Assessment of site index and forest growth capacity across the Pacific and Inland Northwest U.S.A. with a MODIS satellite-derived vegetation index

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Abstract

It is difficult to map forest growth potential across regions with different environmental conditions from limited field measurements of productivity. Climatically sensitive biophysical models and remotely sensed data on vegetation offer the potential to overcome this problem. We combine both approaches in this paper. We calibrated the midsummer value of NASA's MODIS instrument's enhanced vegetation index (EVI) against site indices (SI) mapped at 10 widely dispersed locations for Douglas-fir or ponderosa pine, ranging in height from 16 to 48 m at 50 years (age at breast height). Median values of EVI derived from a 3 km × 3 km grid centered on commercial forest lands of known productive capacities produced a linear regression with site indices ($R^2 = 0.83$). We matched stand growth properties generated by a physiologically based stand growth model (3-PG) with site-specific yield tables and inferred from model predictions, as well as from the literature, that a close relation exists between maximum leaf area index (max L), maximum periodic annual increment (max PAI), and SI. We tested the ability of median EVI to predict SI values derived from height and tree age measurements made at 5263 federal inventory and analysis (FIA) survey plots in Oregon with comparable success ($R^2 = 0.53$) to that derived from previous application of 3-PG using 1 km resolution of climate and soil data. Based on the general agreement between the two approaches, we used mid-summer EVI valves to generate a 1 km resolution map predicting spatial variation in SI of Douglas-fir over 630,000 km^2 in the Pacific and Inland Northwest, U.S.A.
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1. Introduction

Although many forestry enterprises produce their own maps to delineate variation in productivity on their property, such information is not widely available in a consistent form across regions. Some attempts have been made to extend ground-based measurements through correlation with remotely sensed data (Tomppo et al., 1999; Treuhaft et al., 2004), but these approaches lack an underlying basis for predicting future changes. When one considers that atmospheric chemistry (e.g., ozone, CO_2, NO_x) and climate change may already affect forest growth, the challenge of mapping potential forest productivity increases. Foresters, scientists, and policy makers would therefore benefit if region-wide maps of potential forest productivity were available at decadal intervals to record changes, seek causes, and plan for the future.

One approach to producing such maps would be to select from an array of process-based ecosystem models (see reviews by Landsberg, 2003; Nightingale et al., 2004) to predict changes in potential forest growth under a wide range of environmental conditions, both real and anticipated. Although many models have been calibrated and tested locally on pure stands (Korol et al., 1991; Law et al., 2000; Rodriguez et al., 2002; Landsberg et al., 2003), maps derived to show variation in potential forest yields across regions are of questionable accuracy because they are based on extrapolated soil properties and climatic conditions (Milner et al., 1996; Swenson et al., 2005).

Another option might be to determine whether the linear relationship between site index (SI) and maximum leaf area

Table 1
Site locations, climatic summaries, and site productivity indices

Site no. and species	Lat. (N)	Long. (W)	Elev. (m)	Year precip. (cm)	Year av. temp. (°C)	Year (days < 0 °C)	Year rad. (MJ m^{-2})	SI ht. 50 years, BH (m)
1-DF	47°04′12″	120°55′34″	1474	113	4.0	206	4818	15.9
2-PP	47°37′40″	114°56′46″	1045	71	5.9	195	4850	17.7
3-DF	44°48′44″	115°54′00″	1820	105	3.0	257	5260	18.9
4-PP	47°59′56″	115°00′43″	1051	75	5.4	222	4817	19.5
5-DF	44°47′42″	115°59′49″	1790	102	3.1	258	5444	20.1
6-DF	47°12′36″	121°16′48″	1015	176	6.2	160	4523	21.3
7-DF	47°15′36″	121°39′36″	940	245	5.9	151	4485	30.8
8-DF	44°12′29″	122°44′06″	836	176	9.6	83	4920	37.2
9-DF	44°02′53″	122°41′53″	441	180	8.0	117	4928	38.1
10-DF	44°37′48″	123°45′00″	40	198	13.0	30	3413	47.9

index (max L) reported for pine stands in western Montana (McLeod and Running, 1988) and for a range of conifer species in Washington state (Schroeder et al., 1982) applies more generally. Leaf area index can be estimated by remote sensing (see below), so if the relationship holds, it should be possible to estimate SI by remote sensing. Values of a number of other variables relating to forest productivity can then be calculated from SI. These include maximum mean annual increment (max MAI, m^3 ha^{-1} yr^{-1}), the standard metric that specifies potential productivity of fully stocked stands. Rotations at the age of max MAI necessarily maximize yield over multiple rotations. Maximum periodic annual increment (max PAI), the metric commonly reported at decadal intervals in most yield tables, is also a valid indicator of potential productivity as the correlation between max MAI and max PAI is high and the latter occurs at the attainment of max L (Almeida et al., 2004a,b).

The remote sensing community has made estimates of L from spectral reflectance in the red and near-infrared bands over the last two decades (Tucker et al., 1986; Running et al., 1986). Estimates of max L from these vegetation indices are relatively insensitive to the type of vegetation present so that an area recovering from a disturbance may quickly attain a "greenness" value similar to undisturbed forests (Franklin et al., 1997). Moreover, in natural forests, as early components reduce their canopy density with age, an understory develops that maintains essentially a constant leaf area (or light absorbing capacity) for the site (Waring and McDowell, 2002). Until recently, problems associated with variation in atmospheric conditions, scene saturation, and soil background limited the accuracy of remotely sensed estimates of L (Goward et al., 1993). The enhanced vegetation index (EVI), produced from the moderate resolution imaging spectroradiometer (MODIS) since February 2000, contains a number of strategically placed spectral bands that minimize errors associated with all of the above mentioned problems (Huete et al., 2002).

