless, older stands are often operationally fertilized due to the economic benefits of late-rotation fertilization (Webster et al. 1976; Harrington and Wierman 1990; Antos et al. 2016).

4.3 Stand Density and Growth Response to Fertilization

Several studies have assessed how initial stand density or thinning interact with fertilization to influence western hemlock growth. Debell (1975) reported that western hemlock trees growing in thinned stands generally responded slightly better to N fertilizer than trees in unthinned stands in the Pacific Northwest. On Haida Gwaii, trees in stands thinned to 1600 stems per hectare responded more to fertilization (250 kg N/ha and 100 kg P/ha) than did trees in unthinned stands (Reynolds and de Montigny 2015). After 20 years, the lightly thinned and fertilized stand had reached the volume of the dense, unthinned, and unfertilized control (Reynolds and de Montigny 2015). In installations of Experimental Project 703 in British Columbia (Omule and Britton 1991), cumulative net basal-area response of western hemlock to combined fertilization (225 kg N/ha) and thinning (20% basal area removed) was higher than that of thinning or fertilization alone. Additional basal area resulting from fertilizing thinned stands ranged from 2 to 7 m^2/ha after 9 years. Reports from the RFNRP and Weyerhaeuser installations also indicated that thinned western hemlock stands are more responsive to fertilization than unthinned stands in Oregon and Washington (Webster et al. 1976; Olson et al. 1981; Chappell et al. 1992). Nonetheless, thinned western hemlock stands did not consistently respond to N fertilization (Olson et al. 1981), suggesting that factors other than growing space influence western hemlock response to N fertilization.

In naturally regenerated western redcedar stands in Washington, precommercial thinning (to 1100 trees per hectare) did not affect diameter growth response to fertilization with N and P (300 kg N/ha and 100 kg P/ha), during the first 5 years, and basal-area growth was greater in unthinned than thinned stands during this phase (Harrington and Wierman 1990). However, during years 13 through 25, the highest individual-tree basal-area growth was in plots that received both fertilization and thinning (Devine and Harrington 2009). Combined fertilization and thinning resulted in the largest individual trees, and many trees in different diameter classes (Harrington and Devine 2010). The authors interpreted the greater benefit of thinning to fertilized trees during years 13 through 25 to more intense competition among trees during this stage of stand development (Devine and Harrington 2009). On northern Vancouver Island, volume growth of fertilized western redcedar in plots planted to 500 stems per hectare did not reach that of plots planted to 1500 and 2500 stems per hectare during the 22 years following initial treatment (Prescott et al. 2013).

Combined fertilization and thinning is often recommended because these treatments result in greater foliar biomass, photosynthesis, and growth (Harrington and Wierman 1985; Chappell et al. 1992; Brix 1993) and distribute the growth gain from fertilization among fewer, larger stems (Lee 1968; Chappell et al. 1992; Harrington and Devine 2010), thereby producing a greater amount of valuable wood (Omule and Britton 1991).

4.4 Site Quality and Growth Response to Fertilization

Site index is often used as a measure of site quality in relating growth response to fertilization (e.g., Debell 1975; Brix 1993), but complex relationships have been reported in the literature. Site index may underestimate potential site productivity because it does not consistently associate with nutrient availability (Kayahara et al. 1995), nor does it take into account all the factors that influence growth response to fertilization (Chappell et al. 1992). For western hemlock,

some studies have suggested that growth response is greater on poorer sites. In a review of western hemlock responses to N fertilization in the Pacific Northwest, Debell (1975) reported that growth response tended to decrease as site index increased. Radwan et al. (1984) reported that relative height, basal-area, and volume growth responses of 17- to 28-year-old natural stands of western hemlock to N fertilization were greater in plots on the nutrient-poor Cascade Mountains than on nutrient-rich coastal sites in Washington. They attributed the poor response on the coastal sites to high total and mineral N and low P in the soils (Radwan et al. 1984).

Other studies have concluded that western hemlock growth response is unrelated to site quality. Webster et al. (1976) analyzed a network of regional and Weyerhaeuser fertilization trials on western hemlock in Oregon and Washington, covering a site index range (at age 50) of 20–38 m, and found no clear relationship between growth response and site quality. In coastal and Cascade zones of western Washington, site index did not correlate with western hemlock growth response to N fertilization (Radwan and Shumway 1983). Chappell et al. (1992) found no relationship of site index to western hemlock fertilization response in the Pacific Northwest. At sites spanning the ecological range of western hemlock in British Columbia, Carter et al. (2001) did not find any relationship between site quality and western hemlock growth response to fertilization.

