

Assessing the impact of current and projected climates on Douglas-Fir productivity in British Columbia, Canada, using a process-based model (3-PG)

Nicholas C. Coops, Robbie A. Hember, and Richard H. Waring

Abstract: Predicted climate change is expected to significantly affect tree growth in many areas. We used a process-based model (Physiological Principles for Predicting Growth, 3-PG) to evaluate how climatic variation might alter growth of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *glauca* (Beissn.) Franco and *Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*) across biogeoclimatic zones in British Columbia. The results indicate that there will be significant changes in site index (defined as the height (in metres) of dominant trees at 50 years) over this century. In the interior, a reduction in site index is likely, particularly in stands with mid-range values of site index (25–30 m), with many of the interior biogeoclimatic zones predicted to experience a gradual mean decrease in site index by up to 10%. Individual sites may decrease by as much as 40% from current values. In contrast, site index along the coast overall is predicted to increase to a maximum of 43 m by 2080. In the Coastal Western Hemlock zone, however, mean site index is likely to increase from 26 m to only 34 m. We believe that combining process-based models with fine-spatial resolution climate forecasts offers a viable approach to assess future changes in forest productivity.

Résumé : On prédit que les changements climatiques auront une influence significative sur la croissance des arbres dans plusieurs régions. Nous avons utilisé un modèle de processus (Principes physiologiques pour prédire la croissance, 3-PG) pour évaluer de quelle façon les variations climatiques pourraient modifier la croissance des douglas de Menzies bleu et typique (*Pseudotsuga menziesii* (Mirb.) Franco var. *glauca* (Beissn.) Franco et *Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*) dans les différentes zones biogéoclimatiques en Colombie-Britannique. Les résultats indiquent qu'il y aura des changements importants de l'indice de station (défini comme la hauteur en mètres des arbres dominants à l'âge de 50 ans) au cours de ce siècle. Il est probable que l'indice de station diminue dans la zone intérieure, particulièrement dans les peuplements dont l'indice de station se situe parmi les valeurs intermédiaires (25–30 m) et on prédit que plusieurs des zones biogéoclimatiques de l'intérieur vont subir une diminution moyenne graduelle de l'indice de station pouvant atteindre 10 %. La diminution pourrait atteindre 40 % par rapport aux valeurs actuelles dans certaines stations. À l'inverse, on prédit que l'indice de station le long de la côte augmentera globalement jusqu'à un maximum de 43 m vers 2080. Cependant, dans la zone côtière de la pruche de l'Ouest l'indice de station augmentera probablement de 26 m à seulement 34 m. Nous croyons que la combinaison des modèles de processus et de la prédiction du climat avec une haute résolution spatiale offre une approche viable pour évaluer les changements futurs de productivité forestière.

[Traduit par la Rédaction]

Introduction

Over the past 30 years, Canada has experienced increased variability in weather conditions, which is expected to continue in response to global warming (Parmesan and Yohe 2003). The implications of a warmer and wetter climate on the growth and distribution of commercial tree species are unknown; however, they are likely to pose challenges to

sustainable management of resources (Green et al. 1989; Monserud et al. 2008). One might imagine that a warmer and wetter climate should enhance tree growth across the Province of British Columbia (BC) because the growing season will lengthen and water will be used more efficiently (Marshall and Monserud 1996), but a rise in temperature also increases the evaporative demand while reducing precipitation (Spittlehouse 2003; Hogg and Bernier 2005). As a result, some forests may become stressed, causing an increase in the frequency and intensity of wildfires, as well as insect and disease outbreaks (Kurz et al. 2008).

Although periodic forest inventories can document disturbances and changes in productivity across the province, they are unable to forecast where changes in productivity are expected to occur or to explain the reason for these changes (Green et al. 1989). To forecast the implications of projected climatic variation, an analysis is required that explores seasonal and interannual climatic variation as they affect

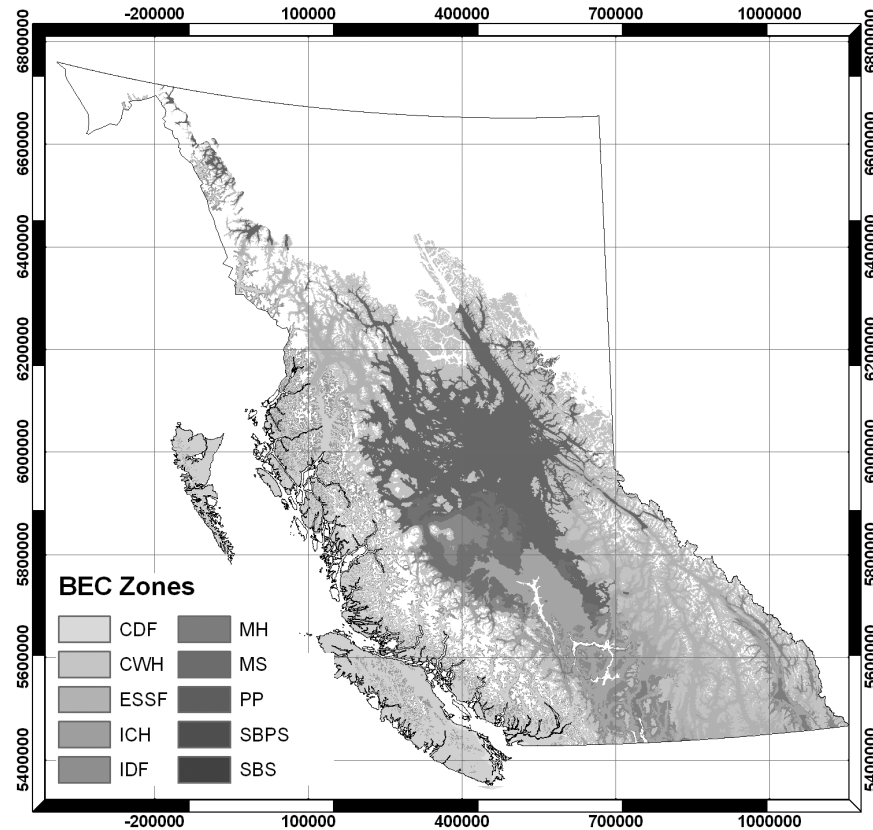
Received 10 March 2009. Accepted 30 November 2009.
Published on the NRC Research Press Web site at cjfr.nrc.ca on 8 March 2010.

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Fig. 1. Biogeoclimatic Ecosystem Classification (BEC) zones of British Columbia. BEC zone abbreviations are defined in Table 1.



site productivity. Such analyses may be performed with process-based simulation models, given that they are calibrated under current climatic conditions.

In this paper, we applied a widely used forest growth model (Physiological Principles for Predicting Growth model (3-PG)) (Landsberg and Waring 1997) to map current productivity of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *glauca* (Beissn.) Franco and *Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*) across BC and to contrast these projections with those expected through the rest of the century. We chose Douglas-fir because it is currently found in 10 of 14 recognized Biogeoclimatic Ecosystem Classification (BEC) zones (Fig. 1). The 3-PG model predicts volume growth annually under stable or varying climatic conditions. Mean periodic annual increment can be converted into site index (SI), which in BC is conventionally expressed as mean height (in metres) of dominant and codominant trees at 50 years of age (Green et al. 1989). We compared changes in SI in those ecological zones in which Douglas-fir currently grows. Following these comparisons, we used the model to assess the extent that each of four climatic variables affected growth under current conditions within designated BEC zones and how these variables might change in importance at three-decade intervals throughout this century, starting in 2020.

