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Mapping site indices for five Pacific Northwest conifers using a physiologically based model

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Keywords
3-PG model; British Columbia; Forest Productivity; Oregon; Physiological modelling; *Picea glauca*; *Pinus contorta*; *Pseudotsuga menziesii*; *Thuja plicata*; *Tsuga heterophylla*; Washington

Abbreviations
3-PG = Physiological Processes to Predict Growth; AUC = area under curve; BEC = Biogeoclimatic Ecosystem Classification; DEM = digital elevation model; NARR = North American Regional Reanalysis; SIBEC = Site Index Biogeoclimatic Ecosystem Classification; SRTM = Shuttle Radar Topography Mission

Nomenclature
Pojar & Mackinnon (1994)

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Abstract

Questions: How well can we predict tree growth potential (site index) of five, locally dominant tree species in reference to estimates made with a detailed vegetation classification?

Location: The forested region of the Pacific Northwest, USA and Canada.

Methods: We employed a physiologically based process model (3-PG, Physiological Processes to Predict Growth) to generate estimates of site index under averaged climatic conditions (1971–2000) generated from hundreds of weather stations and extrapolated, with adjustments for topography, across the region at 1-km resolution. The model was parameterized from published information, but we had to assume fixed values of soil water storage capacity at 200 mm and soil fertility at 70% of maximum across the region. Field estimates of site index for the five dominant species were derived from published correlations with detailed mapping of vegetation provided by The British Columbia Ministry of Forests and Range.

Results: The site indices projected with the 3-PG model for the five species combined, when compared with those produced by the Ministry of Forests and Range, produced an r^2 averaging $\sim$0.5 with a standard error of 2.8 m at 50 yr, equivalent to 10% of the mean. Some of the variation may be attributed to inadequate information on soil properties. Importantly, the relationship between the two estimates was not significantly different from a 1:1 line, with an intercept of zero.

Conclusions: The 3-PG modelling approach offers a means of predicting spatial variation in site indices across the Pacific Northwest and provides a basis for predicting future site indices under a changing climate.

Introduction

In North America, site quality, as measured by the capacity of land to produce wood (maximum or mean annual increment), is generally assessed indirectly, based on a measure of height growth achieved at a given age (Sturtevant & Seagle 2004). The latter measurement, termed site index, has proved essential for effective forest management, and is also useful to understand nutrient cycling (Prescott et al. 1993), and to predict habitat quality and biodiversity (Nightingale et al. 2008).

A tree can be expected to exhibit sigmoid growth in height with age only if it remains unimpeded by competition with neighbouring trees and the environment does not change significantly (Sturtevant & Seagle 2004). Ideally, those trees on which site index is evaluated should make up the majority of those present, show no visible damage, and represent the larger or largest trees of similar age (Hagglund 1981; Monserud 1988; Green et al. 1989). Age is conventionally assessed at breast height or extrapolated to the age of establishment. In this paper, we reference site index as the height of dominant trees at age 50 yr.

Forestry yield tables present site index curves and associated volume, basal area, mean diameters and stocking densities for a wide variety of species (Carmean et al. 1989). At times when no suitable trees are present to measure,

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correlations with physiography, climatic indices, soil properties and plant associations have proven useful surrogates for site index (Curt et al. 2001).

In recent decades, with the development of process-based growth models, long-term climatic datasets have been used, along with estimates of soil water storage and fertility, to predict maximum mean annual increments and site indices (see reviews by Landsberg et al. 2001a, b; Nightingale et al. 2004). Site indices have been mapped across regions with some success using process-based models (Tickle et al. 2001; Swenson et al. 2005).

In this paper we employed a physiologically based process model, Physiological Principles Predicting Growth (3-PG), to predict and map site indices for five common tree species across forested lands in the Pacific Northwest. We compared these predictions with those derived independently across the Province of British Columbia.

