# EFFECTS OF SITE, PROVENANCE, AND PROVENANCE AND SITE INTERACTION IN SITKA SPRUCE IN COASTAL BRITISH COLUMBIA

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## ABSTRACT

The IUFRO International Sitka spruce (*Picea sitchensis*) provenance experiments were planted at eight sites in Coastal British Columbia in 1975. The tests were planted in two series, with four sites in each series and 10 provenances at each test. A total of 14 provenances were tested with 6 provenances common to both series. Total height and survival were recorded at 3, 6, 10, 15 and 20 years after planting, and diameter at ages 10, 15 and 20 at most tests.

Test sites accounted for about two-thirds of the total variation. Size of provenance variance components was different between the two site series. Interaction between provenance and site was high and statistically significant in both series. Site climate and attack by the white pine weevil (*Pissodes strobi*) were the major determinants of site productivity and also the main causes of the interactions. Latitudinal pattern in provenance variation was eminent at most sites at early ages and maintained throughout at sites with strong maritime climate and free of weevil attack; at harsh northern and inland sites, geographic pattern of provenance variation shifted toward longitudinal (coast – inland) at later ages, and the harsher the site environment the earlier the shift. Practical implication in terms of seed transfer of the fast growing southern coastal sources and weevil resistant provenances in reforestation in coastal British Columbia was discussed.

**Key words:** *Picea sitchensis*, site environment, provenance, interaction, growth.

## INTRODUCTION

This report summarizes the 20-year (plantation age) testing results of the IUFRO international cooperative Sitka spruce (*Picea sitchensis* (Bong.). Carr.) provenance experiments at eight sites in coastal British Columbia (B.C.), in relation to the effects of site environment, provenance, and provenance and site interaction (G × E). Age trends in growth pattern among provenances at different sites were emphasized in elucidating the nature and causes of provenance-site interaction. The north-south pattern in growth shown in early results (ILLINGWORTH 1978) is still evident at sites with strong Pacific influence in the maritime outer coast and free of the white pine weevil (*Pissodes strobi* Peck.). However, at sites in the inner coast, vulnerability to winter injury of these fast-growing south coast provenances increasingly becomes apparent as tests age. This vulnerability of the south coast provenances was the major cause of provenance-site interaction. Weevil attack also contributed to this interaction.

Sitka spruce occurs naturally along a narrow strip of the Pacific coast spanning about 22 degrees of latitude. It is a fast growing conifer reaching a site index (100 years) of over 40 m at the productive sites (FARR & HARRIS 1979). Its stumpage rate (government levy on harvesting public forest lands) is the second highest among all the native species in British Columbia. Despite its high wood value, Sitka spruce accounts for only about 1% of the total annual planting in B.C. (B.C. MINISTRY OF FORESTS 1992). Productive site for this species is limited to the maritime outer coast, and weevil hazard has further reduced its planting. Extensive planting of Sitka spruce is now limited to the weevil-free zone on Queen Charlotte Islands and northern Vancouver Island (HALL 1994). However, provenance test results indicate a potential of 50% increase in growth by introducing the southern coastal sources (*e.g.* Brookings, Oregon coast) (ILLINGWORTH 1978), and have also identified provenances (*e.g.* Haney and Big Qualicum) highly resistant to the spruce weevil (YING 1991). Given these promising results, it is tempting to transfer a long distance these fast growing and resistant provenances to expand reforestation and to increase productivity. The major concern is the long-term safety margin in long distance transfer. Critical examination of age trend in geographic pattern of provenance variation, and the causes and magnitude of G × E would allow objective assessment of biological risk in seed transfer; this is the focus of this report.

 

## PROVENANCE SAMPLES AND TESTS

Background details about the IUFRO international Sitka spruce provenance experiment were reported by FLETCHER (1976) and O'DRISCOLL (1976). FLETCHER (1976) provided rationale for this cooperative international provenance experiment, and described sampling procedures, cone and seed handling, and protocol for distribution and organization of seeds. O'DRISCOLL (1976) elaborated on the experimental design, nursery culture, and data collection and analyses.

In British Columbia, the experiment was established in two series, with four sites in each series (Fig. 1, Table 1). Both series (B.C. code: EP702.04 and 05) were planted in May 1975 except the Rennell Sound site in EP702.05 which was planted one year later. The experimental design followed the recommendation of O'DRISCOLL (1976) – complete randomized block with 9 replications and 9-tree line plot spaced 3 × 3m. Ten provenances were tested at each site with six provenances common to both series. A total of 14 provenances (Fig. 1, Table 2) were tested. The 14 provenances cover the species' main coastal range from Alaska to the southern Oregon coast extending inland into the Sitka-white spruce (*Picea glauca* (Moench) Voss) hybridization zone (provenance 32), and from sea level to 600m. At most sites, height was measured 3, 6, 10, 15 and 20 years after planting (no 6-year measurement at Rennell Sound), and diameter at 1.3m after 10, 15 and 20 years. Survival was recorded when trees were measured. Extensive weevil attack occurred at three sites, Nass, Kitimat and Head Bay (Fig. 1) and was recorded every year since 1989.

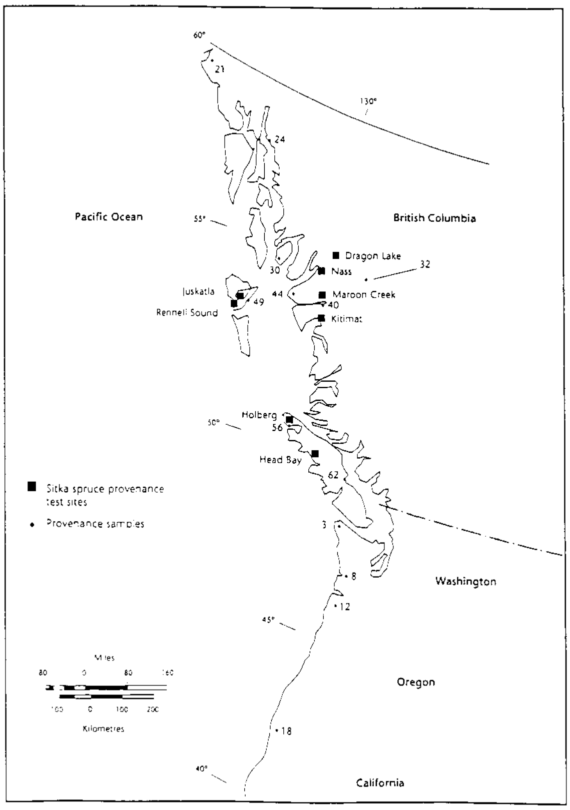


**Figure 1**. Locations of provenance samples and tests.

## DATA ANALYSIS

All analyses were based on plot means. Data were subjected to variance analyses of both individual sites and sites combined to assess the effects of test site, provenance and their interaction. Stepwise regression screening (SAS 1985) was used to examine geographic patterns of provenance variation in height growth by relating provenance mean height with provenance origin of latitude, longitude, elevation, and their quadrats and cross products. Stepwise regression was also employed to examine the effects of site climate and weevil attack on site mean height growth (as indicator of site productivity). Climate data from weather stations climatically closest to the test sites were used, including mean annual temperature (MAT, °C), mean annual precipitation (MAP, mm), number of frost free days (NFFD), and degree days above 5 °C (DD5) (Table 1). Weevil attack was treated as a qualitative variable, 0 or 1 (Table 1). Dragon Lake was excluded because of high mortality (the site is outside the range of "typical" Sitka spruce sites). A regression model was considered adequate in describing geographic pattern if both the model and partial regression coefficient of individual explanatory variables were significant at 0.05 probability level except weevil at 0.10%. Graphic presentation of age trends in site and provenance variation in height growth (both observed and derived from the regression models) were emphasized in examining the nature of provenance-site interactions (CLEVELAND 1993). Height growth is sensitive to site climate (*e.g.* frost, CANNELL *et. al.* 1985) and terminal leader is the target site of weevil attack (ALFARO 1989). Therefore, height growth pattern is apt to reveal the nature of G × E.