Methods

Geographic distribution and associate species

Douglas-fir (*P. menziesii* var. *glauca*) grows in the BC in-

terior under cooler winters and warmer and drier summers than the coastal variety (*P. menziesii* var. *menziesii*). Interior stands frequently occur with a grassy understory on much hotter and drier sites than typical of those occupied by the coastal variety. In these situations, the interior variety is often associated with ponderosa pine (*Pinus ponderosa*). On more mesic environments, it occurs in dense stands with white spruce (*Picea glauca*). At higher elevations, Douglas-fir often grows in a mixture with lodgepole pine (*Pinus contorta*). Nearer the coast, pure stands of Douglas-fir occur in limited areas where conditions are warmer and drier than normal, and in a mixture with Pacific madrone (*Arbutus menziesii*), Garry oak (*Quercus garryana*), and occasionally with shore pine (*Pinus contorta* var. *contorta*). In moister areas, Douglas-fir is associated with grand fir (*Abies grandis*), western redcedar (*Thuja plicata*), and bigleaf maple (*Acer macrophyllum*). Both the interior and the coastal varieties are shade-intolerant, pioneer species with thick, fire-resistant bark, which exhibit faster growth rates than their more shade-tolerant counterparts. Douglas-fir comprises a large fraction of the land base in both regions because it is favored for its high commercial value (Pojar and MacKinnon 1994).

Over its full range in BC, Douglas-fir productivity is strongly influenced by the availability of water (Brix 1972; Spittlehouse 1985; Carter and Klinka 1990). The coastal variety rarely occurs in areas with frequent heavy snowfall (Spittlehouse 2003). Suboptimal temperatures, cloudiness, and high atmospheric humidity deficits combine to limit productivity, even without drought in many areas (Littell and Peterson 2005). Given that climatic variables interact, a

Table 1. The major Biogeoclimatic Ecosystem Classification (BEC) zones associated with Douglas-fir.

Zone code	Zone	Species
CDF	Coastal Douglas-fir	Douglas-fir, western redcedar, grand fir, arbutus, Garry oak, red alder
CWH	Coastal Western Hemlock	Western hemlock, western redcedar, Douglas-fir, silver fir, yellow-cedar, lodgepole pine, grand fir, western white pine, bigleaf maple, red alder, Sitka spruce
ESSF	Engelmann Spruce – Subalpine Fir	Engelmann spruce, subalpine fir
ICH	Interior Cedar – Hemlock	Western redcedar, western hemlock, grand fir, white spruce, Engelmann spruce, subalpine fir, Sitka spruce, western larch, Douglas-fir, western white pine, ponderosa pine, black cottonwood
IDF	Interior Douglas-fir	Douglas-fir, lodgepole pine, ponderosa pine, white spruce, western redcedar, trembling aspen, grand fir, paper birch, western larch, Rocky Mountain juniper
MS	Montane Spruce	Engelmann spruce, subalpine fir, Douglas-fir, white spruce, lodgepole pine
PP	Ponderosa Pine	Ponderosa pine, Douglas-fir, trembling aspen, water birch
SBS	Sub-Boreal Spruce	Hybrid white spruce, subalpine fir, lodgepole pine, trembling aspen, Douglas-fir, black spruce
MH	Mountain Hemlock	Mountain hemlock, silver fir, yellow-cedar, western redcedar, western hemlock, Sitka spruce, Douglas-fir, western white
SBPS	Sub-Boreal Pine – Spruce	Lodgepole pine, white spruce, trembling aspen, Douglas-fir, subalpine fir, black spruce, black cottonwood

Note: At this scale, the two most productive zones are CDF and the CWH BEC zones. Of the interior BEC zones, the most productive is the SBS zone followed by the MS zone. The zones with low site indices include the SBP and the IDF BEC zones.

relatively small change in one of these variables may significantly alter the growth and composition of forests that currently contain Douglas-fir.

The BC Ministry of Forests and Range has adopted and refined the Biogeoclimatic Ecosystem Classification system developed by Krajina (1959, 1969). The BEC system classifies sites according to the potential to grow resident tree species registered at mapping scale of 1:250 000, with the smallest recognized unit of 156 ha. Plant communities that have developed to a relative stable state are considered a reflection of a site's potential and serve as the basis for classification. The classification is hierarchical, with BEC zones, subzones, and variants mapped at progressively finer spatial scales. The finest scale distinguishes differences associated with local variation in the availability of soil water and nutrients. The BEC classification forms the basis of forest management across BC and helps define seed zones, protected areas, forest pest risk, and wildlife habitat units. In addition, the system is used for site-specific management decisions concerning the most suitable tree species for regeneration, the appropriate level of stocking, the need to control competing vegetation following harvest, and is a means to infer site limitations to growth (Meidinger and Pojar 1991). Based on its widespread use by BC forest management agencies, we believe that an assessment of changes in Douglas-fir growth within BEC units will be readily understood and that the assessment follows a convention set by others (Hamann and Wang 2005). Table 1 describes the major BEC zones in which Douglas-fir currently grows (Meidinger and Pojar 1991), thus defining the BEC zones of interest in this study. At this scale, the more productive sites for Douglas-fir include the Coastal Douglas-fir and the Coastal Western Hemlock BEC zones. In the interior, the most productive zone is Sub-Boreal Spruce, followed by the Montane Spruce zone. Douglas-fir productivity is ranked lowest in the Sub-Boreal Pine – Spruce and the Interior Douglas-fir BEC zones.

Model predictions of site index

Site-specific yield tables provide decadal estimates of tree numbers, diameters, basal area, standing volume growth, and periodic mean annual increment, all keyed to a height that a particular tree species reaches in a specified number of years (SI). Such yield tables are developed from empirical information acquired from field surveys and destructive analysis of many trees. SI is often modeled locally as a function of topography, soil properties, and seasonal variation in precipitation and temperature (Curt et al. 2001). Over the last two decades, a number of process-based forest growth models have emerged that integrate many of the environmental constraints on productivity at monthly or finer time steps (see reviews by Landsberg et al. (2001) and Nightingale et al. (2004)). To be accurate, these process-based models require good meteorological and soil data (Tickle et al. 2001). However, it is possible to assess relative changes in site productivity associated with climate by holding soil properties constant and varying meteorological conditions over time (Coops et al. 2005). We employed a general, physiologically based process model, the Physiological Principles Predicting Growth (3-PG) model developed by Landsberg and Waring (1997), to predict Douglas-fir SI across BC by using monthly mean climatic data averaged over sequential 30 year periods at a cell resolution of 1 km.