Yet other studies have reported better western hemlock responses to N or N+P fertilization on good-quality sites. Van den Driessche et al. (2002)[3] found that spaced stands of young (11–18 years old) natural western hemlock on good-quality sites had greater volume response to N+P than did western hemlock stands on poor- and medium-quality sites. Omule and Britton (1991) reported that the best net basal-area responses to N fertilizer were found in thinned stands on fresh and moist sites on northern Vancouver Island, while the poorest responses were observed in unthinned stands on moderately dry sites. Likewise, Negrave et al. (2007) found greater 5-year periodic annual increments in volume of western hemlock on HA sites (site index at 50 years [SI50] 31m) than on CH sites (SI50 17m), 10 growing seasons after fertilization. These findings prompted Negrave et al. (2007) to recommend giving HA sites priority for fertilization over CH sites. After 22 years, volumes of both western redcedar and western hemlock on CH sites (at 2500 stems per hectare) were about 100 m^3/ha greater than those on unfertilized plots; on HA sites, volumes of western redcedar in fertilized plots were about 180 m3/ha greater than those in unfertilized plots, while western hemlock volumes were about 250 m3/ha greater in fertilized plots (at 2500 stems per hectare) (Prescott et al. 2013).

The lack of relationship between fertilization growth response and site quality in this synthesis may be attributable to the small number of studies and the necessity of using response ratio to accommodate the differences in stand age and density among the studies. Dedicated research trials are needed to elucidate the relationship between site quality and growth response of these species.

3 van den Driessche, R., K.R. Brown, and J.S. Sandford. 2002. Growth responses of juvenile western hemlock to N, P, K, and S fertilization in different combinations on two sites. Unpubl. manuscript.

5 CONCLUSIONS AND INFORMATION NEEDS

From this synthesis of the published literature on responses of western hemlock, western redcedar, and amabilis fir to fertilization in British Columbia and northern Washington, we make the following conclusions:

1. Addition of N alone or a combination of N and P usually increases growth of the three species.
2. The strongest and most consistent growth responses of both western hemlock and western redcedar result from fertilization (repeated N, single P) of both CH and HA sites on northern Vancouver Island.
3. The response of western hemlock is more variable than that of western redcedar.
4. The effect of stand age on response to fertilization is difficult to discern, but younger stands tend to respond more than older stands.
5. Stand density does not have a clear relationship with growth response of western hemlock and western redcedar, but thinning usually increases their growth response to fertilization.
6. The responses of western hemlock and western redcedar to fertilization do not appear to be related to the quality of the site, but dedicated research trials are needed to properly address this issue.
7. Foliar nutrient concentrations are the most promising indicator of potential growth response of western hemlock to fertilization.

Although the established networks of research installations and fertilization trials have increased understanding of the growth responses of western hemlock, western redcedar, and amabilis fir to fertilization, additional information is needed to support current and future reforestation efforts under the Forests for Tomorrow (FFT) program and the Forest Carbon Initiative (FCI). This synthesis of the published literature indicates the following priority information needs:

- growth responses to repeated fertilization, and response duration
- fertilization response in older stands (>30 years old; thinned and unthinned)
- fertilization of sites other than northern Vancouver Island
- fertilization effects on amabilis fir
- growth responses in mixed-species stands
- factors underlying variable response of western hemlock
- assessment of relationships among stand age, stand density, and crown characteristics on growth responses to fertilization
- field experiments that specifically assess the relationship between site quality and growth responses of western hemlock to fertilization
- further assessment of the reliability of foliar nutrient concentrations and ratios for predicting growth response of western hemlock and other coastal tree species to fertilization

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TABLE A1.1 *Overview of western hemlock studies used in the synthesis*