## RESULTS AND DISCUSSION

### Site Effect

Site effect was large and statistically significant (Tables 2 and 3). Trees at the most productive site (Rennell Sound) were 6 times taller than trees at the poorest (Dragon Lake) (Table 2). Sites located at the windward maritime coast and without weevil infestation (Rennell Sound and Holberg) maintained more than a half meter height growth yearly. On the other hand, at Dragon

**Table 1. Descriptions about test sites.**

| Site | Series | Latitude °N | Longitude °W | Elevation m | MAP mm | MAT °C | NFFD | DD >5 °C | Weevil |
|---|---|---|---|---|---|---|---|---|---|
| Dragon Lake | EP 702.04 | 55° 19′ | 128° 58′ | 210 | 1943 | 5.4 | 131 | 1101 | 0 |
| Nass | EP 702.04 | 55° 04′ | 129° 26′ | 15 | 1748 | 6.5 | 145 | 1311 | 1 |
| Maroon Creek | EP 702.04 | 54° 46′ | 128° 39′ | 600 | 1500 | 4.5 | 165 | 1000 | 0 |
| Holberg | EP 702.04 | 50° 44′ | 128° 07′ | 60 | 3857 | 8.8 | 297 | 1667 | 0 |
| Juskatla | EP 702.05 | 53° 34′ | 132° 20′ | 20 | 1535 | 7.5 | 257 | 1347 | 0 |
| Rennell Sound | EP 702.05 | 53° 23′ | 138° 28′ | 50 | 4218 | 8.2 | 313 | 1441 | 0 |
| Kitimat | EP 702.05 | 54° 12′ | 128° 33′ | 100 | 2299 | 6.4 | 229 | 1449 | 1 |
| Head Bay | EP 702.05 | 49° 48′ | 126° 28′ | 15 | 2721 | 8.8 | 254 | 1844 | 1 |

| Site | Series | Soil and typography |
|---|---|---|
| Dragon Lake | EP 702.04 | Flat valley bottom, clay soil |
| Nass | EP 702.04 | Flat valley bottom,deep silt loam |
| Maroon Creek | EP 702.04 | Gentle lower slope (10–20%) |
| Holberg | EP 702.04 | Flat valley bottom, clay soil of marine origin with large size stone outcrop |
| Juskatla | EP 702.05 | Flat valley bottom, clay soil, restrictive drainage |
| Rennell Sound | EP 702.05 | Flat lower slope, deep silt/loam |
| Kitimat | EP 702.05 | Flat alluvial terrace, deep rich silty clay soil |
| Head Bay | EP 702.05 | Flat valley bottom, silty loam to clay soil of marine origin |

[1] MAP mean annual precipitation; MAT – mean annual temperature; NFFD – number of frost-free days; DD>5 °C – degrees of days above 5 °C; Weevil: 0 = free of weevil attack, 1 = heavily weeviled.

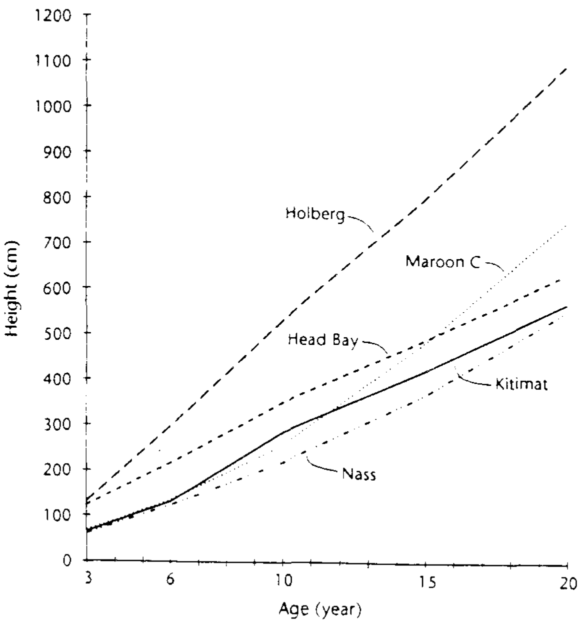


**Figure 2. Age trend in site mean height growth.**

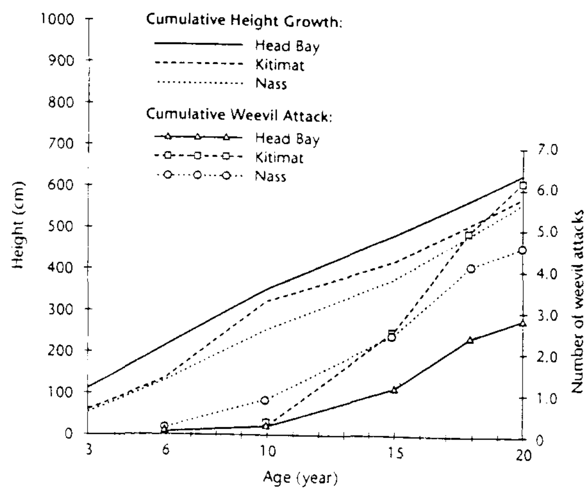


**Figure 3. Comparison in height growth and cumulative weevil attack at Head Bay, Kitimat and Nass.**

Lake, only the local provenance (No. 32, Kitwanga, rom Sitka-white hybridization zone) grew well and was not cold injured; all other provenances suffered repeated winter injury and had over 50% mortality, and the more southern and maritime the provenance origin the higher the mortality (Table 2). The Dragon Lake site is located in the coast-interior transition (submaritime) zone subject to the influence of continental climate. The high mortality of all the coastal provenances at this site including those from the north coast (Alaska Panhandle) suggests Sitka spruce is sensitive to cold climate.

Large site differences are rather expected as the eight tests are located at such contrasting environments, *e.g.*, frost free days varied from 131 to 313 days (Table 1). Results of regression analyses (Table 4) suggest tree

 

