Predicting site index with a physiologically based growth model across Oregon, USA

Jennifer J. Swenson, Richard H. Waring, Weihong Fan, and Nicholas Coops

Abstract: With expanded interests in sustaining productivity under changing climate, management, and disturbance regimes, we sought a means of mapping the potential productivity of forests across the state of Oregon in the Pacific Northwest, USA. We chose the mapping tool 3-PG, a simplified physiologically based process model that can be driven with monthly averaged climatic data (DAYMET) and estimates of soil fertility based on soil nitrogen content. Maximum periodic mean increment (MAI, m³·ha⁻¹·year⁻¹), a measure of the forest’s productive potential, was generated by the 3-PG spatial model and mapped at 1-km² resolution for the most widely distributed tree species, Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco). Maximum MAI is linearly correlated with yield table site indices and therefore comparable with field-derived estimates of site indices obtained from measurement of tree heights and ages at 5263 federal forest survey points. The model predicted 100-year site index (SI) reasonably well (R² = 0.55; RMSE = 9.1), considering the difference in spatial resolution between the modeled (1 km²) and field-measured SI (<0.1 ha) and that field plots were offset for confidentiality by 1–3 km. We created a map of the differences between modeled and field-measured SI and found that the 3000 points within ±6 m error were relatively evenly distributed across Oregon. Improving the accuracy in modeling and mapping forest productivity using 3-PG will likely require refinements in soil surveys, the quality of climatic data, the location of field plots, and the model functions and species parameters.

Introduction

In 1999, Oregon became the first state in the United States to adopt international standards of sustainability as baseline criteria for evaluating its 11.3 million ha of forest lands (Oregon Forest Resources Institute 2004). At that time, however, no map was available to serve as a benchmark for reference. To address this deficiency, over 5000 survey points of
site index (SI), calculated with tree heights and ages, were mapped across the state of Oregon using US Forest Service survey data (J. Ohmann, USDA Forest Service, personal communication, 2001; Fig. 2b in Waring et al. 2002).

With an increasing human population, we might expect more regional pollution, which could lower the productive capacity of Oregon’s forests, even under stable climatic conditions. Climate, however, has varied substantially over the last century and is predicted to continue to do so, having implications on both productivity and species composition (e.g., Coops et al. 2005). At the same time, management practices are changing, resulting in more extensive application of commercial fertilizers and herbicides. The latter practice reduces shrub competition while initially enhancing height growth of coniferous trees, but it also limits the contributions of nitrogen (N)-fixing species.

Estimates of potential growth across regions are unaffected by short-term natural and human disturbance and enhancements (e.g., fertilization) and are necessary for broad-scale, long-term evaluation and management of timber resources, reforestation, and land use planning. Alternatively, estimates of actual productivity reflect existing stand conditions, which are dependent on stocking levels, age, species composition, and recent natural disturbances as well as those introduced through management. Estimates of actual productivity across large areas over frequent intervals are probably best attained through remote sensing (see review by Turner et al. 2004). Both actual and potential growth estimates are valuable for ecosystem management. Potential growth predictions provide a benchmark for the analysis of climate change and carbon (C) budget modeling.

Although the current productive capacity across a forested region would likely be more stable than a measure of actual productivity, it too would require extensive field surveys and extrapolation of empirical data that might not be warranted. Regional maps of SI, therefore, are fairly rare but have been developed for some areas using a variety of techniques. Isaac (1949) produced the only known map of SI for coastal areas of Washington and Oregon, based on field reconnaissance and elevation information. Many of the recent spatial predictions of SI found in the literature have been created by relating multiple environmental variables in a geographic information system through techniques of regression tree analysis, multiple regression, or geostatistics (Höck et al. 1993; Iverson et al. 1997; Payn et al. 1999; Chen et al. 2002; McKenney and Pedlar 2003; Gustafson et al. 2003).