Reference	Description
Reynolds and de Montigny 2015	Naturally regenerated western hemlock in mixed Western hemlock-Sitka spruce stands fertilized with prilled urea and triple superphosphate once. Stands were located in CWHwh1 on Haida Gwaii, B.C., and thinning treatments were applied. Stands were approximately 20 years old, and initial stand density ranged from 5968 to 7195 stems/ha prior to fertilization. Site index at age 50 years breast height was 30 m for Hw.
Weetman et al. 1989	Planted western hemlock fertilized with ammonium nitrate, triple superphosphate and micronutrients once. Plantations were located between Port McNeill and Port Hardy in CWHvm1 on northern Vancouver Island, B.C. Trial was established on Cedar-Hemlock site (site index at age 50 years breast height, 17 m). Plantations were 7 years old, and initial stand density was 3300 stems/ha.
Prescott and Blevins 2005	Four installations fertilized once with organic fertilizer (municipal biosolids) or chemical fertilizer (ammonium nitrate and triple superphosphate). Plantations were located between Port McNeill and Port Hardy in CWHvm1 zone on northern Vancouver Island, B.C. Trial was established on Cedar-Hemlock site (site index at age 50 years breast height, 17 m). Plantations were 9 years old, and initial stand density was 3300 stems/ha.
Negrave et al. 2007	Western hemlock planted at three stand densities (500, 1500, and 2500 stems/ha) fertilized with NPK once. Experimental trial was established on both Cedar-Hemlock (site index at age 50 years breast height, 17 m) and Hemlock-Amabilis fir (HA) sites (site index at age 50 years breast height, 31 m) located between Port McNeill and Port Hardy in CHWvm1 on northern Vancouver Island, B.C. Stands were 15 years old.
Prescott et al. 2013	Western hemlock planted at three stand densities (500, 1500, and 2500 stems/ha) fertilized earlier with NPK, and again with N. Trial was established on both Cedar-Hemlock, (CH) (site index at age 50 years breast height, 17 m) and Hemlock-Amabilis fir (HA) sites (site index at age 50 years breast height, 31 m) in CHWvm1 on northern Vancouver Island, B.C. Stands were 22 years old.
Radwan et al. 1984	Western hemlock growing in natural stands located both in the coastal hemlock zone and in the Cascades, Washington were fertilized with urea and ammonium nitrate once. Stands were from 17 to 28 years old, with initial stand density ranging from 270 to 325 for hemlock in coastal sites and 800 for those on the Cascade Mountains. Site index at age 50 years breast height was 35 m for coast and 25 m in Cascades.
Devine and Harrington 2009	Naturally regenerated western hemlock fertilized with urea or ammonium nitrate only, and ammonium nitrate plus triple superphosphate repeatedly. Stands were located on Olympic Peninsula in Washington, and were approximately 15–20 years. Stands were fertilized following precommercial thinning with stand densities ranging between 920 and 6290.
Harrington and Devine 2011	Naturally regenerated western hemlock fertilized with urea or ammonium nitrate only, and ammonium nitrate plus triple superphosphate repeatedly. Stands were located on Olympic Peninsula in Washington, and were approximately 15–20 years. Stands were fertilized following precommercial thinning with stand densities ranging between 920 and 6290.

CWHwh1: Coastal Western Hemlock Submontane Wet Hypermaritime biogeoclimatic variant; CWHvm1: Coastal Western Hemlock Submontane Very Wet Maritime biogeoclimatic variant.