**Table 2. Site and provenance means in 20-year height (H = m), diameter (D = cm) and survival (S = %), (provenances arranged from south to north).**

| Test site | Dragon Lake | | | Maroon Creek | | | Nass | | | Kitimat | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Provenance | H | D | S | H | D | S | H | D | S | H | D | S |
| 18 Brookings, OR | 0 | . | 0 | 0 | 0 | 0 | 3.8 | 5 | 19 | – | – | – |
| 12 Necanicum, OR | 2.2 | . | 19 | 6.6 | 12 | 81 | 5.8 | 12 | 86 | 5.8 | 13 | 98 |
| 08 Hoquiam, WA | – | . | – | – | – | – | – | – | – | 6.2 | 15 | 99 |
| 03 Forks, WA | 1.6 | . | 19 | 7.7 | 15 | 95 | 5.8 | 14 | 94 | 6.4 | 15 | 100 |
| 62 Big Qualicuom, B.C. | 1.7 | . | 28 | 8.3 | 15 | 95 | 7.6 | 18 | 91 | 7.5 | 16 | 99 |
| 61 Tahsis, B.C. | 1.7 | . | 30 | 7.4 | 13 | 95 | 5.4 | 13 | 87 | – | – | – |
| 56 Holberg, B.C. | 1.8 | . | 32 | 7.4 | 14 | 99 | 5.0 | 11 | 77 | 5.6 | 14 | 100 |
| 49 Link Rd. B.C. | 2.3 | . | 41 | 7.9 | 16 | 99 | 5.2 | 15 | 79 | 5.1 | 14 | 96 |
| 44 Inverness, B.C. | 2.3 | . | 33 | 7.9 | 15 | 91 | 5.3 | 12 | 82 | 4.8 | 12 | 100 |
| 40 USK Ferry, B.C. | – | . | – | – | – | – | – | – | – | 7.4 | 13 | 98* |
| 32 Kitwanga, B.C. | 5.2 | . | 86* | 8.3 | 15 | 98* | 7.6 | 16 | 95 | – | – | – |
| 30 Ward L., AK. | – | . | – | – | – | – | – | – | – | 4.7 | 11 | 94 |
| 24 Duck Cr. AK. | – | . | – | – | – | – | – | – | – | 4.4 | 10 | 96 |
| 21 Yakutat, AK. | 2.7 | . | 49 | 6.9 | 12 | 99 | 4.1 | 8 | 72 | – | – | – |
| **Mean** | **2.4** | . | **37** | **7.6** | **14** | **95** | **5.6** | **12** | **78** | **5.8** | **13** | **98** |

| Test site | Juskatla | | | Rennell Sound | | | Holberg | | | Head Bay | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Provenance | H | D | S | H | D | S | H | D | S | H | D | S |
| 18 Brookings, OR | – | – | – | – | – | – | 14.0 | 18 | 99 | – | – | – |
| 12 Necanicum, OR | 5.9 | 10 | 91 | 14.8 | 26 | 100 | 12.6 | 18 | 99 | 7.9 | 15 | 99 |
| 08 Hoquiam, WA | 5.5 | 10 | 96 | 14.4 | 24 | 100 | – | – | – | 7.4 | 13 | 94 |
| 03 Forks, WA | 5.3 | 10 | 96 | 14.5 | 25 | 100 | 12.0 | 17 | 99 | 7.2 | 14 | 90 |
| 62 Big Qualicuom, B.C. | 5.6 | 10 | 100 | 13.5 | 22 | 100 | 11.6 | 16 | 98 | 8.7 | 14 | 88 |
| 61 Tahsis, B.C. | – | – | – | – | – | – | 11.1 | 15 | 99 | – | – | – |
| 56 Holberg, B.C. | 5.0 | 9 | 96 | 13.3 | 22 | 100 | 11.0 | 15 | 99* | 5.8 | 11 | 85* |
| 49 Link Rd. B.C. | 5.6 | 11 | 98* | 12.0 | 20 | 100 | 10.6 | 16 | 100 | 5.8 | 12 | 89 |
| 44 Inverness, B.C. | 4.7 | 9 | 98 | 12.3 | 19 | * | 10.5 | 15 | 100 | 5.4 | 10 | 89 |
| 40 USK Ferry, B.C. | 5.1 | 8 | 98 | 11.4 | 16 | 98 | – | – | – | 5.8 | 9 | 79 |
| 32 Kitwanga, B.C. | – | – | – | – | – | 100 | 7.5 | 9 | 95 | – | – | – |
| 30 Ward L., AK. | 4.5 | 8 | 93 | 10.5 | 15 | – | – | – | – | 4.8 | 9 | 80 |
| 24 Duck Cr. AK. | 4.6 | 7 | 96 | 9.3 | 13 | 100 | – | – | – | 4.6 | 8 | 86 |
| 21 Yakutat, AK. | – | – | – | – | – | 99 | 9.1 | 11 | 99 | – | – | – |
| **Mean** | **5.2** | **9** | **96** | **12.6** | **20** | – **99** | **11.0** | **15** | **99** | **6.3** | **11** | **88** |

Provenance not tested at the site; – not includend; . measured; * provenance climatically most close to the test site

growth at early years (up to age 10) was strongly influenced by site temperature factors (MAT and NFFD). And precipitation (MAP) and weevil attack accounted for most of the site differences at ages 15 and 20. High coefficients of determination ($R^2$) (Table 4) suggest predictive correlations of height growth with site climate variable and weevil attack. Young Sitka spruce is known to be susceptible to frost (CANNELL 1985). Soil moisture may become critical to sustaining growth after the juvenile phase (MALCOLM 1987). Weevil attack tends to occur at a threshold height (ALFARO 1989). Therefore, age trend in height growth-site factor correlations shown in Table 4 reflects a cause-effect relationship.

Site factors not included in the analyses, *e.g.* edaphic factors, no doubt also affect the growth of Sitka spruce; the large growth difference between Rennell Sound and Juskatla on Queen Charlotte Islands (Table 2) can largely be attributed to the restricted drainage at the latter (Table 1).

Weevil infestation could potentially cause an average reduction in growth of 3m at age 20, based on the estimate from the regression coefficient (Table 4). Severity of weevil infestation on site productivity

**Table 3. Variance components (%, block effects excluded and value of residual component ($\sigma_e^2$) derived from variance analyses of sites in each series and series combined using the 6 common provenances, the Dragon Lake site excluded from analysis.**

| Experiment | Source | Site | Provenance | S × P | Residual | $\sigma_e^2$ |
|---|---|---|---|---|---|---|
| Series 1 | Height 3 | 61** | 12* | 18** | 9 | 103 |
| | Height 6 | 81** | 0$^N$ | 16** | 3 | 367 |
| | Height 10 | 82** | 0$^N$ | 15** | 3 | 997 |
| | Height 15 | 79** | 1$^N$ | 15** | 5 | 3262 |
| | Height 20 | 76** | 0$^N$ | 17** | 7 | 6514 |
| Series 2 | Height 3 | 40** | 36** | 4** | 20 | 175 |
| | Height 6 | 49** | 19** | 3* | 29 | 1122 |
| | Height 10 | 32** | 31** | 8** | 29 | 4046 |
| | Height 15 | 71** | 12** | 4** | 13 | 6895 |
| | Height 20 | 81** | 6** | 4* | 9 | 12701 |
| Combined | Height 3 | 61** | 13** | 6** | 20 | 163 |
| | Height 6 | 78** | 4** | 4** | 13 | 877 |
| | Height 10 | 69** | 7** | 5** | 18 | 3298 |
| | Height 15 | 80** | 4** | 3** | 13 | 6373 |
| | Height 20 | 84** | 4** | 3** | 9 | 10793 |

**, * statistically significant at 0.01 and 0.05 probability; $^N$ not significant

becomes obvious when age trends in cumulative height growth at different sites are compared (Fig. 2). Convergence between cumulative height growth and cumulative number of weevil attack – coincidence between the beginning of growth decline and peaking of weevil attack – at the three sites with heavy weevil attack also revealed the effect of weevil attack on height (Fig. 3).