Methods

3-Pmodel overview

The 3-PG model developed by Landsberg & Waring (1997) is widely applied around the world. One reason for the model's success is that it is based on established biophysical relationships and constants, which make its application suitable for a range of species (Landsberg et al. 2001a, b) (Table 1). The model is deterministic and like most process-based approaches, calculates rates of photosynthesis, transpiration, growth allocation and litter production (Coops & Hember 2009). Another advantage of the 3-PG model is its capacity to predict a number of stand characteristics of interest to foresters, such as stem density, mean tree diameters, basal area, standing volume and current and mean annual increment.

The 3-PG model has been described in many papers, so a complete model description will not be presented here. Readers interested in more details on model development and calibration are referred to Landsberg & Waring (1997) and Landsberg et al. (2001a, b). Waring et al. (2010) reviews advances in remote sensing that may be improve model performance across landscapes with variable soil properties and stand structural composition.

Species selection and probability of occurrence

We selected five coniferous species for analysis: (1) western hemlock, *Tsuga heterophylla* (Raf.) Sarg.; (2) western red-cedar, *Thuja plicata* Donn ex D. Don; (3) lodgepole pine, *Pinus contorta* Dougl. ex Loud.; (4) Douglas-fir, *Pseudotsuga menziesii* (Mirb.) Franco; and (5) white spruce, *Picea glauca* (Moench) Voss. This assortment of species covers a wide range of environments, although some of the ranges overlap.

Because the 3-PG model was designed to project growth of a single species, its application requires that each 1 km cell be assigned just one of the five selected species. We assigned species to a given cell based on its probability of occurrence. To do this, we took advantage of the work of Schroeder et al. (2010), who applied non-parametric multiplicative regression to climatic data and species inventories collected from $>$ 38 500 field plots to forecast the probability of a species' occurrence. Schroeder et al. (2010) incorporated a total of 13 climatic and topographic variables in their analysis but found only three variables – annual aridity index, a measure of the length of winter and its harshness and elevation – were required to predict the occurrence of the five species selected in our study. The area under curve (AUC) statistic was used to evaluate the extent to which the species

Table 1. Compilation of 3-PG studies from which species parameters were used in this study.

Species	Common Name	Location	3-PG variant	References
Picea mariana– Pinus banksiana		Canada	TRIPLEX	Zhou et al. (2004)
		Canada	ECO-Leap	Hall et al. (2006)
Pinus contorta		Canada	ECO-Leap	Hall et al. (2006)
		Canada	Standard	Coops et al. (2009, 2010)
Pinus nigra var. *maritima*		UK	Standard	Patenaude et al. (2008)
Pinus patula		South Africa	Standard	Louw & Scholes (2006)
Pinus sylvestris		Finland	3-PG with modifications	Landsberg et al. (2005)
		Scotland	3-PG Nitrogen	Xenakis et al. (2008)
		USA	Standard	Landsberg et al. (2001a, b)
Pseudotsuga menziesii	Douglas-fir	USA	Standard	Coops & Waring (2001a)
				Waring & McDowell (2002)
		Canada	Standard	Coops & Hember (2009)
				Coops et al. (2009, 2010)
		New Zealand	Standard	Waring et al. (2008)
Tsuga heterophylla	Western Hemlock	Canada	Standard	R. Gaulton, N.C. Coops, W. Warttig unpublished data

probability of occurrence estimates could be accurately separated into discrete presence–absence categories. As AUC represents the chance that a randomly selected presence plot will have a predicted probability higher than a randomly selected absence plot, strong models have AUC near 1.0, while poor models have AUC near 0.5. Overall, AUC statistics were strong, with all species having better than average AUC values (average = 0.84) (Schroeder et al. (2010).

Model parameterization

The 3-PG model can be run using sequential monthly meteorological data or by repeating long-term (typically 30-year) monthly averages (Coops et al. 2005). Actual time-series are appropriate for short-term comparisons, particularly where inter-annual climatic variability is high (Law et al. 2000; Almeida et al. 2004). Long-term monthly averages are appropriate here because we must assume a relatively uniform climate to maintain a stable site index and productive capacity. In this study, the species parameters used were derived in previous studies, as highlighted in Table 1.