TABLE A1.2 *Overview of western redcedar studies used in the synthesis*

Reference	Description
Weetman et al. 1989	Naturally regenerated western redcedar fertilized with ammonium nitrate, triple superphosphate and micronutrients once. Stands were located between Port McNeill and Port Hardy in CWHvm1 zone on northern Vancouver Island, B.C. Trial was established on Cedar-Hemlock (CH) sites (site index at age 50 years breast height, 22 m). Stands were 8 years old, and initial stand density was 3300 stems/ha.
Weetman et al. 1989	Planted western redcedar fertilized with ammonium nitrate, triple superphosphate and micronutrients once. Plantations were located between Port McNeill and Port Hardy in CWHvm1 zone on northern Vancouver Island, B.C. Trial was established on Cedar-Hemlock (CH) sites (site index at age 50 years breast height, 22 m).Plantations were 8 years old, and initial stand density was 3300 stems/ha.
Prescott and Blevins 2005	Four installations fertilized once with organic fertilizer (municipal biosolids) or chemical fertilizer (ammonium nitrate and triple superphosphate). Plantations were located between Port McNeill and Port Hardy in CWHvm1 zone on northern Vancouver Island, B.C. Trial was established on Cedar-Hemlock (CH) sites (site index at age 50 years breast height, 22 m).Plantations were 9 years old, and initial stand density was 3300 stems/ha.
Negrave et al. 2007	Western redcedar planted at three stand densities (500, 1500 and 2500 stems/ha) fertilized with NPK once. Experimental trial was established on both Cedar-Hemlock (CH) sites (site index at age 50 years breast height, 22 m) and Hemlock-Amabilis fir (HA) (site index at age 50 years breast height, 25 m) located between Port McNeill and Port Hardy in CHWvm1 zone on northern Vancouver Island, B.C. Stands were 6 years old.
Prescott et al. 2013	Western redcedar planted at three stand densities (500, 1500 and 2500 stems/ha) fertilized earlier with NPK, and again with N. Experimental trial was established on both Cedar-Hemlock (CH) sites (site index at age 50 years breast height, 22 m) and Hemlock-Amabilis fir (HA) (site index at age 50 years breast height, 25 m) located between Port McNeill and Port Hardy in CHWvm1 zone on northern Vancouver Island, B.C. Stands were 17 years old.
Harrington and Wierman 1990	Naturally regenerated western redcedar stand was fertilized with urea or ammonium nitrate, monodicalcium phosphate and potassium sulfate once. The fertilization trial was established on a poor-quality site (site index at age 50 years breast height, 20 m) about 10 km from the Pacific Coast in Clallum County, Washington. Stand was 15-20 years old, and stands thinned, and initial stand density ranged from 915 to 6290 stems/ha.
Devine and Harrington 2009	Naturally regenerated western redcedar fertilized with urea or ammonium nitrate only, and ammonium nitrate plus triple superphosphate repeatedly. Stands were located on Olympic peninsula in Washington, and were approximately 15 to 20 years. Stands were fertilized following precommercial thinning with stand densities ranging between 920-6290. Site index at age 50 years breast height was 18 m.
Harrington and Devine 2011	Naturally regenerated western redcedar fertilized with urea or ammonium nitrate only, and ammonium nitrate plus triple superphosphate repeatedly. Stands were located on Olympic peninsula in Washington, and were approximately 15 to 20 years. Stands were fertilized following precommercial thinning with stand densities ranging between 920-6290. Site index at age 50 years breast height was 18 m.

CWHwh1: Coastal Western Hemlock Submontane Wet Hypermaritime biogeoclimatic variant; CWHvm1: Coastal Western Hemlock Submontane Very Wet Maritime biogeoclimatic variant.

TABLE A1.3 *Overview of amabilis fir studies used in the synthesis*

Reference	Description
Prescott and Brown 1998	Planted amabilis fir was fertilized with organic fertilizer (municipal biosolids, municipal biosolids mixed with pulp sludge, fish silage mixed with wood ash, silage and ash mixed with pulp sludge, wood ash alone) or chemical fertilizer (ammonium nitrate and triple superphosphate) once. Plantations were located between Port McNeill and Port Hardy in CWHvm1 zone on northern Vancouver Island, B.C. Plantations were 9 years old, and initial stand density was 3300 stems/ha.
Prescott and Blevins 2005	Four installations fertilized with organic fertilizer (municipal biosolids) or chemical fertilizer (ammonium nitrate and triple superphosphate) once. Plantations were located between Port McNeill and Port Hardy in CWHvm1 zone on northern Vancouver Island, B.C. Plantations were 9 years old, and initial stand density was 3300 stems/ha.

CWHvm1: Coastal Western Hemlock Submontane Very Wet Maritime biogeoclimatic variant.

APPENDIX 2 Location, elevation, biogeoclimatic zone, site series, and soil classification of studies used in the synthesis

TABLE A2.1 *Location, elevation, biogeoclimatic zone, site series and soil classification of western hemlock studies used in the synthesis*

Reference	ID	Latitude	Longitude	Elevation (m)	BEC zone	BEC unit	Site series	Soil classification
Reynolds and de Montigny 2015	01	53°40'N	132°30'W	140–180	CWH	wh1	01	–
Weetman et al. 1989	02–06	50°60'N	127°35'W	50	CWH	vm1	03	Deep mor-humus Podzol
Prescott and Blevins 2005	07	50°60'N	127°35'W	< 300	CWH	vm1	03	Duric Humo-Ferric Podzols
Negrave et al. 2007	08–13	50°60'N	127°35'W	50	CWH	vm1	03	Duric Humo-Ferric Podzols
Prescott et al. 2013	14–19	50°60'N	127°35'W	50	CWH	vm1	03	Duric Humo-Ferric Podzols
Radwan et al. 1984	20–23	–	–	270–800	–	–	–	Sandstone and pumice over andesite
Harrington and Devine 2011	24–26	48°08'N	124°38'W	100	–	–	Kydaka	Humic Gleyson with mor humus

CWH: Coastal Western Hemlock; wh1: Submontane Wet Hypermaritime biogeoclimatic variant; vm1: Submontane Very Wet Maritime biogeoclimatic variant.