Both Holberg and Head Bay are located on the west coast of Vancouver Island (Fig. 1) with similar climate and site characteristics, except severe weevil attack at the latter (Table 1). Height growth at Head Bay declined steadily relative to that at Holberg after weevil started to invade the former, and at age 20 Holberg had nearly twice the growth of Head Bay, though both sites had similar height at age 3 (Fig. 2). Weevil effect becomes even more evident when age trends of growth patterns at Head Bay and Maroon Creek (minor weevil attack occurred only in recent years) are compared. Maroon Creek is a high elevation site in the submaritime climate (Table 1), climatically a much less favorable site for Sitka spruce. Superiority in height growth at Head Bay was maintained at around 40% over that at Maroon Creek until age 10; after that growth at Head Bay started to decline whereas at Maroon Creek growth maintained its accelerated rate (Fig. 2). The change in growth patterns between the two sites coincided with the peaking of weevil attack at Head Bay (Fig. 3). Both Kitimat and Nass had heavy attack, but the attack peaked much earlier at the latter (about age 10) than at the former (from about age 15 to 20) (Fig. 3), and so did the change in growth patterns – decline in height started at about the same time when weevil attack was peaking (Fig. 3).

**Provenance Effect**

Provenance differences at individual sites were statistically significant at all measurement ages. When sites combined, provenance differences were not significant in Series 1 except age 3, but significant in Series 2 or Series 1 and 2 combined using the six common provenances (Table 3). Sites in Series 1 cover a much broader range of climate (Table 1) where high G × E may have masked provenance differences statistically. Provenance variance components declined with age in both Series (Table 3). Only at the mild and weevil-free sites (Rennell Sound and Holberg), did southern coastal provenances from Oregon and Washington (Nos. 18, 12, 08 and 03) maintain their growth superiority; at other maritime sites (Head Bay and Juskatla), they did not fare any better than some other provenances, e.g. Big Qualicum (No. 62) partly due to the latter's high resistance to the white pine weevil (YING 1991); at inland sites, they lost growth superiority to "local" provenances; and at the most harsh site (Dragon Lake) they suffered the highest mortality (Table 2). So for the potential of a fast growing seed source of Sitka spruce

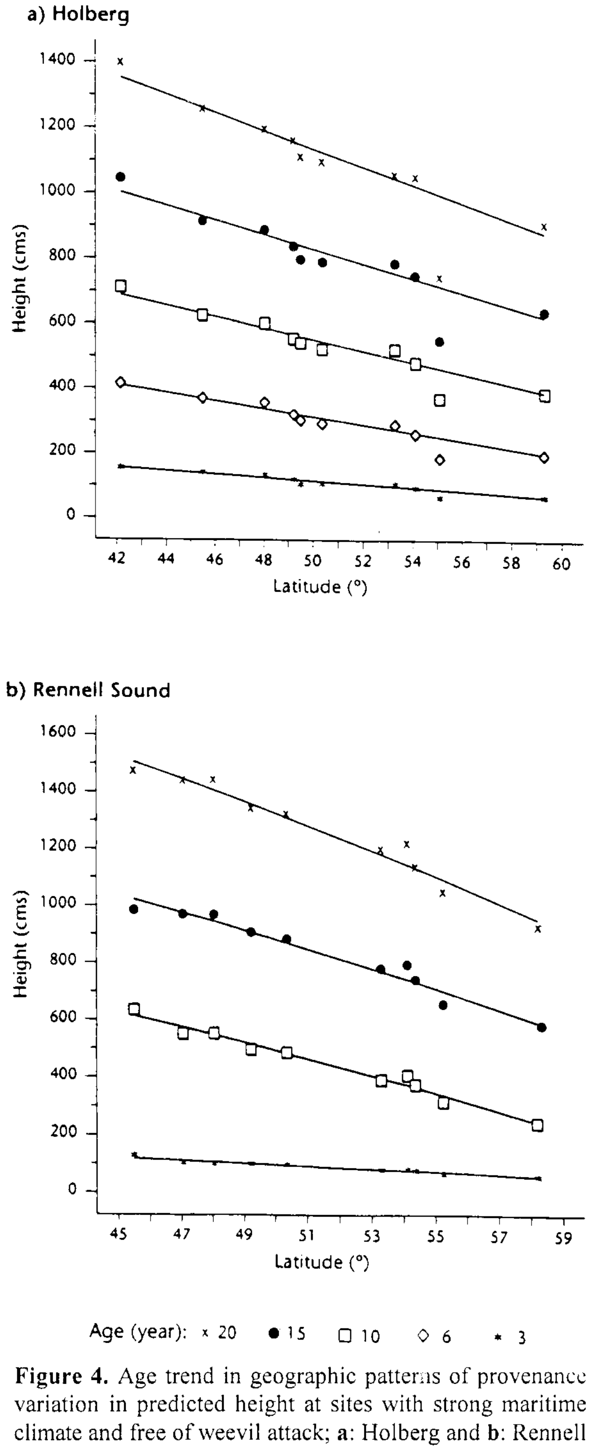


**Figure 4.** Age trend in geographic patterns of provenance variation in predicted height at sites with strong maritime climate and free of weevil attack; **a**: Holberg and **b**: Rennell Sound.

to be fully realized, a precise match of site quality is essential.

Provenance variation exhibited discernible patterns of geographic variation at all sites except Maroon Creek as described by regression models, though age trend in geographic pattern varied from site to site (Table 5). Latitudinal trend was dominant at early ages at all sites, and most evident at mild sites with strong maritime influence, *e.g.* Holberg and Rennell Sound where latitudinal trend (ILLINGWORTH 1978) was maintained throughout the measurement ages (Figs. 4a and b, Table 5). At inland sites or sites with heavy weevil infestation, geographic pattern showed age trend, evident from age 15 on (Table 5). Age trends in predicted height (based on regression models in Table 5) at three inland sites were plotted in Figures 5a to c and four provenances representing the geographic range were identified to illustrate the shifting in geographic patterns from early to late ages. At Nass, geographic pattern shifted from a near linear north-south latitudinal one at early age to a more coast-inland longitudinal one at later ages. This was most evident by comparing the changing growth patterns between No. 12 (Necanicum, Oregon) and No. 32 (the most inland provenance) (Fig. 5a, Table 5). Similarly at Kitimat, geographic pattern in height growth shifted from north-south latitudinal to coast-inland longitudinal (Fig. 5b, Table 5). Again, it was most evidently revealed by comparing the changing growth patterns between the inland provenance (No. 40) and No. 12. Both weevil damage and climate contributed to this pattern shift. No. 62 did not follow this general pattern shifting at both sites due largely to its resistance to weevil. A weevil-caused shift in geographic pattern was most evident at Head Bay where geographic pattern shifted from a near perfect latitudinal pattern to a longitudinal one at age 20 (Fig. 5c, Table 5) as cumulative weevil attack peaked at about age 15 (Fig. 3). Changes in geographic patterns call for prudence in decisions on seed source selection based on early testing results, inland sites in particular.

## Provenance and Site Interaction

Effect of provenance by site interaction was significant at all measurement ages in both series or combined (Table 3). The G × E component was much higher in Series 1 than Series 2, apparently due to the wide range of test site environments in the former (Table 1). Age trends in site and provenance variation presented above revealed climate and weevil attack as the major determinants affecting site productivity and geographic pattern of provenance variation. The same factors also contributed to their interactions. To illustrate the same factors invoking the G × E, age trends in cumulative height growth of four provenances at individual test sites were graphically compared. The four provenances are No. 12 (a fast growing Oregon coast source), No. 62 (a weevil resistant provenance from eastern Vancouver Island), and Nos. 32 and 40 (sources from the Sitka-white hybridization zone, slow growing but hardy

**Table 4 Age trend in relationship between site mean height and site climate variables and weevil attack based on regression analyses**

| Height | Variable | Coefficient | P>F | $R^2$ | P>F |
|---|---|---|---|---|---|
| Height 3 | MAT | 11.1907 | 0.014 | 0.73 | 0.014 |
| Height 6 | NFFD | 1.0110 | 0.032 | 0.72 | 0.032 |
| Height 10 | NFFD | 1.5335 | 0.007 | 0.79 | 0.007 |
| Height 15 | MAP | 0.0993 | 0.011 | 0.89 | 0.013 |
| | Weevil | –186.7720 | 0.034 | | |
| Height 20 | MAP | 0.1389 | 0.046 | 0.78 | 0.046 |
| | Weevil | –294.4266 | 0.082 | | |

MAT – mean annual temperature; NFFD – number of frost-free days; MAP – mean annual precipitation; Weevil – weevil attack as qualitative variable 0 or 1.