These above-cited approaches typically use field data to develop an empirical model and reserve a portion of the data for model validation. These models tend to predict well across moderately sized areas (e.g., for a single county; Iverson et al. 1997), whereas predictions for large areas still appear to be problematic but useful for regional planning (e.g., an area of 556 000 km² in McKenney and Pedlar 2003). However, Louw and Scholes (2002) anticipated that in the future these multiple variable methods will likely be replaced by physiologically based simulation models such as 3-PG (Physiological Principles in Predicting Growth) (Landsberg and Waring 1997) or PROMOD (Battaglia et al. 1999) to predict growth and site quality spatially (e.g., Milner et al. 1996). These process-based models, adaptable to a wide range of species, are driven by climatic data and constrained by soil properties that affect the storage of water and availability of nutrients (see review by Makela et al. 2000). Previous work in southwestern Oregon suggests that process-based models, provided with adequate data, can predict forest growth potential across a wide range of environments with acceptable accuracy ($N = 18, R^2 = 0.75$; Coops and Waring 2001a). An additional advantage of using a reliable process model is that all available field data can be applied for model validation once the model is parameterized. With the recent availability of state-wide soil maps and averaged climatic data resolved at a spatial resolution of 1 km², we aimed to create a benchmark estimate of the spatial variability of potential forest productivity across the state of Oregon. To provide confidence in our estimates we converted model predictions of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) maximum periodic annual increment to equivalent site indices to compare with SI measurements on 5263 federal forest inventory plots distributed across public and private lands in Oregon.

**Materials and methods**

**Study area**

Almost half of Oregon’s 250 000 km² is covered by coniferous forests that vary in productivity from 3 to 35 Mg·ha⁻¹·year⁻¹, a range equal to that found throughout the entire nation (Jarvis and Leverenz 1983). The moist, temperate forests in western Oregon generally experience mild, wet winters and moderate summer drought, whereas eastern Oregon’s forests are subjected to much colder winters with a more pronounced summer drought. In Oregon, annual precipitation ranges from 45 to over 450 cm and annual mean temperatures range from −2 to 12 °C across forested areas.

**The simulation model**

Landsberg and Waring (1997) developed the forest growth model, 3-PG, based on a number of established biophysical relationships and constants. As with other process models, 3-PG contains subroutines to calculate photosynthesis, transpiration, respiration, and growth allocation. 3-PG differs from other process models in that it predicts stand properties measured by foresters (tree density, basal area, mean diameter, standing volume) as well as those of interest to ecologists (C and water balances). Relatively few variables are needed to run the model and parameter values for well-studied species, and site characteristics may be obtained from the literature or field measurement. Modeled estimates of forest growth begin from bare ground using specified stocking and site parameters. The monthly time step of the model requires averaged daily shortwave incoming radiation, daily mean vapor pressure deficits, temperature extremes, and monthly precipitation. At yearly time steps, estimates of soil fertility (fertility and texture) and soil water storage capacity must be attained in the circumstances where commercial fertilizer is applied or when young trees extend their roots to deeper soil horizons, increasing access to water.

Absorbed photosynthetically active radiation ($φ_{pa}$) is estimated from global solar radiation and leaf area index ($L$); the utilized portion, $φ_{part}$, is calculated by reducing $φ_{pa}$ by an amount determined by a series of modifiers that take values between zero (system “shutdown”) and one (no constraint).
to limit photosynthesis (Landsberg and Waring 1997; Landsberg et al. 2003). Fractional reductions in $\phi_{pa}$ are imposed depending on the degree to which stomatal conductance is limited by high averaged daytime vapor pressure deficit ($D$), subfreezing conditions, and drought, which to-gether affect the soil water balance. Drought limitations are imposed as a function of soil texture when total monthly precipitation and soil water supply are significantly less than transpiration, estimated with the Penman–Monteith equation.