TABLE A2.2 *Location, elevation, biogeoclimatic zone, site series and soil classification of western redcedar studies used in the synthesis*

Reference	ID	Latitude	Longitude	Elevation (m)	BEC zone	BEC unit	Site series	Soil classification
Weetman et al. 1989	35–41	50°60'N	127°35'W	50	CWH	vm1	03	Deep mor-humus Podzol
Prescott and Blevins 2005	42	50°60'N	127°35'W	< 300	CWH	vm1	03	Duric Humo-Ferric Podzols
Negrave et al. 2007	43–48	50°60'N	127°35'W	50	CWH	vm1	03	Duric Humo-Ferric Podzols
Prescott et al. 2013	49–54	50°60'N	127°35'W	50	CWH	vm1	03	Duric Humo-Ferric Podzols
Harrington and Wierman 1990	55–59	48°08'N	124°38'W	100	–	–	Kydaka	Humic Gleyson with mor humus
Devine and Harrington 2009	60–62	48°08'N	124°38'W	100	–	–	Kydaka	Humic Gleyson with mor humus
Harrington and Devine 2011	63–65	48°08'N	124°38'W	100	–	–	Kydaka	Humic Gleyson with mor humus

CWH: Coastal Western Hemlock; vm1: Submontane Very Wet Maritime biogeoclimatic variant.

TABLE A2.3 *Location, elevation, biogeoclimatic zone, site series and soil classification of amabilis fir studies used in the synthesis*

Reference	ID	Latitude	Longitude	Elevation (m)	BEC zone	BEC unit	Site series	Soil classification
Prescott and Brown 1998	66	50°60'N	127°35'W	50	CWH	vm1	03	Duric Humo-Ferric Podzols
Prescott and Blevins 2005	67	50°60'N	127°35'W	50	CWH	vm1	03	Duric Humo-Ferric Podzols

CWH: Coastal Western Hemlock; vm1: Submontane Very Wet Maritime biogeoclimatic variant.

APPENDIX 3 Stand description of tree species

TABLE A3.1 *Stand descriptions of western hemlock studies used in the synthesis*

Reference	ID	Site history	Site index (m at 50 years)	Stand density pre-thin or at establishment (stems/ha)	Stand density post-thin or at fertilization (stems/ha)	Stand age at fertilization (yr)	Stand age at post-fertilization measure (yr)	Year of fertilization	Year of post-fertilization measure
Reynolds and de Montigny 2015	01	Harvested in 1966 and 1970, natural regeneration	30	5968–7195	971–3189	20	39	1991	2010
Weetman et al. 1989	02–06	Logged in 1978–1980, broadcast burned	17	3300	–	7	10	1987	1989
Prescott and Blevins 2005	07	Clearcut and burned in 1981 and planted with conifers in 1982	17	3300	–	9	20	1990	2001
Negrave et al. 2007	08–13	Clearcut in 1986, broadcast and burned and planted in 1987	17, 31	500–2500	500–2500	6	11–16	1993	2002
Prescott et al. 2013	14–19	Clearcut in 1986, broadcast and burned and planted in 1987	17, 31	500–2500	500–2500	9 and 17	22	1993 and 2004	2009
Radwan et al. 1984	20–23	Naturally regenerated stands. Closed canopy with negligible understorey vegetation	28 (Cascade) and 35 (Coastal)	270–800	–	28 (Cascade) and 17–19 (Coastal)	32 (Cascade) 21-23 (Coastal)	1978	1982
Harrington and Devine 2011	24–26	Clearcut in 1961, salvage harvested, trials established in naturally regenerated stands in 1981	18	5350	8365	15–20 and 28–33	40–45	1981 and 1993	2005

TABLE A3.2 *Stand descriptions for western redcedar studies used in the synthesis*