**Table 5 Age trends in geographic patterns derived from regression analyses relating provenance mean height to provenance origin at individual site (sites arranged from harsh to mild)**

| Site | Height 3 | | | Height 6 | | | Height 10 | | |
|---|---|---|---|---|---|---|---|---|---|
| | Variable | Coefficient | $R^2$ | Variable | Coefficient | $R^2$ | Variable | Coefficient | $R^2$ |
| Maroon C [1)] | Latlong | –0.0063 | 0.49 | * | | | * | | |
| Nass [1)] | $Lat^2$ | –0.0019 | 0.76 | Lat | 58.6610 | 0.73 | Lat | 38.4870 | 0.69 |
| | | | | $Lat^2$ | –0.5296 | | Latlong | –0.2295 | |
| Kitimat [1)] | $Lat^2$ | –2.8405 | 0.95 | $Lat^2$ | –0.0486 | 0.89 | $Lat^2$ | –0.1057 | 0.94 |
| | | | | | | | $Elev^2$ | 0.0014 | |
| Juskatla [2)] | Latlong | –0.0194 | 0.90 | Latlong | –0.0420 | 089 | Latlong | –0.0545 | 0.91 |
| Rennell S. [2)] | Lat | –4.8774 | 0.93 | – | – | – | $Lat^2$ | –0.2813 | 0.97 |
| Holberg [2)] | Lat | –5.0095 | 0.95 | Lat | –12.1219 | 0.97 | $Lat^2$ | –17.1158 | 0.97 |
| | $Elev^2$ | –0.0001 | | $Elev^2$ | –0.0001 | | $Elev^2$ | –0.0002 | |
| Head Bay [2)] | Lat | –5.9297 | 0.90 | Lat | –11.0086 | 0.89 | Lat | –16.8585 | 0.91 |

| Site | Height 15 | | | Height 20 | | |
|---|---|---|---|---|---|---|
| | Variable | Coefficient | $R^2$ | Variable | Coefficient | $R^2$ |
| Maroon C. [1)] | * | | | * | | |
| Nass [1)] | Long | –40.0498 | 0.83 | Long | –64.5718 | 0.85 |
| | Latlong | 0.1892 | | Latlong | 0.3271 | |
| Kitimat [1)] | $Long^2$ | –0.0583 | 0.72 | Lat | 169.1615 | 0.77 |
| | | | | Latlong | –1.0486 | |
| Juskatla [2)] | Latlong | –0.0615 | 0.86 | Lat | –9.3793 | 0.65 |
| Rennell S. [2)] | $Lat^2$ | –0.3266 | 0.96 | $Lat^2$ | –0.4198 | 0.96 |
| Holberg [2)] | Lat | –21.9368 | 0.96 | Lat | –27.2433 | 0.98 |
| | $Elev^2$ | –0.0003 | | $Elev^2$ | –0.0006 | |
| Head Bay [2)] | Latlong | –0.1319 | 0.84 | Long | –31.8356 | 0.82 |

* No discernible pattern detected; [1)] inland sites; [2)] coastal sites.

and with high tolerance of weevil); the former two were tested at all sites and the latter two tested only in one series (Fig. 1, Table 2) (YING 1991). Local and other provenances were added at some sites for comparison or emphasis.

Comparing the growth patterns of the three provenances at Holberg (Fig. 6a) and Dragon Lake (Fig. 6b), that is, the shortest provenance, No. 32, at the mild Holberg site became the tallest at the harsh Dragon Lake site, one component of the genetic nature of the interaction can be clearly established – fast growing is inherently associated with low tolerance of cold. In the

 

**5a) Nass**

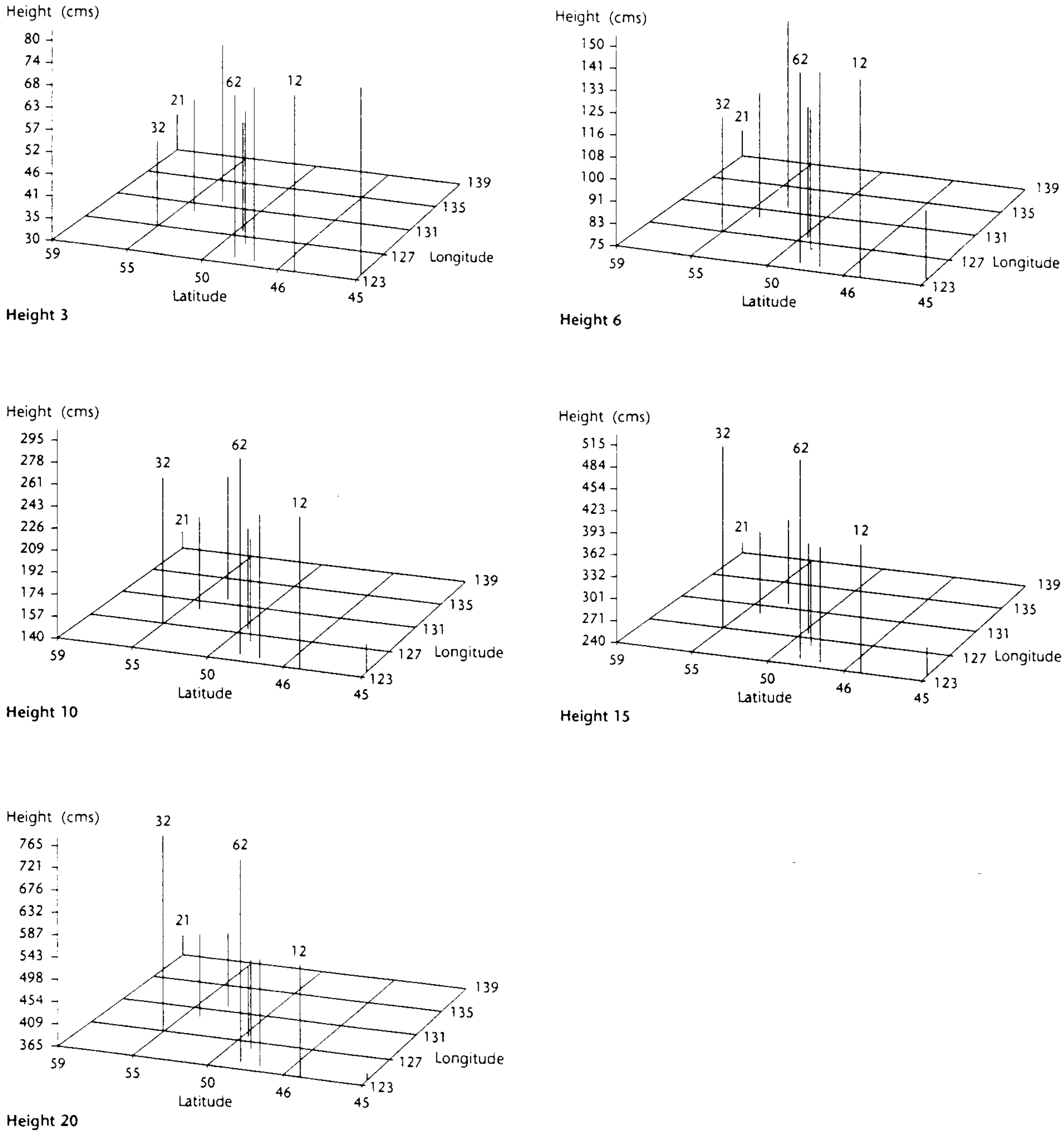


**Figure 5.** Age trend in geographic patterns of provenance variation in predicted height at inland sites with heavy weevil attack, **a**: Nass and **b**: Kitimat, and maritime sites with heavy weevil attack, **c**: Head Bay..