3-PG model overview

The 3-PG model is process-based, deterministic, and non-stochastic. The model has been widely applied in forestry (see reviews of its use by Landsberg et al. (2001)) because of its flexibility, relative simplicity, and limited requirements for biophysical parameters. Almeida et al. (2004) calibrated 3-PG for fast-growing plantations in Brazil and found that it provided accurate predictions of stem, root, and foliage biomass; leaf area index; basal area; mean annual increment; and stand volume over a rotation under varying climatic conditions, given adequate information on soil properties. In

a two-model intercomparison, Law et al. (2000) found that the 3-PG model tracked variation in stand leaf area and net primary production (NPP) of a ponderosa pine and that estimates of gross carbon uptake were closely correlated with that derived from eddy-flux tower measurements. Siqueira et al. (2006) conducted a multi-scale model intercomparison with 3-PG and three other models. They found that 3-PG showed reasonable agreement with the mean flux observed at a maturing loblolly pine forest. The 3-PG model did well in calculating a soil water balance that closely matched observed patterns in soil moisture.

The 3-PG model includes a number of simplifying assumptions: (1) that climatic data can be summarized at monthly intervals with little loss in modeling accuracy; (2) that NPP is a fixed fraction of gross photosynthesis (Waring et al. 1998); (3) that canopy conductance approaches a maximum value above a leaf area index of 3.0; (4) that the proportion of photosynthate allocated below-ground increases as water and nutrients become more limiting; and (5) that aboveground growth and accumulated biomass of foliage, stems, and branches can be estimated with species-specific allometric relationships and knowledge of annual leaf turnover (Landsberg et al. 2001). The model calculates rates of photosynthesis, leaf litterfall, and transpiration at monthly time steps, and growth allocation annually. Most importantly, it also calculates variables recorded in forestry yield tables (i.e., tree density, basal area, mean diameters, standing volume, current and mean annual increment). No other process-based model is available that specifically accounts for reductions in leaf photosynthesis and transpiration as trees age, which is an essential property required to match yield tables values recorded for long-lived species.

The 3-PG model can be applied with actual time series of monthly meteorological data or with long-term average monthly values ('normals') acquired over a specified period (Coops et al. 2005). Because SI determinations assume a stable climate, long-term averages are the appropriate choice for this study. The model assumes that absorbed irradiance is the main driver of productivity, which is subsequently adjusted by dimensionless modifiers that vary between zero (shut down) and unity (optimum). They represent the degree to which photosynthesis is limited by (i) high daytime atmospheric vapour pressure deficits (D), (ii) soil water deficits, (iii) subfreezing temperatures, and (iv) suboptimal temperatures (Landsberg and Waring 1997).

The commercial importance of Douglas-fir has resulted in a large body of research regarding allometry and physiology. A number of papers have parameterized the 3-PG model for Douglas-fir, including studies in Oregon (Coops and Waring 2001a), Washington (Waring and McDowell 2002), British Columbia (Coops et al. 2007), and most recently, New Zealand (Waring et al. 2008). In this study, species parameters were the same as those used by Waring and McDowell (2002) and Coops et al. (2007).

Coops and Hember (2009), in a precursor to this study, applied the 3-PG model to predict and map current SIs of Douglas-fir across BC using the same CLIMATE-BC climate estimates as applied in this study, and compared the model with independent estimates of average SI at 50 years for subzones derived as part of the Site Index BEC initiative

(Mah and Nigh 2003). The relationship was significant for coastal Douglas-fir, with a correlation (r) of 0.83 and a standard error of the estimate (SE) of 2.34 m, and for interior Douglas-fir ($r = 0.72$). Combining model estimates for all BEC subzones, the correlation with SI was highly significant ($r = 0.86$, $p < 0.001$, $n = 68$, $SE = 3.0$ m) at 50 years.

Climate surface generation

Long-term climate observations for stations throughout the region were interpolated across BC using CLIMATE-BC, which includes a bilinear interpolation of the PRISM (Parameter-elevation Regressions on Independent Slopes Model) records, along with elevation corrections to temperature records for mountainous terrain (see Hamann and Wang 2005 for details of climate surface fitting approaches and use of PRISM). To derive monthly minimum and maximum temperature extremes and precipitation, a 90 m Digital Elevation Model was obtained from Shuttle Radar Topography Mission and resampled to a 1 km resolution for this analysis. Mean monthly D values for daylight periods were estimated by assuming that saturation at the average monthly minimum temperature would be equivalent to water vapor concentrations present throughout the day (Kimball et al. 1997). The average difference between the saturated vapor pressure at the maximum temperature and that at the minimum temperature represents the mean maximum D for each month. Mean daytime D was assumed to be two-thirds of the daily maximum (Waring 2000; Coops and Waring 2001b). The number of days per month with subfreezing temperatures was also estimated from empirical correlations with minimum mean monthly temperatures (Coops et al. 1998). Subfreezing temperatures are important because they cause complete stomatal closure and may prevent photosynthesis for an entire day, even when air temperatures rise above freezing (Marshall et al. 2001). Global solar radiation was derived using a topographic analysis and regionally defined cloudiness estimates provided from the North American Regional Reanalysis since 1979, as detailed in Schroeder et al. (2009).

Climate change scenarios

To simulate changes in Douglas-fir productivity under projected future climates, we utilized the climate scenarios developed by the Intergovernmental Panel on Climate Change (IPCC 2000) in their special report *Emission Scenarios*. These scenarios include "a business as usual" prediction that includes a revised assessment of the impact of greenhouse gas emissions. As with other work undertaken in Canada (Hamann and Wang 2005; Monserud et al. 2008), we applied the Canadian Climate Centre (CGCM2, Flato et al. 2000) predictions based on the A2 scenarios, which are considered close to the upper bound of the climate scenarios in *Emission Scenarios* (IPCC 2000; Monserud et al. 2008). There are three runs for the CGCM2 A2 scenarios (A21, A22, and A23). We used ensemble averages (A2x) to generate the future climate scenarios. We used three 30 year time intervals designated by the mid-decade, i.e., 2020s (2011–2040), 2050s (2041–2070), and the 2080s (2071–2100). The scenarios were referenced in terms of the variation from the

Fig. 2. Current precipitation, maximum temperature, and minimum temperature (A, C, E, respectively), and 2080 predicted values, representing the last 30 years of the century predictions, of precipitation, maximum temperature, and minimum temperature (B, D, F, respectively), for Biogeoclimatic Ecosystem Classification zones currently with Douglas-fir. See Table 1 for an explanation of the zone abbreviations and their descriptions.