Reference	ID	Site history	Site index (m at 50 years)	Stand density pre-thin or at establishment (stems/ha)	Stand density post-thin or at fertilization (stems/ha)	Stand age at fertilization (yr)	Stand age at post-fertilization measure (yr)	Year of fertilization	Year of post-fertilization measure
Weetman et al. 1989	27–41	Logged in 1978–1980, broadcast burned	22	3300	–	8	3	1985	1990
Prescott and Blevins 2005	42	Clearcut and burned in 1981 and planted with conifers in 1982	22	3300	–	9	20	1990	2001
Negrave et al. 2007	43–48	Clearcut in 1986, broadcast and burned and planted in 1987	22, 26	500–2500	500–2500	6	11–16	1993	2002
Prescott et al. 2013	49–54	Clearcut in 1986, broadcast and burned and planted in 1987	22, 26	500–2500	500–2500	6 and 17	22	1993 and 2004	2009
Harrington and Wierman 1990	55–59	Clearcut in 1961, salvage harvested, trials established in naturally regenerated stands in 1981	20	915–6290	915–6290	15–20	5	1981	1985
Devine and Harrington 2009	60–62	Clearcut in 1961, salvage harvested, trials established in naturally regenerated stands in 1981	18	920–6290	920–6290	15–20 and 28–33	40–45	1981 and 1993	2006
Harrington and Devine 2011	63–65	Clearcut in 1961, salvage harvested, trials established in naturally regenerated stands in 1981	18	920–6290	920–6290	15–20 and 28–33	40–45	1981 and 1993	2006

TABLE A3.3 *Stand descriptions for amabilis fir studies used in the synthesis*

Reference	ID	Site history	Site index (m at 50 years)	Stand density pre-thin or at establishment (stems/ha)	Stand density post-thin or at fertilization (stems/ha)	Stand age at fertilization (yr)	Stand age at post-fertilization measure (yr)	Year of fertilization	Year of post-fertilization measure
Prescott and Brown 1998	66	Clearcut and burned in 1981 and planted with conifers in 1982	–	3300	–	9	5	1990	1995
Prescott and Blevins 2005	67	Clearcut and burned in 1981 and planted with conifers in 1982	–	3300	–	9	20	1990	2001

APPENDIX 4 Fertilization treatment description and relative growth responses of tree species

TABLE A4.1 *Detailed fertilization treatments for western hemlock studies used in the synthesis*

Reference	ID	Fertilizer source	Total fertilizer applied (kg/ha)	Fertilizer blend	Fertilizer regime	No. of fertilizations	Years since fertilized	Plot size (ha)	Height response (%)	Basal area response (%)	Volume response (%)
Reynolds and de Montigny 2015	01	Urea and triple superphosphate	250 N, 100 P	NP	Single	1	19	0.0625	7.31	0	5.87
Weetman et al. 1989	02	Ammonium nitrate and triple superphosphate	100 N, 100 P	NP	Single	1	3	0.09	313.89	–	–
	03	Ammonium nitrate and triple superphosphate	200 N, 100 P	NP	Single	1	3	0.09	394.44	–	–
	04	Ammonium nitrate and triple superphosphate	300 N, 100 P	NP	Single	1	3	0.09	475.00	–	–
	05	Ammonium nitrate and triple superphosphate	300 N, 150 P	NP	Single	1	3	0.09	447.22	–	–
	06	Ammonium nitrate, triple superphosphate, and mix micronutrients	300 N, 100 P, 1170 (P, K, Ca, Mg, S, Fe, Mn, B, Mo)	NP+ Micronutrients	Single	1	3	0.09	577.8	–	–
Prescott and Blevins 2005	07	Ammonium nitrate and triple superphosphate	225 N, 75 P	NP	Single	1	11	0.0225	62.22	–	190.91
Negrave et al. 2007	08	Urea and triple superphosphate	225 N, 100 P	NP	Single	1	9	0.2916	120.82	664.38	1196.32
CH plots	09	Urea and triple superphosphate	225 N, 100 P	NP	Single	1	9	0.1024	86.75	500.00	875.00
	10	Urea and triple superphosphate	225 N, 100 P	NP	Single	1	9	0.1296	162.11	1576.39	3466.99
	11	Urea and triple superphosphate	225 N, 100 P	NP	Single	1	9	0.2916	26.14	97.13	104.60
HA plots	12	Urea and triple superphosphate	225 N, 100 P	NP	Single	1	9	0.1024	64.04	176.40	264.40
	13	Urea and triple superphosphate	225 N, 100 P	NP	Single	1	9	0.1296	64.91	144.39	208.64