same way by comparing the growth patterns of the same provenances at Maroon (Fig. 6c) and Kitimat (Fig. 6d) (both climatically less harsh than Dragon Lake) with that at Holberg (Fig. 6a), age trends in provenance-site interaction emerged – at harsh sites the superiority of the fast growing provenance (No. 12) declined as age increased, and this decline occurred earlier at the harsher Maroon site than at Kitimat (Figs. 6c and d). At Maroon No. 32 (climatically most close to the test site) outperformed No. 12 shortly after planting (before age 6) (Fig. 6c). At Kitimat, No. 12 lost its superiority to No. 40 (climatically most close to the test site) at age 10–15 and No. 3 at age 15–20. Provenance No. 3 from the Washington coast was added to Figure 6d to emphasize the gradual nature in emergence of growth pattern showing provenance-site

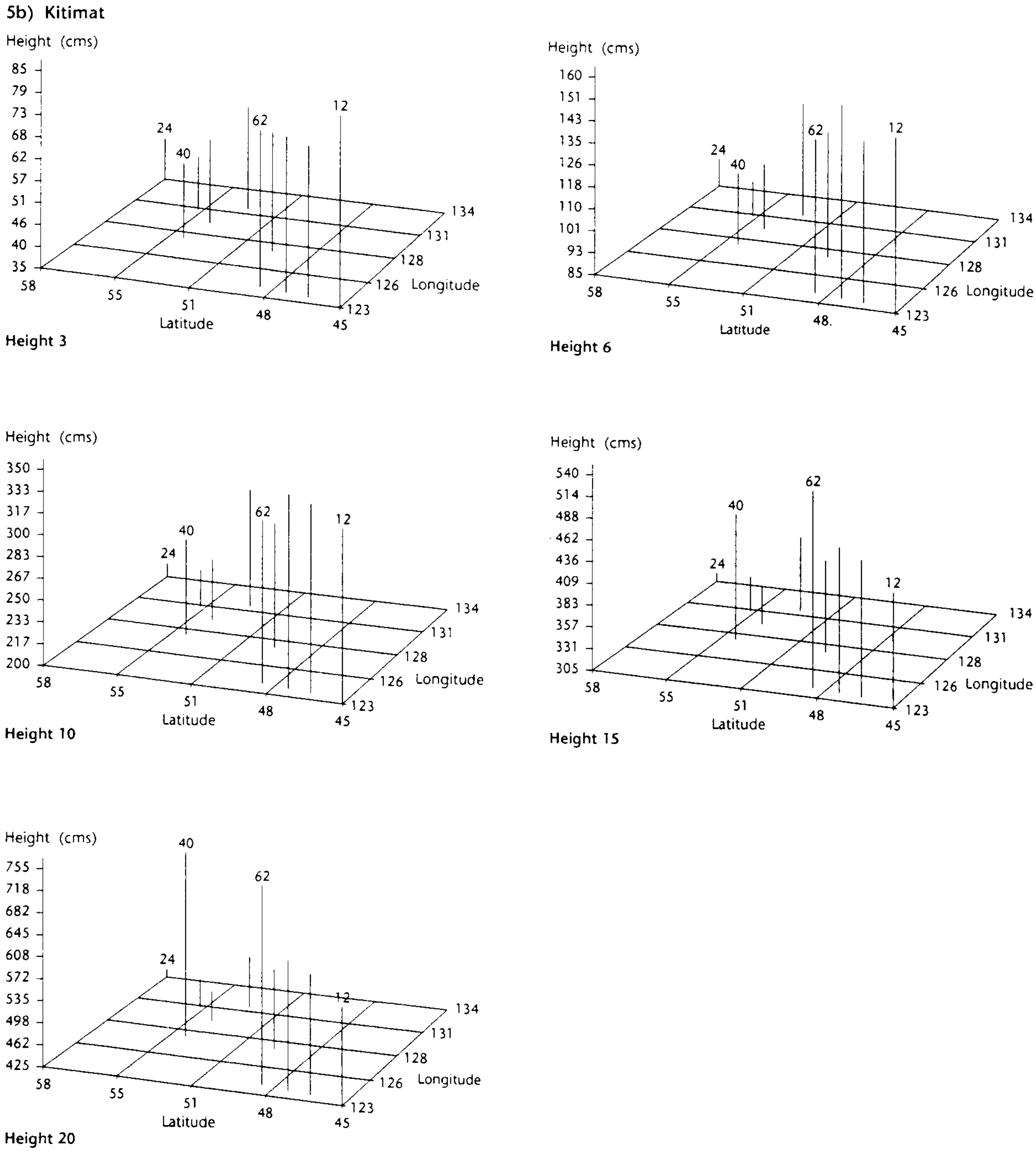


**Figure 5b**, (continued).

interaction.

This pattern of provenance-site interaction caused by negative association between fast growing and low cold tolerance is very similar to the testing results in other regions, *e.g.* in Britain (LINES & SAMUEL 1993), Ireland (PFEIFER 1993), Newfoundland (KHALIL 1993), and others (SAMUEL 1993).

The second component contributing to the G × E – weevil attack – can be shown by comparing the age trend in growth pattern among the same provenances at Head Bay (heavily weeviled), with that at Holberg and Rennell Sound (free of weevil) (Table 1). Provenance No. 62 (weevil resistant) started to outgrow No. 12 (susceptible) at around age 14 at Head Bay (Fig. 6e), whereas the latter still maintained its superiority at Holberg (Fig. 6a) and Rennell Sound (Fig. 6g). This clearly indicates the effect of weevil attack as the major causal factor since the sites are climatically similar, 5c) Head Bay