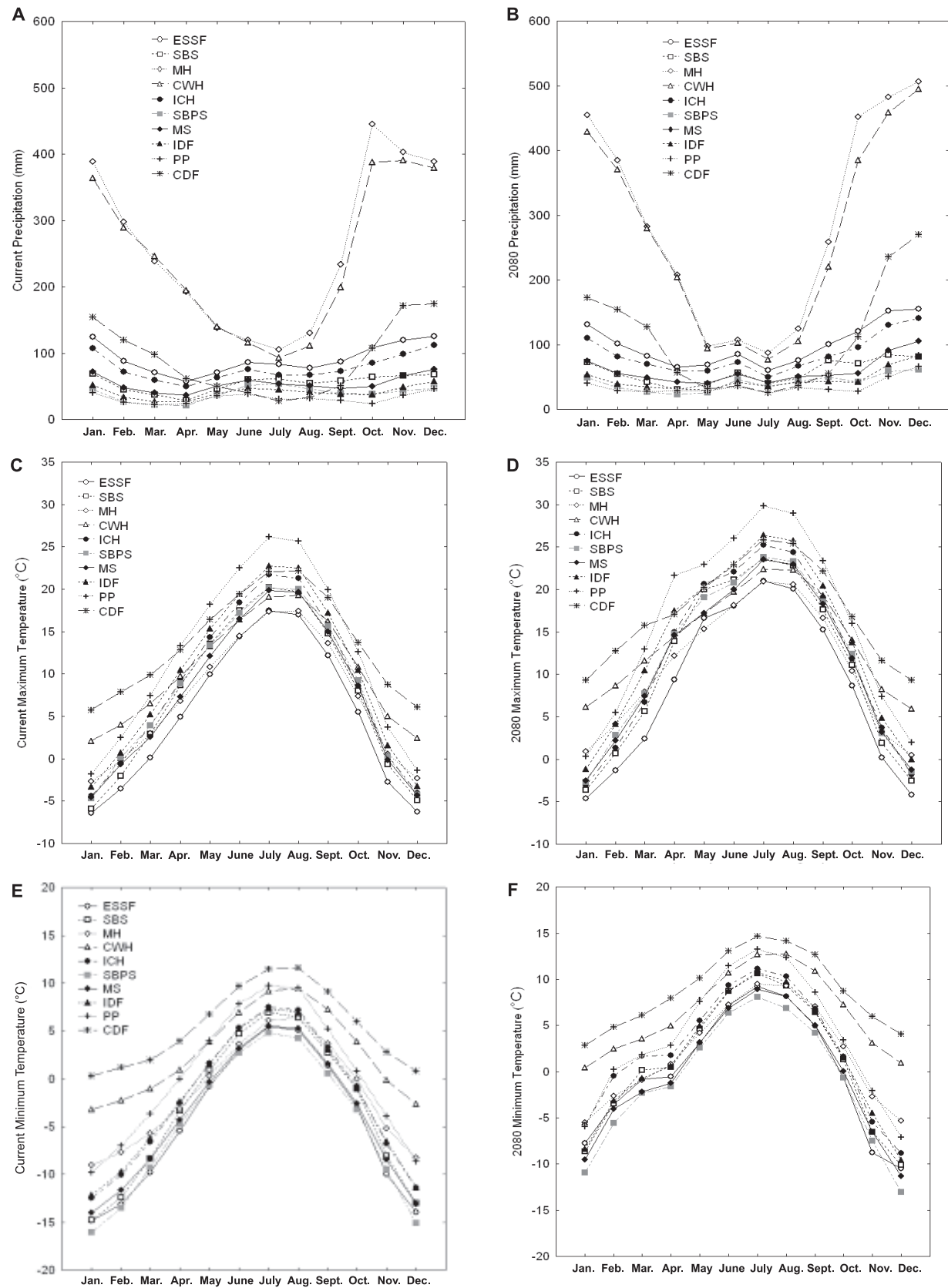


Fig. 3. Monthly environmental modifiers to Douglas-fir growth (1 signifies no limitation) averaged over Biogeoclimatic Ecosystem Classification zone, shown as temporal trajectories for the last 30 years (A, C, E, G) and for comparable periods in the 2080s (B, D, F, H). See Table 1 for an explanation of the zone abbreviations and their descriptions.

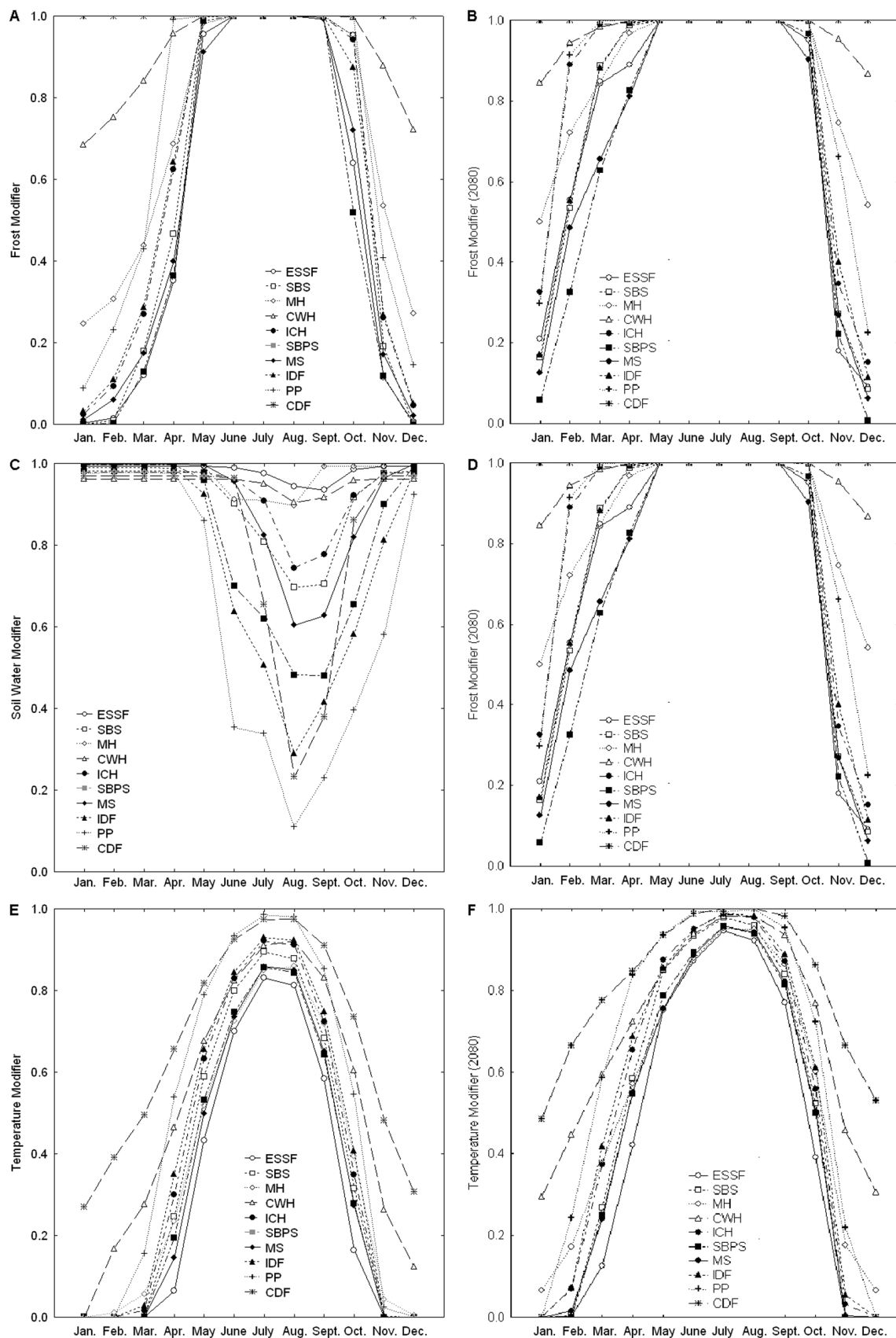
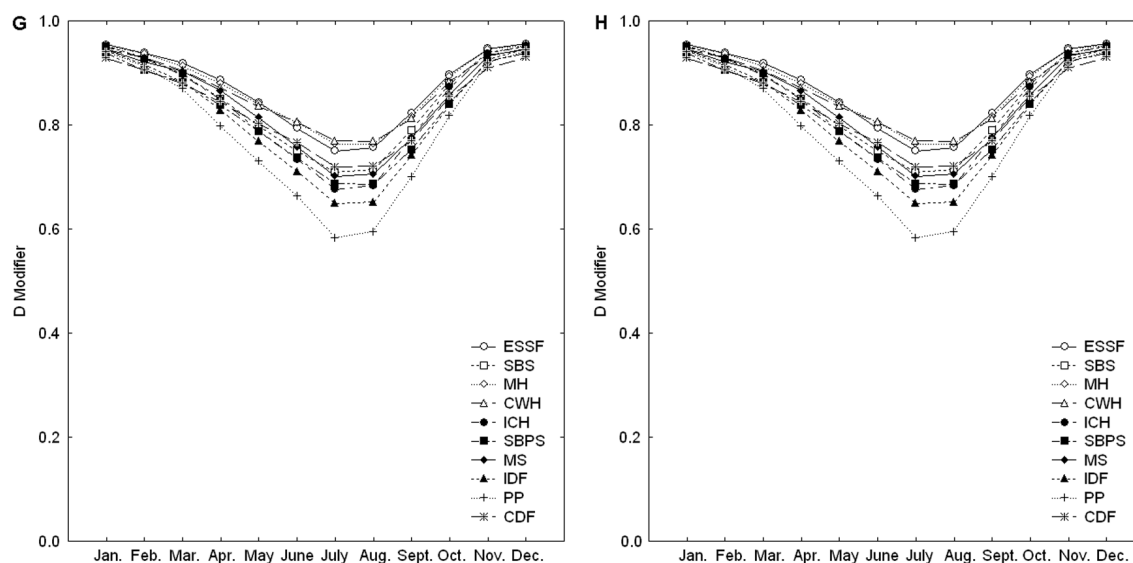