Reference	ID	Fertilizer source	Total fertilizer applied (kg/ha)	Fertilizer blend	Fertilizer regime	No. of fertilizations	Years since fertilized	Plot size (ha)	Height response (%)	Basal area response (%)	Volume response (%)
Prescott et al. 2013	14	Urea and triple superphosphate	450 N, 100 P	NP	Repeated	2	22	0.2916	121.40	582.10	1118.9
CH site	15	Urea and triple superphosphate	450 N, 100 P	NP	Repeated	2	22	0.1024	77.10	373.00	809.70
	16	Urea and triple superphosphate	450 N, 100 P	NP	Repeated	2	22	0.1296	198.40	866.70	2189.70
	17	Urea and triple superphosphate	450 N, 100 P	NP	Repeated	2	22	0.2916	29.3	87.10	105.90
CH site	18	Urea and triple superphosphate	450 N, 100 P	NP	Repeated	2	22	0.1024	65.10	154.20	243.00
	19	Urea and triple superphosphate	450 N, 100 P	NP	Repeated	2	22	0.1296	68.80	126.90	193.00
Radwan et al. 1984 Cascade site	20	Urea	224 N	N	Single	1	4	0.04	35.14	30.91	–
	21	Ammonium nitrate	224 N	N	Single	1	4	0.04	27.03	30.91	–
Coastal site	22	Urea	224 N	N	Single	1	4	0.04	17.50	17.31	–
	23	Ammonium nitrate	224 N	N	Single	1	4	0.04	80.00	50.00	–
Harrington and Devine 2011											
Thinned	24	Ammonium nitrate	600 N	N	Repeated	2	25	0.15	–	11.10	20.1
Unthinned	25	Ammonium nitrate, monodicalcium phosphate and potassium sulfate, triple superphosphate	600 N, 200 P, 129 Ca, 100 K, 41 S	NPK+Ca+NP	Repeated	2	25	0.15	–	8.90	31.70
Thinned	26	Ammonium nitrate and triple superphosphate	600 N, 200 P, 129 Ca	NP+Ca+NP	Repeated	2	25	0.15	–	95.60	146.60

TABLE A4.2 *Detailed fertilization treatments for western redcedar studies used in the synthesis*

Reference	ID	Fertilizer source	Total fertilizer applied (kg/ha)	Fertilizer blend	Fertilizer regime	No. of fertilizations	Years since fertilized	Plot size (ha)	Height response (%)	Basal area response (%)	Volume response (%)
Weetman et al. 1989	27	Ammonium nitrate	75 N	N	Single	1	3	0.008	29.85	–	–
	28	Ammonium nitrate	150 N	N	Single	1	3	0.008	49.25	–	–
	29	Ammonium nitrate	225 N	N	Single	1	3	0.008	53.73	–	–
	30	Triple superphosphate	75 P	P	Single	1	3	0.008	6.52	–	–
	31	Ammonium nitrate and triple superphosphate	75 N, 75 P	NP	Single	1	3	0.008	2.17	–	–
	32	Ammonium nitrate and triple superphosphate	150 N, 75 P	NP	Single	1	3	0.008	6.52	–	–
	33	Ammonium nitrate and triple superphosphate	225 N, 75 P	NP	Single	1	3	0.008	15.22	–	–
	34	Ammonium nitrate, triple superphosphate, and mix micronutrients	75 N, 75 P, 75 K	NP+ Micronutrients	Single	1	3	0.008	6.52	–	–
	35	Ammonium nitrate, triple superphosphate, and mix micronutrients	75 N, 75 P, 75 K	NP+ Micronutrients	Single	1	3	0.008	9.78	–	–
	36	Ammonium nitrate, triple superphosphate, and mix micronutrients	225 N, 75 P, 75 K	NP+ Micronutrients	Single	1	3	0.008	26.09	–	–
	37	Urea and triple superphosphate	100 N, 50 P	NP	Single	1	4	0.008	48.21	–	–
	38	Urea and triple superphosphate	200 N, 50 P	NP	Single	1	4	0.008	45.54	–	–
	39	Urea and triple superphosphate	300 N, 50 P	NP	Single	1	4	0.008	53.57	–	–
	40	Urea and triple superphosphate	300 N, 150 P	NP	Single	1	4	0.008	47.32	–	–
	41	Urea and triple superphosphate	300 N, 50 P, 50 (P, K, Ca, Mg, S, Fe, Mn, B, Mo)	NP+ Micronutrients	Single	1	4	0.008	57.14	–	–