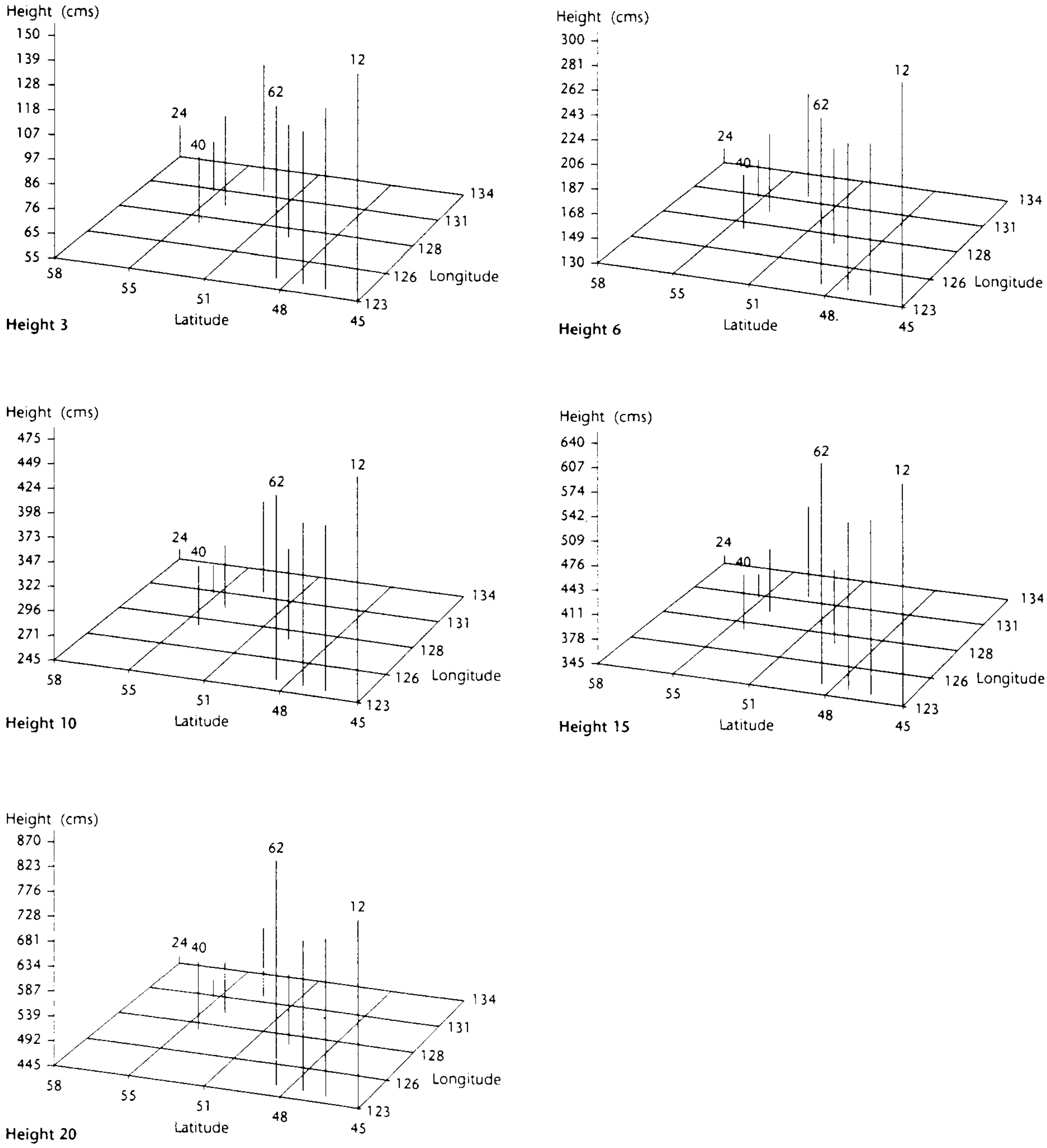


**Figure 5c**, (continued).

particularly between Head Bay and Holberg (Fig. 1). The coincidence between changes in growth pattern and cumulative weevil attack at Head Bay (Fig. 3) further reinforce this conclusion of causal effect of weevil attack on G × E.

The convergence in growth between Nos. 62 and 40 at Kitimat (Fig. 6d), and between Nos. 62 and 32 at Nass (Fig. 6f) reflected the joint causal effect of both weevil and climate factors contributing to G × E. Nos. 40 and 32 were slow growing as evidenced at weevil-free sites, Rennell (Fig. 6g) and Holberg (Fig. 6a), and both had similar levels of weevil tolerance as No. 62 (YING 1991). If this convergence continues – it will, judging from the age trends in geographic patterns of provenance variation (Table 5) – Nos. 40 and 32 will eventually outgrow No. 62. No. 62 is from the maritime climate and about 4 to 5 degrees latitude south of the test sites. This convergence in growth patterns –

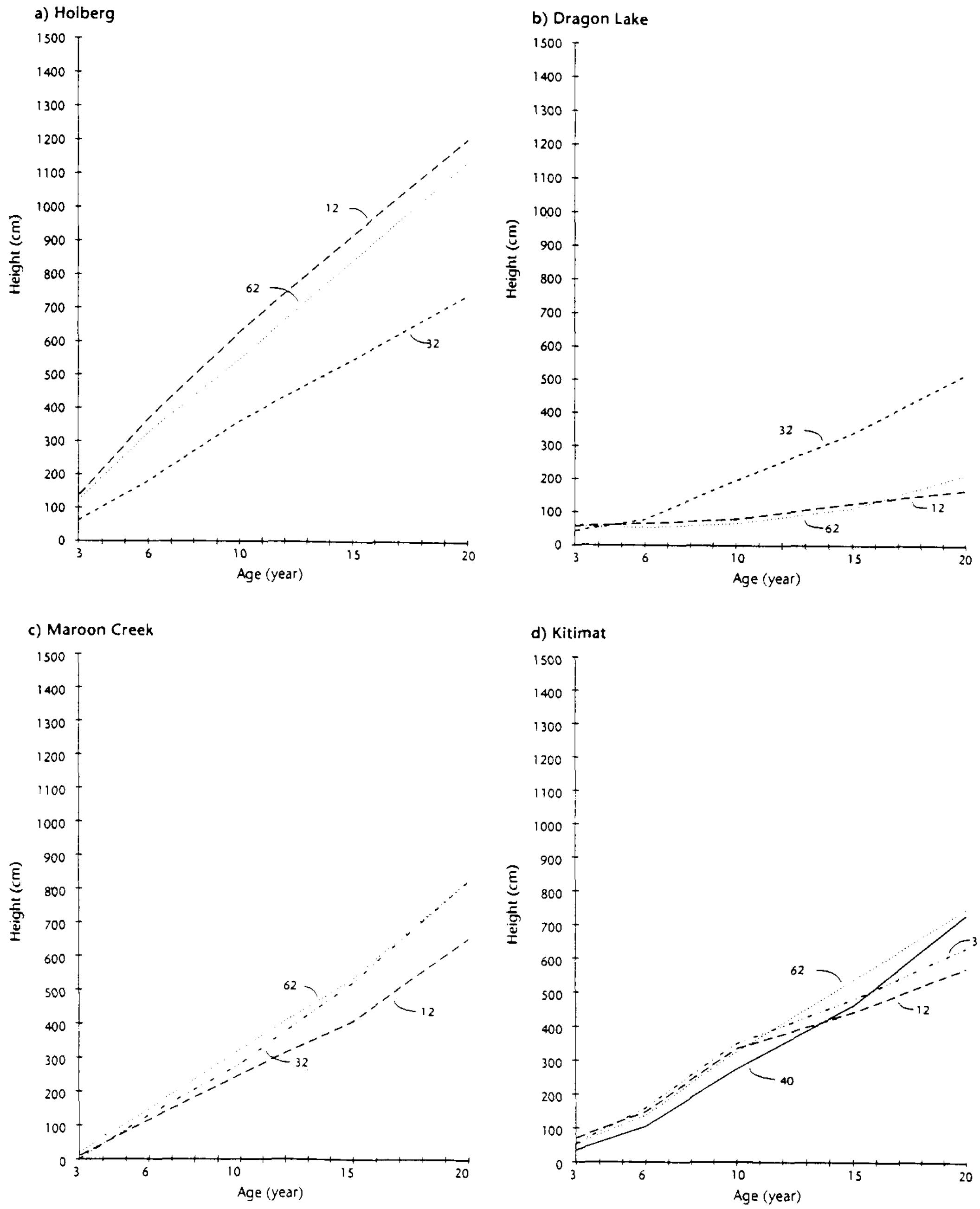


**Figure 6.** Comparison of age trends in height growth among provenances Nos. 32, 40, 62, and12 at individual sites, **a**: Holberg, **b**: Dragon Lake, **c**: Maroon Creek, **d**: Kitimat, **e**: Head Bay, **f**: Nass, and **g**: Rennell Sound.

cumulative decline in growth superiority of No. 62 relative to that of the "local" (Figs. 6d and f) – suggests either the cumulative effect of minor maladaption or the collapse of resistance induced by maladaption in No. 62.