Fig. 3 (concluded).



baseline period, as derived from CLIMATE-BC, using climate station data over the 30 year period 1961–1990.

In previous research, Monserud et al. (2008) utilized three GCM climate outputs (CGCM2, UK Hadley Centre, and the Max Plank Institute) and found that all three produce similar trends of changing climate over the next 100 years across Alberta. Mote et al. (2005) compared the ability of 20 global climate models to track recently recorded trends in temperature and precipitation in the Pacific Northwest and reported that the Canadian model was consistent in predicting a relatively rapid rate in warming and a significant increase in precipitation. As a result, we believe utilizing this climate scenario provides an appropriate demonstration of the methodology to link process-based models of forest growth to future climate scenarios.

Future radiation scenarios were not available, thus the monthly mean global solar radiation estimates for the past 30 years were used in all simulations. We also did not incorporate the effects of a predicted continuous rise in atmospheric CO₂, as this variable is highly interactive with soil fertility, which affects phenology, photosynthetic capacity, and allocation of growth above ground and below ground (Eamus and Jarvis 1989; Guak et al. 1998).

Soil information

In addition to the climate data described above, 3-PG generally requires data for soil water-holding capacity and an indication of soil fertility ranking, between 0 (poorest) and 1 (best). As stated above, variation in soil fertility affects the partitioning of photosynthate below ground as well as the photosynthetic capacity (quantum efficiency, α). In 3-PG, a minimum of 25% of NPP is assumed to go below ground on the most fertile sites without water limitations, whereas on the poorest soils, 80% goes below ground (Landsberg and Waring 1997). In this paper, for lack of adequate soil maps, we assume a fixed value of soil fertility with a rank of 0.7, which results in 50% of NPP going below ground. The

equivalent quantum efficiency was set at 0.050 mol C·(mol photon)⁻¹ (2.75 g C·(MJ APAR)⁻¹), which is about half-way between the reported minimum (0.02 mol C·(mol photon)⁻¹) and maximum values (0.07 mol C·(mol photon)⁻¹) for relatively productive coniferous forests in the Pacific Northwest (Waring and Running 1998).

Although soil drought has less effect on photosynthetic capacity, it limits photosynthesis and increases the fraction of NPP allocated below ground in drought-prone months. To obtain realistic ranges of available soil water-holding capacity over BC, we utilized area-weighted average estimates of soil depth and texture from landscape components of the *Soil Landscapes of Canada*, version 2.1 (Agriculture and Agri-Food Canada 2008). Values for soil water-holding capacity across the province ranged between 10 and 260 mm, with an average value of 80 mm. This range corresponds reasonably well with values assigned to the east coast of Vancouver Island (Nagpal et al. 1986; El Maayar et al. 2002).

3-PG model simulations

To estimate SI variation with the 3-PG model across the province, simulations were run with four climate scenarios (current averages and sequential periods of 30 years starting in 2010)². Predictions of SI were extracted along with monthly environmental limitations to photosynthesis in the 50th year of each set of simulations. All statistical analyses were made using standard statistical software (StatSoft 2000).

Results

Changes in precipitation are forecast in only a few of the BEC zones located along the coast (Fig. 2). Specifically, the Mountain Hemlock and Coastal Western Hemlock zones are predicted to receive increases in precipitation during the first 4 months of the year. Conversely, summer precipitation in

² 3-PG code to run the simulations is available, free of charge, from the authors.

Fig. 4. Spatial pattern of the current monthly environmental modifiers to Douglas-fir growth and of the same age stands in 2080. VPD, vapour pressure deficit.