Gross primary production ($P_G$) is calculated by multiplying $\phi_{pa}$ by a canopy quantum efficiency coefficient ($\alpha_c$) set by the soil fertility ranking that is reduced when mean monthly temperatures are suboptimal for a given species. In this paper, a linear increase in $\alpha_c$ with soil fertility rank (FR) was assumed. Such an assumption does not hold for all tree species (e.g., loblolly pine), but has been recorded in multiple cases across a limited range (Waring et al. 1995; Waring 2000; Almeida et al. 2004). A major simplification in the 3-PG model is that it does not require detailed calculation of respiration but rather assumes that autotrophic respiration and total net primary production ($P_N$) in temperate forests are approximately constant fractions (0.53 and 0.47, respectively, SE $= \pm 0.04$) of $P_G$ (Waring et al. 1998; Gifford 2003). The model partitions $P_N$ into root and aboveground biomass. The fraction of total $P_N$ allocated below ground increases from 0.2 to 0.6 as the ratio of $\phi_{pa}/\phi_{pa}$ decreases from 1.0 to 0.2. The remaining $P_N$ is partitioned into aboveground biomass, and, based on species-specific allometric relations, subdivided into two categories: stems and foliage. In this study, we chose to parameterize 3-PG for Douglas-fir, the most widely distributed species in the Pacific Northwest. Current annual increment expressed as stem wood volume ($m^3$ha$^{-1}$year$^{-1}$), is calculated each year from the forest age of zero (seedlings), by converting the fraction of stem biomass that is wood of a known (or assumed) density (400 kg$\cdot$m$^{-3}$). Parameter values used in this study are shown in Table 1.

We used knowledge of stand characteristics and dynamics to select initial stocking levels to insure that maximum L and periodic (decadal) increments would be attained between 20 and 30 years without mortality. Varying initial stocking between 500 and 1500 trees$\cdot$ha$^{-1}$ does not affect the estimate of maximum L or periodic increment, based on simulations at Wind River, Washington (Waring and McDowell 2002). We limited model output of L to $<13$, the highest value recorded for conifers from reliable measurements (Runyon et al. 1994).

Climate and soil data sources for the 3-PG model

Climate data for Oregon were obtained from the DAYMET climate database for the United States (Thornton et al. 1997; Thornton and Running 1999; http://www.daymet.org) at a spatial resolution of 1 km (Table 2). We used 18 years (1980–1997) of averaged mean monthly data for precipitation, temperature, frost occurrence, and shortwave radiation to drive the model, assuming that climate conditions are sufficiently stable to not affect average yield and SI estimates. $D$ was calculated by assuming that the saturated vapor pressure (SVP) of the atmosphere is equivalent to the minimum averaged monthly SVP and that the maximum $D$ represents the difference in SVP between mean monthly temperature extremes. Estimating $D$ for daylight hours during photosynthesis is of primary interest for growth estimates. Therefore, after calculating maximum mean monthly $D$ from DAYMET temperature data, we assumed daytime $D$ was 67% of the maximum $D$ based on past meteorological measurements in Oregon (Law et al. 2000). Mean monthly SVP (kPa) for any given temperature ($T$, °C) was calculated using the following formula:

$$SVP = 0.61078e^{(237.3 - 17.269/273.16)T}$$

Soil FR values required by the model were difficult to attain. As a first approximation we chose N as an index of soil fertility because it is the most limiting factor for tree growth in the Pacific Northwest (Blake et al. 1990; White 2000). Klinka and Carter (1990) reported that variation in SI of Douglas-fir across three climatic zones in British Columbia was highly correlated with mineralizable N, the form most available for root uptake. Research by D.A. Maguire (unpublished data) in the Coast Range of Oregon and Washington indicates that mineralizable N increases as a logarithmic function of total N content in the surface 30 cm of soil ($R^2 = 0.80$, $N = 25$). This linkage between mineralizable N and total N provides a basis for referencing soil surveys because the ratio of C:N in soils is relatively stable in association with major vegetation types ($R^2 > 0.8$; Zinke et al. 1984; Zinke and Strangenberger 2000).