Extrapolating climatic data

Climate-BC (Vancouver, BC, CA) provided mean monthly maximum and minimum temperature and precipitation data (1971–2000). A 90 m digital elevation model (DEM) was obtained from Shuttle Radar Topography Mission (SRTM) (Farr et al. 2007), resampled to 1-km and provided to colleagues at Climate-BC to enable them to refine meteorological estimates in mountainous terrain (Hamann & Wang 2005) by accounting for slope, aspect, and topographically induced rain shadows using a modified PRISM (parameter-elevation regressions on independent slopes model) (Daly et al. 1994).

Mean monthly atmospheric vapour pressure deficits (D) for daylight periods were estimated from mean monthly temperature differences (Kimball et al. 1997). We assumed that D was equivalent to two-thirds of the maximum value calculated from the difference between saturated vapour pressures at mean maximum and minimum monthly temperatures (Waring 2000; Coops & Waring 2001a).

The number of days per month with subfreezing temperatures was estimated from empirical equations with mean monthly minimum temperature (Coops et al. 1998). Monthly global solar radiation was derived by resampling 32-km resolution predictions from the North American Regional Reanalysis (NARR), available from 1979 to the present (http://www.emc.ncep.noaa.gov/mmb/rreanl/). The maps were downscaled to 1 km resolution using a topographic solar radiation model based on a regionally defined clearness index derived from satellite imagery (Schroeder et al. 2009).

Although 3-PG normally requires information of soil water-holding capacity and soil fertility, accurate information on these properties is generally unavailable for mountainous areas. Regional scale mapping of soil attributes is available in both the USA (STATSGO, US Department of Agriculture, Fort Worth, TX, US) and in British Columbia, however, the development of a consistent, and seamless soil attribute coverage across these two jurisdictions using the same attributes was not possible because of different soil classifications systems and spatial resolutions. As a result, we limited our analysis to climatic effects on site index, and set the available water-holding capacity at 200 mm for a sandy loam soil, which has been demonstrated to relate to pre-dawn water potential measurements (a surrogate measurement for soil water availability) at drought-prone sites (Waring & Cleary 1967; Running 1994; Coops & Waring 2001b). The relative low value for soil water storage ensures that if drought occurs, it will be recognized (Nightingale et al. 2007). We selected a soil fertility default value of 0.7 (on a scale between 0 and 1) based on other studies (Coops & Waring 2001a, b; Waring et al. 2010) to accommodate the growth demands of tree species with distributions in the more maritime regions, and assigned a photosynthetic capacity (quantum efficiency) of 0.04 mol C mol^{-1} photo (2.2 g C/MJ absorbed photosynthetically active radiation, PAR), which is about mid-way between the published extremes for conifers.

Field estimates of site index

Comprehensive field estimates of site index, which requires a consistent sampling protocol, are not available for all portions of the study area. We therefore limited our comparison of 3-PG estimates of site index to British Columbia. The British Columbia Ministry of Forests and Range utilizes the Biogeoclimatic Ecosystem Classification (BEC) system (Krajina 1959, 1969) to classify site characteristics based on the composition of vegetation. From maps delineating plant associations and variants, they developed the Site Index Biogeoclimatic Ecosystem Classification (SIBEC) system to estimate a mean site index value for the dominant species in each recognized plant association variant. The first site index estimates were published in tabular form in 1997 by the BC Ministry of Forests and Range. We acquired the most recent SIBEC dataset (2008 approximation) from the website (http://www.for.gov.bc.ca/hre/sibec/) for the site indices of the five selected species, averaged across all variants in which each occurred, to produce a table of mean site index and standard errors for all relevant subzones (Mah & Nigh 2003).