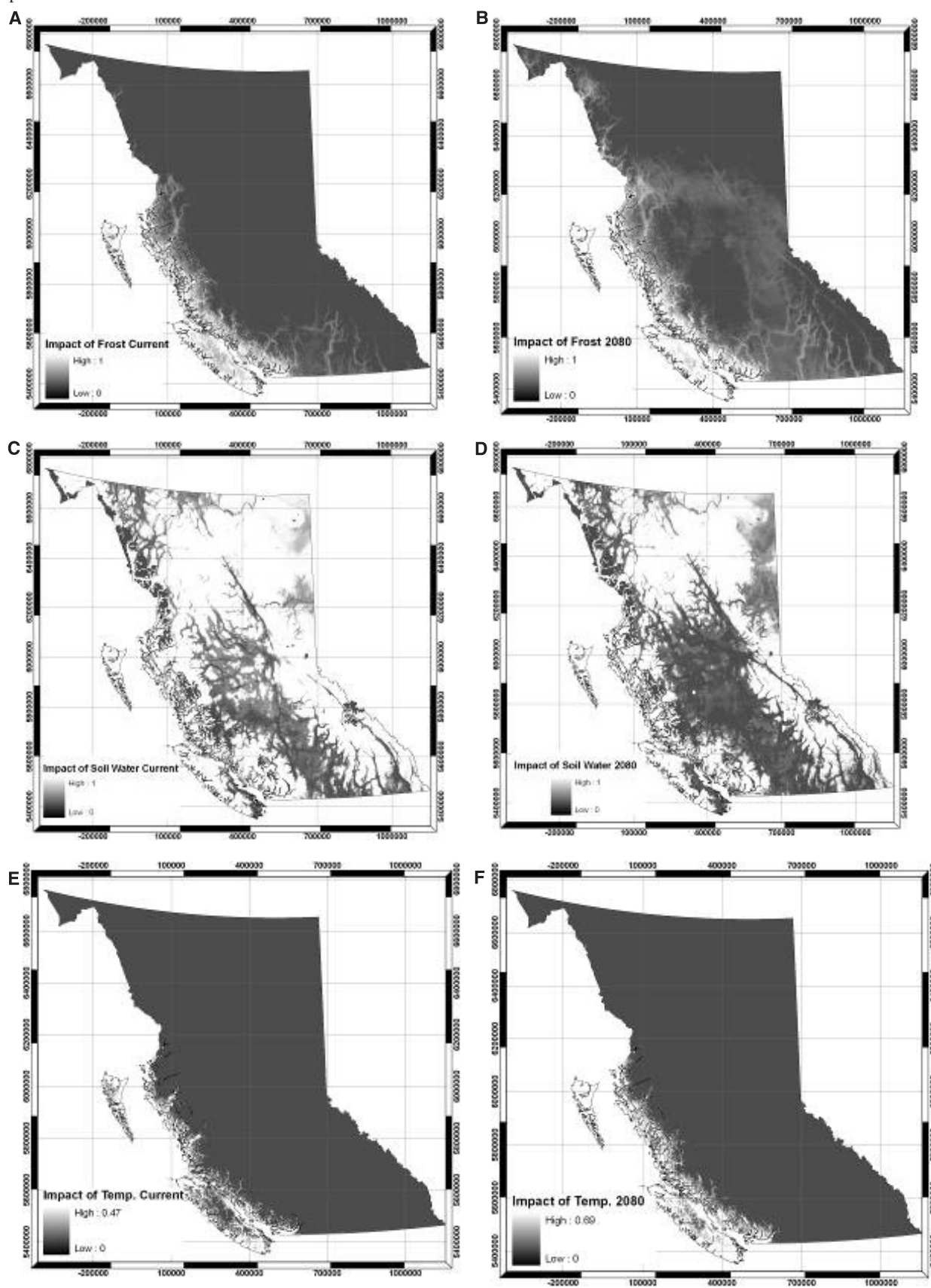
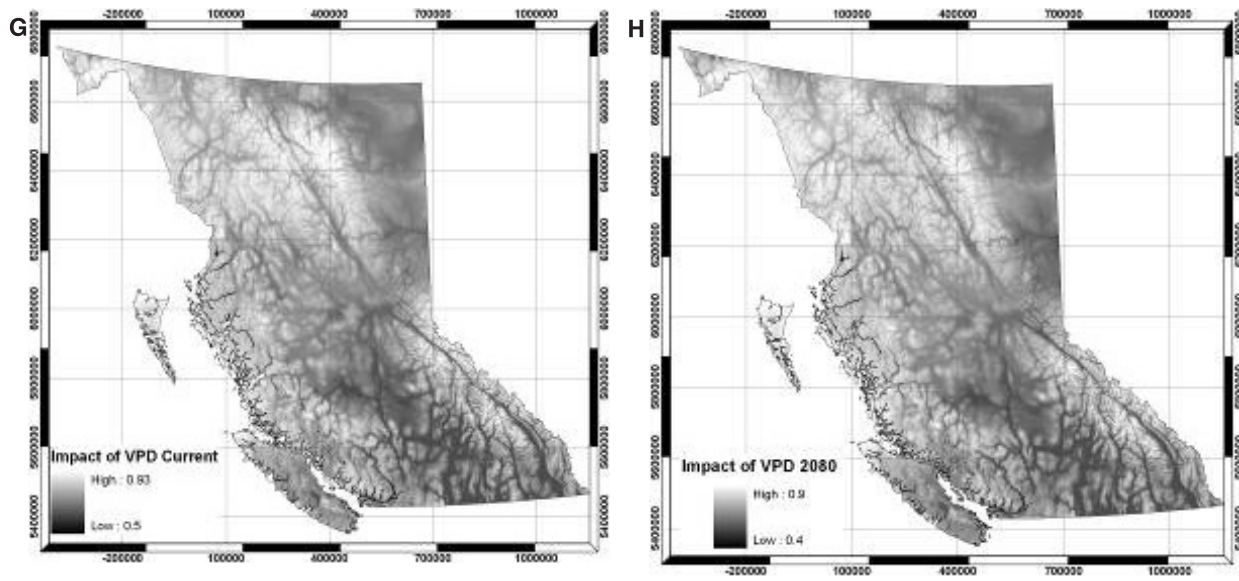


Fig. 4 (concluded).



these zones is predicted to be progressively reduced to the end of the century, although late fall and winter precipitation may increase by as much as 120 mm. In contrast to the coastal areas, the interior BEC zones with Douglas-fir are predicted to experience a change in precipitation of less than 10 mm per month.

In contrast to precipitation, monthly minimum temperatures are expected to increase in all BEC zones by between 1 and 8 °C by the end of the century in the months of March, April, and May. Summer, fall, and winter months are also expected to be warmer by ~3 °C across all BEC zones. The maximum temperature predictions follow trends similar to those projected for monthly minimum temperature. The extremes, however, are even larger, increasing by up to 9.5 °C in winter months. The interior subregions are expected to experience the most change, specifically the Interior Cedar Hemlock, Sub-Boreal Spruce, and Engelmann Spruce – Subalpine Fir zones.

The monthly environmental constraints on Douglas-fir growth, averaged for each of 10 BEC zones under current climate conditions, are contrasted with those predicted under a 2080 climate scenario (Fig. 3) with the spatial pattern over the province shown in Fig. 4. In Figs. 4A and 4H, maps are presented that indicate the extent that different environmental modifiers affect growth during the month that they individually the most limiting. Under the current climate, frost imposes a major restriction on photosynthesis of Douglas-fir throughout the most of the interior of BC (Figs. 3A and 3B). In some areas in the southern interior, and inland from the coast, this restriction is less severe, but frost remains an impediment on productivity, particularly in the spring and fall when solar radiation is adequate to support considerable photosynthetic activity.