To represent soil fertility, a map of soil N for Oregon (Fig. 1) was derived by combining land use information, soils maps, and C:N values measured in the field (unpublished maps for the contiguous United States are available upon request from Dr. WeiHong Fan). Recognizing that major land-use categories differed in their C:N ratios, forests were first separated from agricultural and range lands using published maps (Anderson 1967; US Geological Survey 1996; Vogelmann et al. 2001). Once major land-use categories were delineated, soil C contents, mapped from STATSGO soil classification surveys (USDA 1991), were converted to estimate N content (g N$\cdot$m$^{-3}$) based on reported field estimates of soil bulk densities. For the forested areas of Oregon, N values ranged from 50 to 1580 g N$\cdot$m$^{-3}$. Maximum levels of N in Oregon forest soils have been found to be as high as 2000 g N$\cdot$m$^{-3}$ at depths ranging from 0 to 100 cm (Grier 1976; Remilllard 1999). Clearly, soil N content may vary over time depending on fire, erosion, commercial application of fertilizers, and the presence of N-fixing species. A logarithmic function was fit to provide a range in soil FR:

$$FR = 0.1 \ln(N \text{ content}) - 0.2$$

This equation predicts a minimum soil FR of 0.19 at 50 g N$\cdot$m$^{-3}$ and a maximum of 0.53 at 1580 g N$\cdot$m$^{-3}$ (of a total range of 0–1). We justified this limited range in soil FR based on the reasonable (projected) $L$ values generated by the model between 1 and 12 m$^2$·m$^{-2}$, which compared well with field measurements reported across a transect in western Oregon (Runyon et al. 1994). In the Coast Range and the Siskiyou Range, $L$ varies from 4 to 12 where moisture was not likely to be limiting, and soil fertility is the major constraint on growth other than climate (Coops and Waring 2001a). In parallel with the assumption of a fairly narrow range in soil fertility, the maximum quantum efficiency was restricted so that values fell between 0.03 and 0.047 mol C$(\text{mol photon})^{-1}$ ($1.66-2.58$ g C$\cdot$(MJ $\phi_{pa}$)$^{-1}$; Table 1). This
Main parameter values for modeling Douglas-fir growth.

Table 1.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Functions and parameter values</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light conversion efficiency of photosynthesis</td>
<td>Maximum $\alpha$ = 0.687(FR) + 0.152</td>
<td>Present study</td>
</tr>
<tr>
<td>Constraints of light conversion efficiency associated with temperature</td>
<td>Optimum temperature for photosynthesis was set at 20 °C, $T_{\text{min}} = 0 \degree$ C, and $T_{\text{max}} = 40 \degree$ C</td>
<td>Lewis et al. 1999</td>
</tr>
<tr>
<td>Fraction of radiation absorbed by canopy</td>
<td>$1 - (2.718 \exp(-0.59))$</td>
<td>Landsberg and Waring 1997</td>
</tr>
<tr>
<td>Soil fertility rank (FR) (0–1)</td>
<td>0.19–0.53; calculated based on soil N content, where FR = 0.1ln(N content) – 0.2</td>
<td>Present study</td>
</tr>
<tr>
<td>Available soil water storage</td>
<td>200 mm</td>
<td>Present study</td>
</tr>
<tr>
<td>Boundary layer conductance</td>
<td>0.2 m·s$^{-1}$</td>
<td>Landsberg and Waring 1997</td>
</tr>
<tr>
<td>Maximum leaf stomatal conductance</td>
<td>0.005 m·s$^{-1}$</td>
<td>Landsberg and Waring 1997</td>
</tr>
<tr>
<td>Maximum canopy stomatal conductance</td>
<td>0.02 m·s$^{-1}$</td>
<td>Landsberg and Waring 1997</td>
</tr>
<tr>
<td>Stomatal response to vapor pressure deficit</td>
<td>$g_c = g_{c,\text{max}} \exp(-0.05D)$</td>
<td>Landsberg and Waring 1997</td>
</tr>
<tr>
<td>Specific leaf area</td>
<td>6.0 m$^2$·kg$^{-1}$</td>
<td>Matson et al. 1994</td>
</tr>
<tr>
<td>Allometric eq. for stem mass (kg)</td>
<td>Stem mass = 0.0843(diameter, cm)$^{2.436}$</td>
<td>McArdle 1961, site III</td>
</tr>
<tr>
<td>Allometric eq. for foliage mass (kg)</td>
<td>Foliage mass = 0.1484(diameter, cm)$^{2.167}$</td>
<td>Waring and McDowell 2002</td>
</tr>
<tr>
<td>Foliage turnover</td>
<td>0.02 month$^{-1}$</td>
<td>Gohlz 1982</td>
</tr>
<tr>
<td>Maximum stem biomass</td>
<td>300 Mg·ha$^{-1}$</td>
<td>Present study</td>
</tr>
<tr>
<td>Wood density in stands &lt;25 years old</td>
<td>400 kg·m$^{-3}$</td>
<td>Gohlz 1982</td>
</tr>
<tr>
<td>Fraction of production allocated to roots, monthly</td>
<td>$0.8/(1 + \phi_{\text{pau}}/\phi_{\text{pau}})^{2.5}$</td>
<td>Most restrictive environmental constraint; includes soil fertility</td>
</tr>
</tbody>
</table>