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The site index layers were attributed to an existing polygon coverage of SIBEC subzones available from the British Columbia Bureau of Land Management (BLM) and the layer gridded to match the 1 km cells in which estimates from 3-PG were delineated for the most dominant of the five species. The degree to which the 3-PG and SIBEC predictions of site index agreed was assessed using three regression statistics: the coefficient of determination (R^2), significance level and standard error. All statistical analyses were performed using standard statistical software (Statsoft Inc., Tulsa, OK, USA).

Results

A map of the coniferous species most likely to dominate is shown in Fig. 1 and indicates that of the five coniferous species, Douglas-fir and lodgepole pine are the most widely distributed. In contrast, there are only small, isolated regions along the coast in which western red-cedar is likely to dominate. White spruce is most prevalent in stands in the northeast of BC, while western hemlock dominates in the coastal and western Cascade Mountains from Alaska to northern Washington.

Comparing the 3-PG site index predictions with those estimates from the BEC zones (SIBEC), within British Columbia, indicates that there is reasonable agreement across the Province. The 3-PG model predictions were averaged within each BEC subzone, and compared with the average tabulated site index for all variants within that subzone in the SIBEC database. The values predicted with the 3-PG model accounted for around 50% of the variation

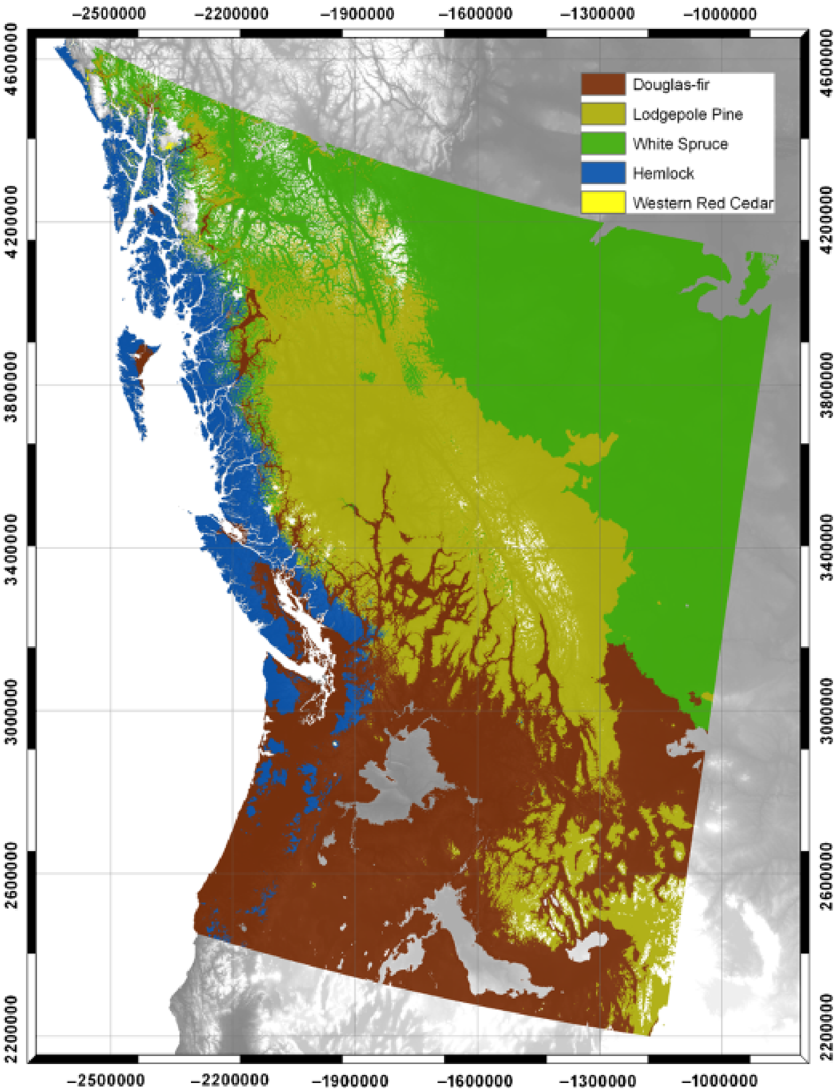

Fig. 1. Map of the species most likely to dominate in each 1 km cell, across the Pacific Northwest derived from models of Schroeder et al. (2010). Grey areas are beyond the extent of the study areas, or where no tree species is predicted (such as alpine areas and desert).