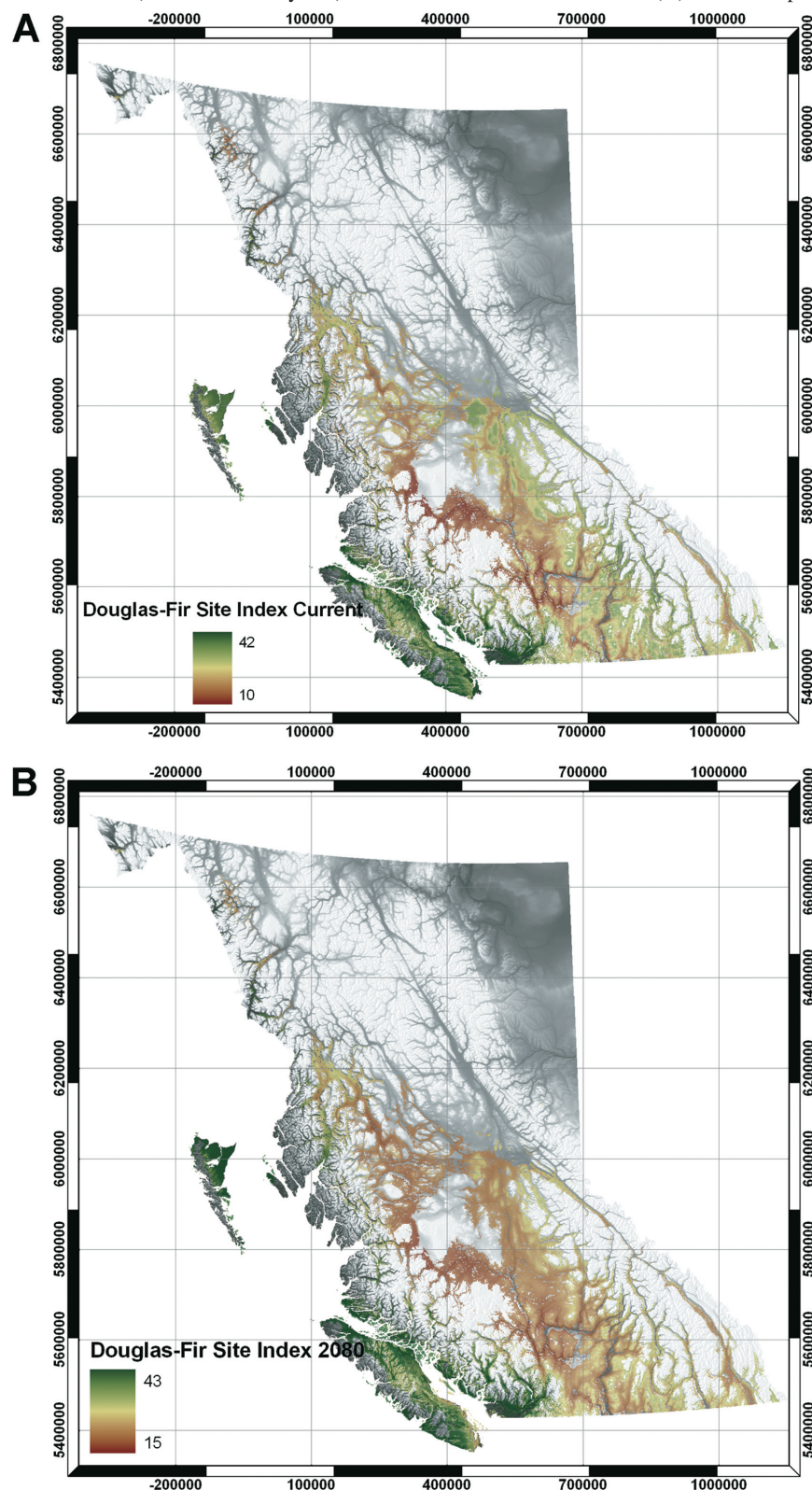
Along the coast, frost is less restrictive, and across Vancouver and the Queen Charlotte Islands, its impact on growth is negligible (Figs. 4A and 4B). Toward the end of this century, warmer temperatures are predicted to reduce frost limitations on the growth of Douglas-fir throughout

the province. In the interior, while frost may still constrain growth somewhat in the Engelmann Spruce – Subalpine Fir and Ponderosa Pine zones, its impact should be much reduced.

Drought will likely increase in many areas (Figs. 3C and 3D). Under current climatic conditions, the coastal zones (i.e., Coastal Western Hemlock) experience little or no drought throughout the year. The eastside of Vancouver Island (i.e., the Coastal Douglas-fir zone) and the more inland areas of the Mountain Hemlock zone exhibit some areas with drought stress (Figs. 4C and 4D). All of the interior BEC zones with Douglas-fir now experience moderate to severe drought during the growing season. As temperature and radiation increase in spring, the demand for water increases while monthly precipitation decreases, resulting in soil-water deficits in many zones. In the Ponderosa Pine zone, severe drought commences in May. In the Sub-Boreal Pine Spruce and Interior Douglas-fir zones, drought is delayed, but by August all zones are predicted to experience drought. As precipitation increases in late September and October, most soils are replenished, although the driest sites do not fully recharge until late November. In contrast, near the end of this century, drought stress is predicted to increase substantially across most of the interior BEC zones that now support Douglas-fir (Fig. 4D). Similarly, on Vancouver Island, drought along the east coast is expected to increase with elevated temperature and no increase in precipitation. The trajectory of soil water stress across the BEC zones by the last three decades of the century shows an abrupt increase in water stress in May and June compared with current conditions in most BEC zones. Still, soils are expected to recharge fully during the winter, but in late spring, reductions in precipitation toward the end of the century are likely to cause major limitations in available soil water in July and in subsequent months for some interior BEC zones.

An analysis of the temperature constraints across the province for Douglas-fir is presented in Figs. 3E, 3F, 4E, and 4F.

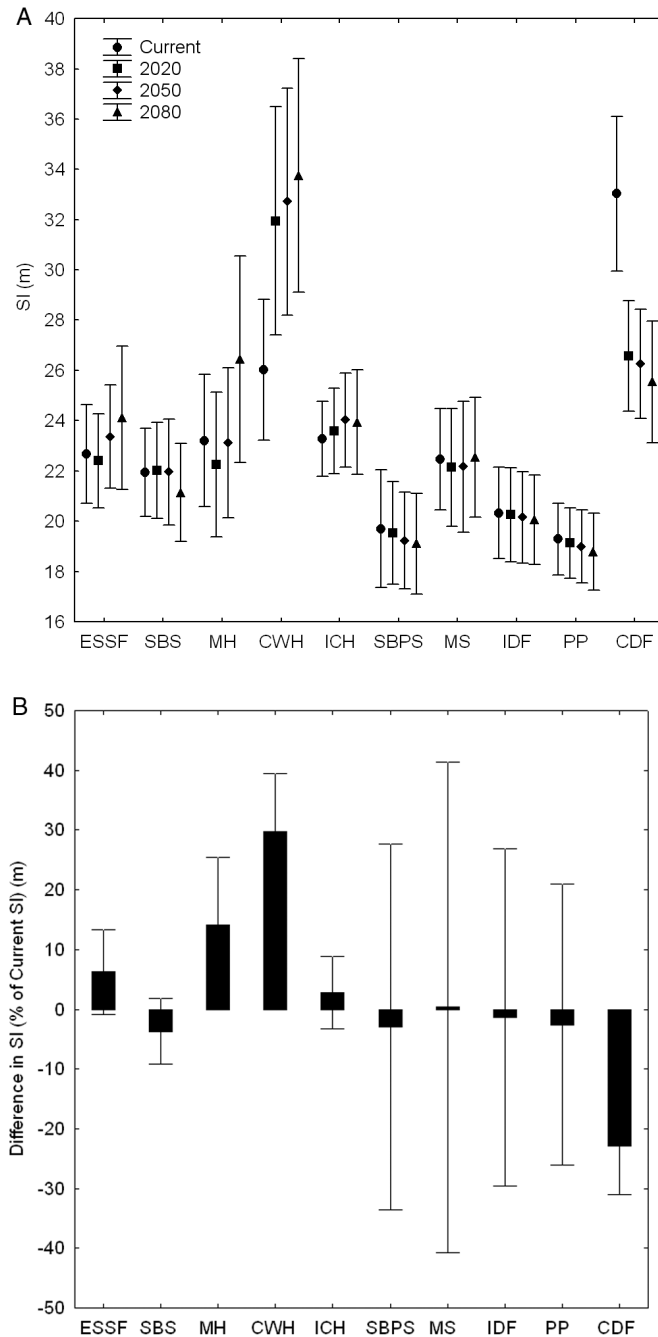
Fig. 5. Spatial predictions of site index (in metres at 50 years) under current climate conditions (A) and those predicted in 2080 (B).