range in $\alpha_c$ is supported from published work on conifers in the Pacific Northwest (Bond et al. 1999; Law et al. 2000; Coops et al. 2001).

In previous analyses with 3-PG, Coops and Waring (2001a, 2001b) also mapped soil water holding capacity as a function of soil texture and physiographic setting. In agreement with Running (1994), they found that where drought restricts growth, a default value of available soil water storage between 200 and 225 mm was reasonable for most sites. A value of 200 mm of soil water storage capacity was assumed in this study for all forested sites in Oregon. We used one general class of soil texture, “sandy loam”, for our study.

SI data from federal surveys

SI, the maximum height attained by trees at a given age, is the most widely used measure of forest potential growth in the United States. The average heights and ages of dominant or codominant site trees were used to calculate SI on 5263 regional inventory plots compiled from multiple federal sources (USDA Forest Service Forest Inventory and Analysis (FIA); Bureau of Land Management Current Vegetation Survey (J. Ohmann, personal communication, 2001); Max et al. 1996; USDA Forest Service 2002). Also used by Waring et al. (2002), this data set samples the two most widely distributed conifer species in the study area, Douglas-fir and ponderosa pine ($P. ponderosa$ Doug.).

Height growth as a function of age was expressed as a logarithmic function using a C program (Nicholas Coops, personal communication, 2001) to estimate tree height at 100 years represented in families of Douglas-fir curves published in McArdle’s (1961) forestry yield tables. Although the shape of growth curves may differ considerably when trees are young, reference heights as trees approach 100 years are strikingly similar whether attained in managed or unmanaged stands or at low or high elevations (Curtis et al. 1974). SI obtained from yield tables can be used to project the actual growth of fully stocked stands over the entire period from establishment to harvest (160 years in the case of McArdle 1961). We chose to use SI for comparison rather than another measure of productivity because many of the FIA plots were not fully stocked and contain a mixture of species of multiple ages experiencing various levels of shading; thus, it is the only reliable and comparable measurement among the FIA survey plots.

These SI values were compared geographically with model predictions. To maintain confidentiality, data provided by the federal government on the location of survey plots were offset by 1–3 km. These imprecise plot locations, together with discrepancy of spatial resolutions (field plot vs. 1-km$^2$ modeled estimates) limited our ability to compare model predictions directly with field observations.

Data analysis

Spatial analyses were performed using Arc/Info 8 desktop and workstation packages (Environmental Research Institute, Redlands, California, 2001). Statistical analysis was conducted using S-Plus (version 6.1). We excluded a total of 110 SI measurements <11 m as unreliable and removed one obvious erroneous record from the data set (SI of 54 m in an area with average SI of 17 m). Linear regression was used to
compare model-derived estimates of SI to those recorded on 5263 field plots. Because of the fairly wide disparity in spatial resolution of the field data set (stand level) and the modeled predictions (1 km²), we averaged both sets of information to 5 km x 5 km cells across the study area to evaluate the model predictions. A cell of 25 km² was chosen to obtain an adequate number of field plots per cell. Deviations of modeled estimates compared with field estimates of SI were mapped across Oregon to assess spatial variation and possible bias in terms of climatic zones and soil fertility (N content). Predicted–observed model differences were plotted with respect to soil N content and observed SI to search for any systematic bias.