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Table 2. Relationship between 3-PG predicted site index and SIBEC site index for BEC variants in the Pacific Northwest for the five key species and for the overall combined model. †Not significantly different than 0. ††Not significantly different than 1.

	Intercept	Slope	R^2	Standard Error (m)	*P*	*N*
Overall	− 0.32†	0.99††	0.50	2.8	< *0.0001*	163

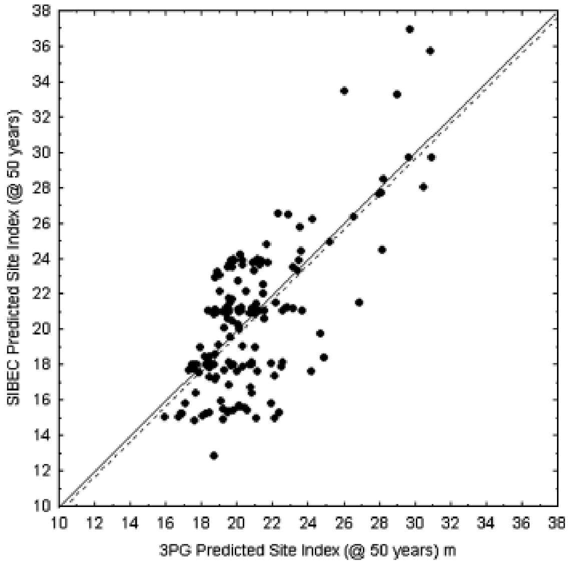

Fig. 2. Relationship between 3-PG (Physiological Processes to Predict Growth) predicted site index, averaged within Biogeoclimatic Ecosystem Classification (BEC) subzones and SIBEC (Site Index Biogeoclimatic Ecosystem Classification) site index estimates for each corresponding subzone (averaged across variants). Statistical comparison information is available in Table 2.

in the SIBEC estimates ($P < 0.00001$) with a standard error of 2.8 m, which equates to ± 10% variation around the mean (statistical information provided in Table 2). Importantly, the two estimates were not significantly different from a 1:1 relationship, with the intercept passing through 0 (Fig. 2).

To obtain estimates of site index across the entire region, the species with the largest probability of occurrence was designated for each 1 km cell. The site index value of that species, in that cell, was then substituted, to construct the map presented in Fig. 3. Histogram distributions of the 3-PG and SIBEC estimates over British Columbia are shown in Fig. 4.

Discussion

The comparison between the SIBEC estimates of site index and 3-PG-based predictions demonstrates a general correspondence between the two estimates of site index. The standard error (± 2.8 m at 50 yr) was less than that reported by Swenson et al. (2005) using 3-PG to predict site index of Douglas-fir across Oregon. The standard error was also less than that reported by Green et al. (1989) based on single species assigned to specific vegetation associations (± 3.0 m at 50 yr) and by Nigh (2006), who used a regression modelling approach that included soil moisture, soil fertility and growing degree days as variables (± 4.67 m at 50 yr). Curt et al. (2001) developed a multiple regression model that also included soil fertility, drainage, as well as topographic exposure and elevation. This model accounted for 40% of the variance with a standard error at age 25 yr of ± 1.82 m. One possible explanation of the improved accuracy of the model to predict site index when compared with Swenson et al. (2005) is the increased environment range observed in this study encompassing five key species from the highly productive coastal forests to the drier and poorer quality forests in the interior and to the north. Similar to previous studies 3-PG appears to slightly under-predict site index at the higher than average productivity classes, although less so than that reported by Swenson et al. (2005).