In the 3-PG model, suboptimal temperatures become particularly important when photosynthesis is not limited by frost, drought, D , and solar irradiance. Generally, ambient air temperatures are well below the optimum for Douglas-fir in the

winter across the province except for the Coastal Douglas-fir zone and parts of the Coastal Western Hemlock zone. In summer, the temperature is close to the optimum for Douglas-fir in most places. The Engelmann Spruce – Subal-

Fig. 6. (A) The mean and standard deviation in site index (SI) summarized by Biogeoclimatic Ecosystem Classification zone for current climate and for that predicted in 2020, 2050, and 2080, and (B) the relative change in SI from current to 2080, normalized to current predicted values. See Table 1 for an explanation of the zone abbreviations and their descriptions.



pine Fir zone experiences optimum temperature for Douglas-fir at present only between May and September. By 2080, most of the BEC zones are predicted to experience longer growing seasons and more favorable temperatures for Douglas-fir.

Limitations imposed by *D* are in the opposite direction to those imposed by suboptimal temperatures (Figs. 3G, 3H,

4G, and 4H). In cooler months, *D* rarely restricts photosynthesis in any zone. As temperature increases, *D* increases exponentially and often imposes limitations on stomatal conductance during the summer. Throughout the province, *D* currently restricts photosynthesis on average between 30% and 40% during in the summer months. By 2080, a warming of the interior climate may limit photosynthesis by an additional 10%–20%.

Spatial variation in predicted SI under current climate conditions and those predicted between 2070 and 2100 are shown in Figs. 5A and 5B. The coastal forests of BC, particularly those on Vancouver Island and the Queen Charlotte Islands, and a fringe along the mainland currently average SI in excess of 40 m at 50 years. In contrast, SI values between 20 and 30 m at 50 years are typical in the southern interior, with the lowest recorded in the Sub-Boreal Pine – Spruce and the Interior Douglas-fir zones. Near the end of the century, marked changes in SI are expected (Fig. 5B). Mid-range sites (25–30 m at 50 years) are likely to be absent in interior zones, whereas SIs along the coast are expected to increase up to 43 m at 50 years.

The mean and standard deviation of SI for current climate and those predicted for 2020, 2050, and 2080, as summarized by BEC zone, are shown in Fig. 6A. Some BEC zones experience very large increases in both the mean SI and the variation in SI throughout the BEC zone during the current century. In the case of the Coastal Western Hemlock zone, the mean SI is predicted to increase from 26 to 34 m. Similarly, the mean of the Mountain Hemlock zone is predicted to increase from 22 to 26 m. In contrast, the Coastal Douglas-fir zone will exhibit a significant reduction in SI, declining from current levels of 32–26 m. Many of the interior zones experience a gradual decrease in SI. Figure 6B shows the mean relative change in SI between the current and 2080 base period, normalized to current levels. Relative changes show increases of between 10% and 30% along the coast (except for the Coastal Douglas-fir zone) and mean decreases in the interior of less than 10%. However, local changes in SI in the interior are likely to reach $\pm 40\%$.

Discussion

Increases in temperature in most of BC are expected to favor tree growth. Our model simulations suggest that predicted climate changes could increase SI by between 10% and 40%. These estimates are similar to those reported by others. Monserud et al. (2008) predicted an increase in SI for lodgepole pine in Alberta by up to 9 m in response to increases in temperature. Other studies conducted in northern forests have predicted similar results (Tchebakova and Parfenova 2003). In some locations, however, warming may increase drought, particularly where precipitation is projected to decrease. Areas that currently experience drought will be particularly susceptible to reductions in productivity in the future, such as the interior of BC. A reduction in the frequency of frost and more suitable temperatures during the growing season are likely to account for an increase in productivity within BEC zones, whereas a depletion in the available soil water will likely be the main cause for any major reduction in future productivity.

In this analysis, we ignored genetic variation, which

would have required specific knowledge of differences in environmental tolerances and separate sets of allometric equations to parameterize 3-PG. It is well known that Douglas-fir has a wide range in adaptive characteristics and varying requirements for chilling, bud break, and photosynthesis (Aitken and Adams 1997, Guak et al. 1998). Given the projected rapid changes in climate across the province, there is a real concern that the best-adapted populations will not be able to shift their ranges, and even if planted, could find themselves less adapted as time progresses.

In this study, we restricted our analysis to the BEC zones where Douglas-fir is currently a resident species. Obviously under these climate scenarios, other BEC zones that currently do not have large populations of Douglas-fir may develop climates conducive to Douglas-fir survival and growth. As a result, over the century migration of Douglas-fir may occur either naturally or as part of regeneration activities following harvesting.

There is broad agreement that warmer climates will result in changes in disturbance regimes across much of northern Canada, with increases in insect infestation and fire, with Gillett et al. (2004) hypothesizing that fire activity has already increased as a result of general climate warming, and Kurz et al. (2008) and others attributing the large current infestation of the Mountain Pine Beetle in western Canada in part to warming climate. It therefore follows that Douglas-fir, as a pioneer species, could benefit from these increased disturbance regimes, allowing it to colonize more effectively than currently possible in areas that have become more climatically optimum. In a study on the impact of climate on the productivity of the Coastal Douglas-fir forests, Nigh (2006) found a strong link between growing degree days and SI and predicted increases in SI of 1.2 m for every increase of 100 in growing degree days. The climate scenarios used in this research predicted increases of between 700 and 800 growing degree days, resulting in an estimated increase in SI of between 8 and 10 m. Our SI values of Douglas-fir within the Coastal Western Hemlock zone are in general agreement.

Process-based modeling approaches, such as that used with 3-PG, allow the impact of multiple environmental modifiers to be assessed simultaneously throughout stand development as the model simulates the integrated response of forest stand development. This is of potential benefit when compared with studies that utilize only one or two modifiers, for example, approaches based solely on growing degree days. As more of these studies use recently produced, consistent, climate predictions and as more process-based modeling approaches become available, these insights will have a key role to play in the future management of forest resources. While forest inventory yield curves will likely remain the foundation for timber supply planning, it is possible to take the results of these studies on a BEC zone basis and incorporate them into the yield curve functions to produce more realistic future growth scenarios. Areas where climate change is predicted to decrease growth curves, in particular, should be tempered to avoid overestimating future timber supply.

Acknowledgments

Funding for this research was provided in part by the NSERC Strategic Project STPGP 336174-06. We thank Dr. Todd Schroeder for development of the global radiation

surfaces and Douglas-fir species predictions, and Raphael Roy-Jauvin for editorial assistance. R.H. Waring's participation was supported by the National Aeronautics and Space Administration's Program on Biodiversity and Ecological Forecasting (NASA grant NNX09AR59G).

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