Reference	ID	Fertilizer source	Total fertilizer applied (kg/ha)	Fertilizer blend	Fertilizer regime	No. of fertilizations	Years since fertilized	Plot size (ha)	Height response (%)	Basal area response (%)	Volume response (%)
Prescott and Blevins 2005	42	Ammonium nitrate and triple superphosphate	225 N, 75 P	NP	Single	1	11	0.0225	–	–	148
Negrave et al. 2007	43	Urea and triple superphosphate	225 N, 100 P	NP	Single	1	9	0.2916	33	129	143
	44	Urea and triple superphosphate	225 N, 100 P	NP	Single	1	9	0.1024	49	217	259
	45	Urea and triple superphosphate	225 N, 100 P	NP	Single	1	9	0.1296	40	159	196
CH plots	46	Urea and triple superphosphate	225 N, 100 P	NP	Single	1	9	0.2916	25	88	94
	47	Urea and triple superphosphate	225 N, 100 P	NP	Single	1	9	0.1024	51	247	289
	48	Urea and triple superphosphate	225 N, 100 P	NP	Single	1	9	0.1296	72	249	277
Prescott et al. 2013	49	Urea and triple superphosphate	450 N, 100 P	NP	Repeated	2	22	0.2916	38	190	220
	50	Urea and triple superphosphate	450 N, 100 P	NP	Repeated	2	22	0.1024	60	248	351
	51	Urea and triple superphosphate	450 N, 100 P	NP	Repeated	2	22	0.1296	62	227	333
	52	Urea and triple superphosphate	450 N, 100 P	NP	Repeated	2	22	0.2916	62	109	124
	53	Urea and triple superphosphate	450 N, 100 P	NP	Repeated	2	22	0.1024	56	231	172
	54	Urea and triple superphosphate	450 N, 100 P	NP	Repeated	2	22	0.1296	80	212	277
Harrington and Wierman 1990 Thinned	55	Urea	300 N	N	Single	1	5	0.08	26	26	–
	56	Ammonium nitrate	300 N	N	Single	1	5	0.08	19	48	–
	57	Ammonium nitrate, monodicalcium phosphate	300 N, 100 P, 129 Ca	NPCa	Single	1	5	0.08	33	29	–
Unthinned	58	Ammonium nitrate, monodicalcium phosphate, and potassium sulfate	300 N, 100 P, 129 Ca, 100 K, 41 S	NPKCaS	Single	1	5	0.08	60	65	–
Thinned	59	Ammonium nitrate, monodicalcium phosphate, and potassium sulfate	300 N, 100 P, 129 Ca, 100 K, 41 S	NPKCaS	Single	1	5	0.08	36	26	–

Reference	ID	Fertilizer source	Total fertilizer applied (kg/ha)	Fertilizer blend	Fertilizer regime	No. of fertilizations	Years since fertilized	Plot size (ha)	Height response (%)	Basal area response (%)	Volume response (%)
Devine and Harrington 2009	60	Ammonium nitrate	600 N	N	Repeated	2	25	0.15	22	–	–
Thinned	61	Ammonium nitrate, monodicalcium phosphate, triple superphosphate	600 N, 200 P, 129 Ca	NPCa	Repeated	2	25	0.15	19	–	–
Unthinned	62	Ammonium nitrate, monodicalcium phosphate and potassium sulfate, triple superphosphate	600 N, 200 P, 129 Ca, 100 K, 41 S	NPKCaS	Repeated	2	25	0.15	25	–	–
Harrington and Devine 2011	63	Ammonium nitrate	600 N	N	Repeated	2	25	0.15	–	49	66
Thinned	64	Ammonium nitrate, monodicalcium phosphate, triple superphosphate	600 N, 200 P, 129 Ca	NP+Ca+NP	Repeated	2	25	0.15	–	58	77
Unthinned	65	Ammonium nitrate, monodicalcium phosphate and potassium sulfate, triple superphosphate	600 N, 200 P, 129 Ca, 100 K, 41 S	NPK+Ca+NP	Repeated	2	25	0.15	–	105	119

TABLE A4.3 *Detailed fertilization treatments for amabilis fir studies used in the synthesis*

Reference	ID	Fertilizer source	Total fertilizer applied (kg/ha)	Fertilizer blend	Fertilizer regime	No. of fertilizations	Years since fertilized	Plot size (ha)	Height response (%)	Basal area response (%)	Volume response (%)
Prescott and Brown 1998	66	Ammonium nitrate and triple superphosphate	225 N, 75 P	NP	Single	1	5	0.0225	80	–	–
Prescott and Blevins 2005	67	Ammonium nitrate and triple superphosphate	225 N, 75 P	NP	Single	1	11	0.0225	75	–	300