We recognize that some errors in 3-PG predictions of site index are associated with environmental variation within 1-km grid cells in mountainous areas where drainage and topography affect water and radiation balances, and soils differ in response to the type and weathering rates of different parent materials (Coops & Waring 2001b). However, previous research indicates that the impact of using constant soil water-holding capacity and fertility inputs is only significant in areas of very low rainfall and poor soil conditions. Nightingale et al. (2008) undertook a sensitivity analysis using 3-PG to assess the impact of spatial variation in available soil water and nitrogen content, for forested areas across the USA. Results indicate that across the majority of forests the prediction of growth was relatively insensitive to dramatic alterations in soil water storage from a constant of 200 mm. Areas where the model was sensitive to changes in soil water were principally in areas where average annual rainfall was very low (< 100 mm yr^{-1}). With respect to soil fertility the use of a constant value tended to overestimate growth to a greater extent in less productive ecoregions than in regions with higher average forest productivity.

Overall, the developed model explains approximately 50% of the variance observed in the SIBEC site index estimates. Part of this unexplained variance may be attributed to the SIBEC values themselves, which are estimates of site index based on a relatively small number of forest inventory plots (minimum of 27). In some cases error estimates are provided around these estimates, but not in all cases making it difficult to assess their overall accuracy. Mah & Nigh (2003) found that the SIBEC

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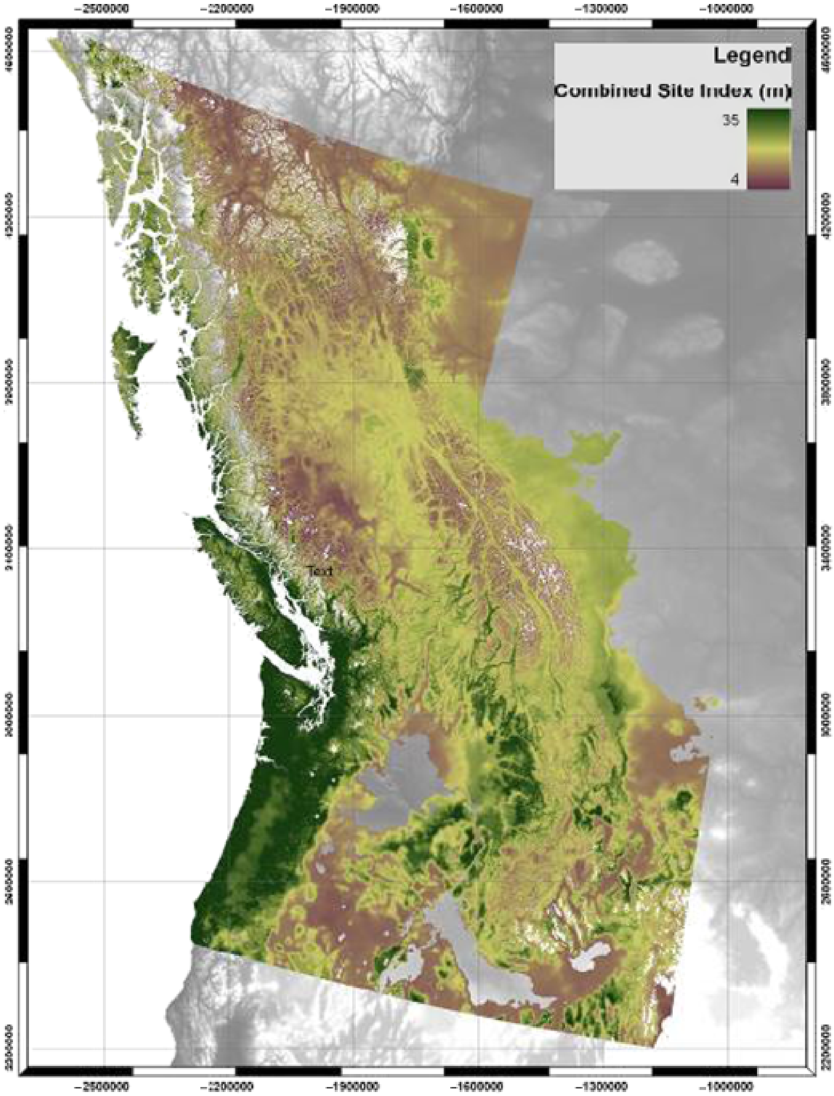