## CONCLUSION AND PRACTICAL IMPLICATIONS

Large effect of site environments, high provenance variation, and negative correlation between growth and hardiness found in tests in coastal British Columbia are also evident in tests in other countries, *e.g.* in Britain (LINES 1987). Strong effect of site environments on expression of geographic patterns of provenance performance (provenance-site interaction) is also obvious at most IUFRO Sitka spruce provenance tests. That is, expression of geographic pattern is sensitive to the climatic and ecological conditions of the test sites. For example, the same 10 provenances exhibited a

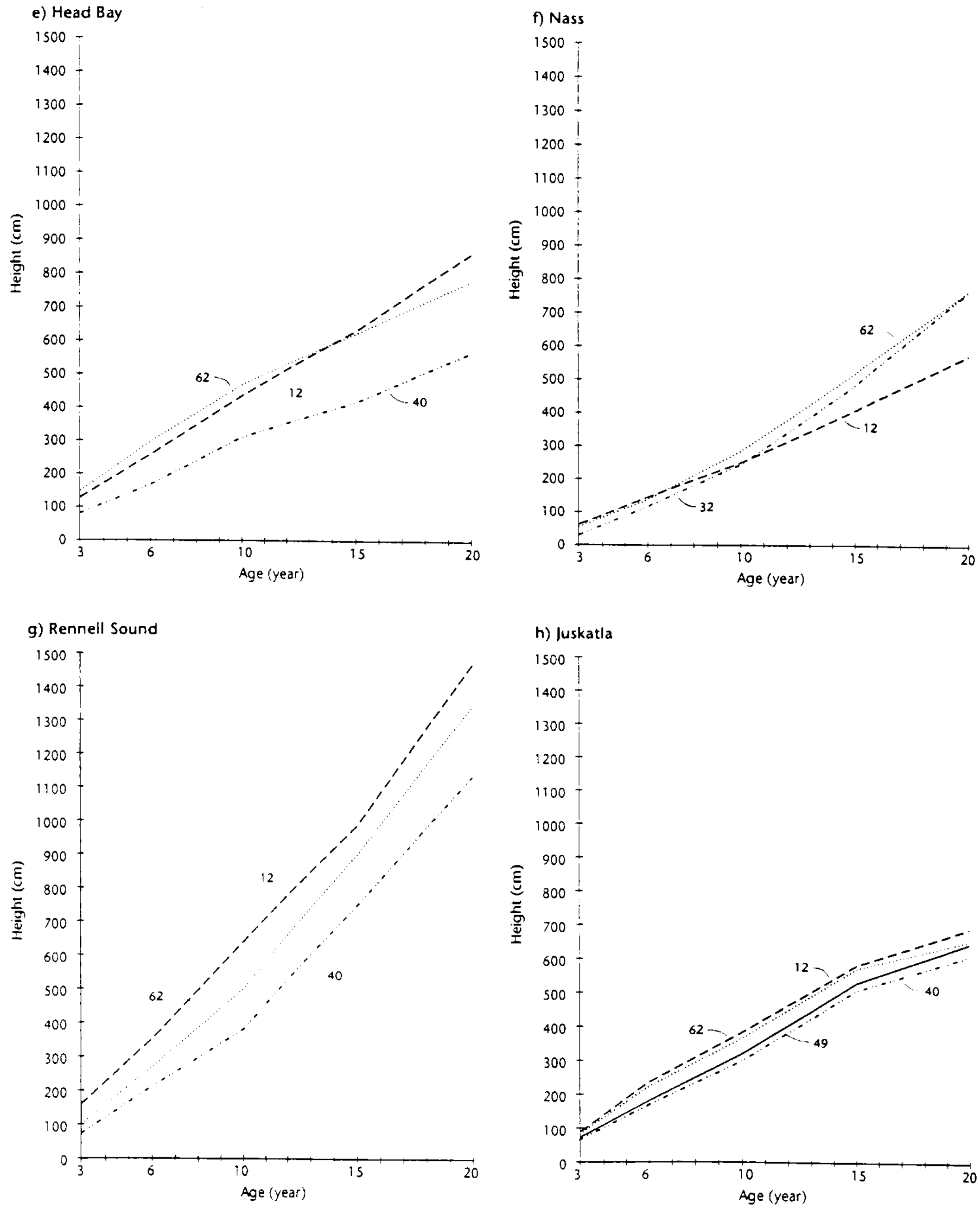


**Figure 6**, (continued).

north-south clinal variation in growth at the test in Denmark (MADSEN 1993), but a cline in reversed order shown at a more northern test in Norway (MAGNESEN 1993). Because of this high "precision" of dependence of provenance performance on its geographic origin and site environment of planting, it seems to be possible to develop a unified predictive model linking provenance performance and site productivity to the climate of both site and seed source origin, which may be capable of predicting the potential impact of climate change on growth of Sitka spruce globally. The IUFRO international Sitka spruce provenance experiments seem to offer a unique set of testing plantations to develop empirical predictive models on effect of global warming (MÁTYÁS 1994).

In British Columbia, questions facing silviculturists are 1) should the current northward seed transfer limit of 2° latitude for the submaritime zone be expanded in order to take advantage of the weevil resistant and fast growing seed source, *e.g.* Big Qualicum, and 2) the current northward transfer limit of 4° for the maritime zone (B.C. Ministry of Forests 1990) to take advantage of the fast growing coastal Oregon and Washington sources, particularly weevil-free sites on northern Vancouver Island and Queen Charlotte Islands?

Local optimality in provenance performance (CAMPBELL *et al.* 1989) seems to be evident at inland sites in submaritime or along the east border of the maritime zone, and the more harsh the site environment the sooner this local optimality emerges (collapsing of coastal provenances), *e.g.* at Dragon Lake and Maroon Creek. The seeming collapse of the resistant provenance, Big Qualicum, at northern sites, *e.g.* at Nass (5° northward transfer) (Fig. 6f) further suggests the risk of distant northward transfer. Also the climate in the submaritime zone is volatile, subject to high influence of local landform. It seems to be prudent not to further expand the current northward transfer limit of 2°.

No decline in growth or change in geographic pattern of provenance performance was evident at mild sites in maritime environment, *e.g.* Holberg (Figs. 2, 4a and 5a), even for provenances originating 8 degrees of latitude south of the test sites, *e.g.* No. 18 (Brookings, Oregon) at Holberg and No. 12 at Rennell Sound (Fig. 1). Will geographic pattern at these mild sites eventually change? We cannot predict that. These tests are still young in terms of rotation age over 100 years. Frost injury did occur to these southern coastal provenances in 1984 and 1985 when less than normal cold temperatures hit these sites. Gain in growth in reforestation use of fast growing southern sources should also be weighed against possible loss in other traits, *e.g.* wood quality (CAHALAN 1987) in addition to biological risk in long-term adaptability. Prudent use of early results has its merits.

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