**Discussion**

The general pattern of site productivity produced by the model appears reasonable, as the better sites are found in the coastal areas and along lower elevations on the western slopes of the Cascade Mountains, where the climate is far less harsh than at higher elevations or east of the Cascade crest. By averaging the modeled and the field data to coarser cells of 5 km x 5 km, the relationship improved, though not substantially. Using the 25-km² cells provides an average measure of productivity and eliminates the effect of incorrectly located plots, but as a trade-off incorporates more environmental variation. Although our model predictions were based on Douglas-fir, the general pattern of forest growth potential presented in Fig. 2 may also reflect the potential growth of other tree species such as *Pinus ponderosa, Picea sitchensis* (Bong.) Carr., and *Pinus contorta* Doug. ex Loud. The basis for this reasoning is that species with narrower distributions are likely to survive and grow equally well or better in areas where Douglas-fir is restricted or absent.

We attribute general errors across the study area to inadequacies of the soil data, to the different resolutions of the predicted (1 km²) and observed data sets (stand level), and to the offset of field plot location by up to 3 km. Some important deviations between model predictions and observations emerge, however, in particular areas (Fig. 5). Overpredictions in southwestern Oregon and underpredictions scattered across the Coast and Cascade Ranges may reflect the combined effects of inaccuracies and bias in soil surveys and variation in topography that likely result in SI varying substantially within the 1-km² unit of analysis. In southwestern Oregon, the map of soil N content may be overestimating fertility by not taking into account such heterogeneous edaphic features such as serpentine outcrops. Model underprediction along the Cascade and Coast Ranges may result from soil surveys in the Cascades not adequately reflecting the steep transitions from fertile sites at lower elevations to more rocky, infertile soils influenced by recent volcanic activities at higher elevations.

The 3-PG model itself is founded upon multiple assumptions and has parameter values that may need to be adjusted, but it has shown excellent agreement with measured forest growth when applied to plantations where suitable climate and soil data are available (Landsberg et al. 2003). It has been successfully calibrated and validated for many different forest ecosystems across various climates (e.g., Law et al. 2000; Tickle et al. 2001; Coops and Waring 2001a, 2001b; Landsberg et al. 2003; Dye et al. 2004). The overall pattern in our study of under- and over-predictions in high and low areas of productivity, respectively (Fig. 4), could be related to the use of an allometric equation between dbh and stem mass that was derived for intermediate (site III) Douglas-fir. Yet research on other continents indicate that using a standard equation will still correctly predict trends in L, stem volume, and basal area following fertilization (Almeida et al. 2004; Dye 2001; Sands and Landsberg 2001). We used 20 °C as the optimal temperature for photosynthesis across the study area, although a value of 15 °C might be more appropriate for higher elevations and to the

**Table 2. Climate data input to 3-PG model.**

<table>
<thead>
<tr>
<th>Climate data from DAYMET* (monthly 18-year averages)</th>
<th>Units</th>
<th>Range (over 12 months)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daily average air temperature</td>
<td>°C</td>
<td>–8 to 20</td>
</tr>
<tr>
<td>Total precipitation</td>
<td>cm</td>
<td>0.5–60</td>
</tr>
<tr>
<td>Number of frost days</td>
<td>days</td>
<td>0–31</td>
</tr>
<tr>
<td>Average daily daytime vapor pressure deficit (calculated using daily average water vapor pressure from DAYMET)</td>
<td>mbar</td>
<td>01.2–21</td>
</tr>
<tr>
<td>Daily total shortwave radiation</td>
<td>MJ·m⁻²·day⁻¹</td>
<td>3.5–26</td>
</tr>
</tbody>
</table>

*DAYMET data (Thornton et al. 1997) are free of charge and may be downloaded or mapped at http://www.daymet.org.