Fig. 3. Map of 3-PG (Physiological Processes to Predict Growth) predicted site index across the Pacific Northwest, using predicted values for the most probable species in each 1 km grid cell.

estimates overestimated site index when compared with inventory estimates in old-growth stands by between 9% and 15%, which was similar to previously reported comparisons (Meidinger et al. 2001). The SIBEC estimates, however, are the only consistent, multispecies site index estimates available for the dominant forest species in British Columbia and are actively used by forestry professionals to estimate potential yields. As a result, they still provide a critical comparison for the 3-PG approach. Combined with the site index analysis conducted by Swenson et al. (2005) in Oregon we believe these papers demonstrate that physiological estimates of site index can provide useful and additional information in addition to that derived from plot and inventory methods.

To address the extent that forest growth and composition might change in the future requires estimates of both the present and future capacity of land. Because of the difficulty in sampling such a large area, we currently lack a rigorous and consistent current baseline of site index for the region. By the cross-comparison presented in Fig. 2, we establish the potential of process-based models to help bridge the gap between site indices as they currently are and how they might be altered in the future.

Some interannual variation in climatic conditions will always exist and throughout the region occurrence of infrequent, but severe, drought has affected stand growth for some years as well as creating conditions favourable for insect outbreaks (Villalba & Veblen 1998; Rouault

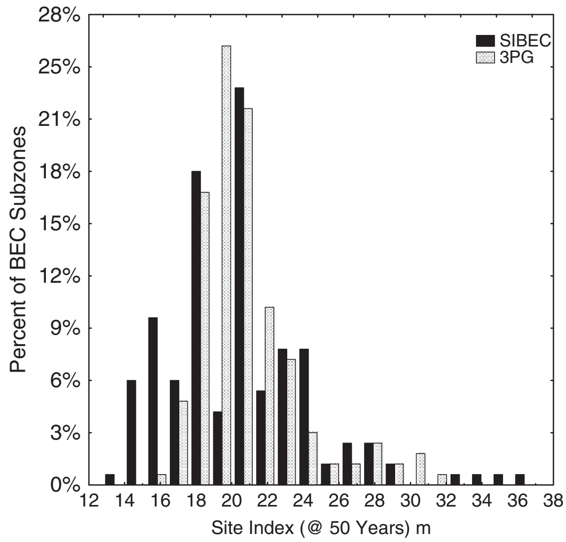

Fig. 4. Histogram distributions of the 3-PG (Physiological Processes to Predict Growth) and SIBEC (Site Index Biogeoclimatic Ecosystem Classification) estimates over British Columbia.

et al. 2006). It is our belief that a more dynamic assessment of forest growth, such as presented here, can be provided by process-based models (even with some error and simplifications such as constant influences of soil water holding capacity and soil fertility) and will prove a valuable asset to those charged with perpetuating forests and a sustaining a wood supply.

From a management perspective, certified land managers in both Canada and the USA are encouraged to apply research and monitoring tools for assurance of sustainability. These new tools may reduce the need for extensive and repeated stand surveys. The analyses by Schroeder et al. (2010) and similar efforts by Coops et al. (2009, 2010) to predict forest composition as a function of climatic variables should assist in making maps of species distributions more accurate, particularly in isolated biogeoclimatic zones.

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