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Fig. 1. Map of soil nitrogen content for forested areas in Oregon (data courtesy of Dr. Weihong Fan, The Richard Stockton College of New Jersey). Hillshade from 500-m digital elevation model (US Geological Survey); forested areas defined by North American Landscape Characterization (Vogelmann et al. 2001).
Fig. 2. Map of 3-PG model predictions of Douglas-fir site index, the height in meters at 100 years.
east side of the Cascade Mountains. Additionally, productivity may be slightly underestimated at high humidity levels; the model is currently being modified to minimize the effect of $D < 10$ mbar.

Future refinements of SI prediction in Oregon with process models could include growth estimates for different species within subregions, though decisions of species range extents, overlap in species ranges, and subregion definition would not be straightforward. Additional improvements in predicting SI might be made by recognizing genetic variation in Douglas-fir across Oregon. Because tree growth slows at 100 years of age (the age of SI used for this study) and growth rates for most dominant tree species in our study area tend to converge, improvements upon our model estimates would not be certain given the other limitations we have described.

As with all models, their parameterization affects outputs. Because the parameters for the 3-PG model have been widely tested in our study area as well as globally, we now turn our discussion to the quality of the climate and soil data available to us in this study. In areas where drought occurs infrequently but constrains growth when it does, it is important to run a process model with annual rather than averaged sets of climate data to avoid overestimating productivity (Almeida et al. 2004). In the Pacific Northwest region, however, areas that experience a summer drought period are highly predictable (Waring and Franklin 1979); thus, 18 years of averaged monthly data seem reasonable to use. On the other hand, predicting precipitation correctly is difficult in mountainous topography. Across the coastal range, annual precipitation varies from 100 to 200 cm over less than 20 km. The precipitation gradient is even steeper on the eastern slope of the Cascades: 150 to less than 50 cm in 20 km. Using model simulations, we varied soil water storage from 100 to 200 cm and did not find that soil drought constrained growth where annual precipitation exceeds 150 cm, as it does in most of the Coastal Mountains and western slopes of the Cascades. On the eastern slope of the Cascade Mountains, model simulations show that variation in soil fertility has little effect on productivity relative to the effect of altering precipitation or soil water storage capacity values. Conversely, where water is not limiting, variation in soil fertility significantly affects tree growth, as demonstrated by sensitivity analyses performed across southwestern Oregon by Coops and Waring (2001b). Although no systematic bias in the model predictions of potential productivity was found with regard to the soil N map, one might consider refining the logarithmic function (listed in Table 1) between soil FR and quantum efficiency to improve model performance. Even where soil surveys are adequate, variation should be expected in soil fertility within similar soils depending on fire and logging history, presence or absence of N-fixing plants, and variation in atmospheric deposition of pollutants. This fine-scale variation likely occurs within our 1-km² unit of analysis that, when compared with a small plot of field-measured SI, increases error between model predictions and field observations.

The application of process-based models to predict growth over large areas is limited not so much by inadequacies in model construction and parameterization (research continues to improve these), but by the paucity of well-instrumented weather stations, privacy issues that limit the precision of field plot location, and soil surveys that do not accurately quantify available soil water storage and soil fertility. In Brazil, Aracruz Cellulose Corporation has addressed these deficiencies and improved predictions of annual growth on extensive short-rotation plantations of eucalyptus, although on a smaller scale than was used in the current study (Almeida et al. 2004).

**Conclusion**

In spite of the recognized data deficiencies mentioned, we believe this study to be significant because it offers the first...
Fig. 5. Map of differences between predicted and measured site index generalized to 5 km x 5 km cells. Lighter colors indicate close agreement, darker colors indicate larger differences.
1-km resolution map of potential growth and SI for this area of 250,000 km². Such maps should be an important component of regional land-use planning and management and also provide a basis for setting limits on C sequestration. This approach can be extrapolated to other areas with different tree species, given the availability of the prescribed environmental data and species parameters.

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