In this paper we combine modeling and remote sensing to produce maps of forest productivity over a large area, using data from 10 widely dispersed locations in the Pacific and Inland Northwest for calibration. For these calibration sites we obtained the expected linear relationship between max L and max PAI, calculated using a process-based stand growth model (3-PG) constrained to reproduce stand properties generated by the best available empirical growth models

(forest projection and planning system, FPS developed by Arney et al., 2004). Next we established that the satellite-derived EVI values acquired in mid-summer were also linearly related to site index; this relationship was expected since the EVI values depend to a great extent on L. The third step involves testing the ability of mid summer EVI to predict Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) site index values derived from >5000 federal inventory and analysis (FIA) field measurements in Oregon. Finally, we generate a 1 km resolution map that predicts site indices across all forested areas in the Pacific and Inland Northwest using the correlation with EVI.

2. Methods

2.1. Site description and field data sources

Height estimates of dominant and co-dominant Douglas-fir or ponderosa pine (*Pinus ponderosa* Dougl. ex Laud.) at 50 years, referenced at breast height (1.37 m) for 10 sites were provided from company maps for this study as broadly representative of lands around the specified locations (Table 1). Site indices at 50 years[1] (breast height, BH) ranged from 16 to 48 m in environments characterized by annual variation in precipitation from 71 to 245 cm, mean temperature from 3.0 to 13.0 °C, days below freezing from 30 to 258, and short-wave radiation from 3400 to 5400 MJ m^{-2} yr^{-1}. With incomplete information on soil properties affecting water holding capacity and soil fertility we set reasonable limits on these variables, as will be described in the next section.

For each of the 10 calibration locations, yield tables at decadal intervals (0–100 years) were generated for pure, even-aged, fully stocked forests of Douglas-fir or ponderosa pine using the FPS software provided by the Forest Biometrics Research Institute at the University of Montana. The FPS model predicts growth, mortality, and regeneration from SI, individual tree growing space, species tolerance, relative tree size and tree vigor. Tree volumes are calculated from height, DBH and

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[1] Site index values generated by the FPS model are similar to those commonly used for Douglas-fir (King, 1966; Cochran, 1979) and ponderosa pine (Barrett and James, 1978) in different regions.

locally calibrated taper equations. The system was designed to provide site-specific local yield tables that predict growth and mortality for a wide range of commercial timber species across Oregon, Washington, Idaho, Montana, and northern California. Site quality acts as a scalar for growth processes and a linear relation exists between site index (height in meters at age 50 breast height) and max PAI (see footnote 1) (Eq. (1)). Max PAI is a convenient metric because it is generated in both yield tables and by the process-based stand growth model described below.

In addition to site index data available at the 10 sites, we utilized field measurements of tree heights and total age to estimate site index from McArdle's (1961) yield tables on 5263 FIA survey plots in Oregon as described in detail by Swenson et al. (2005). The FIA plots are not as representative of surrounding lands as the calibration sites, nor are they as precisely located, being offset by 1–3 km to satisfy concerns of private land owners:

$$\max \text{PAI} = 0.814\,\text{SI} - 8.886, \qquad r^2 = 0.99,$$
$$\text{RMSE} = 0.2\,\text{m}^3\,\text{ha}^{-1}\,\text{yr}^{-1} \tag{1}$$

2.2. Description of the 3-PG model

Landsberg and Waring (1997) developed a deterministic (i.e., non-statistical) forest growth model, 3-PG (**P**hysiological **P**rinciples for **P**redicting **G**rowth) based on a number of established biophysical relationships and constants. As with other process-based models, 3-PG contains subroutines that calculate photosynthesis, transpiration, respiration, growth allocation and litter production. 3-PG differs from most process-based models in that it predicts stand properties measured by foresters (tree density, basal area, mean diameters, standing volume, and mean annual volume increment) as well as those of interest to ecologists (carbon allocation and water balances). Relatively few variables are needed to run the model and these can be obtained from the literature or from field measurements. Detailed, updated descriptions of the model, its input data requirements, and outputs, can be found in Sands and Landsberg (2002), and Landsberg et al. (2003). A brief summary is provided in the following paragraphs.

The model uses a monthly time-step and requires average daily short-wave incoming radiation, mean vapor pressure deficit (D), average daily maximum and minimum temperatures, and total monthly precipitation data. Estimates of soil water storage capacity (ASW) and soil fertility – specified by a rating (FR) that takes values between 0 (very poor nutrition) and 1 (optimum nutrition) – must be provided and updated annually if these vary, as they do when young trees have not established full root extension or following application of commercial fertilizer.

Absorbed photosynthetically active radiation (APAR or $\Phi_{\text{p.a.}}$) is estimated from global solar radiation, assuming that PAR $\approx$ 50% of solar radiation, and L; the utilized fraction ($\Phi_{\text{p.a.u.}}$) is calculated by reducing $\Phi_{\text{p.a.}}$ by an amount determined by a series of modifiers that take values between 0 (system 'shutdown') and 1 (no constraint) to limit photosynthesis. Constraints imposed on $\Phi_{\text{p.a.}}$ depend on the degree to which stomatal conductance is limited by average day-time D, subfreezing conditions (if daily temperatures are below 0 °C it is assumed that there is no growth, i.e., $\Phi_{\text{p.a.}} = 0$) and available soil water (ASW). The soil water balance in any month depends on the ratio of precipitation and stored water to transpiration, estimated with the Penman–Monteith equation. The amount of water that can be stored in the soil (soil water holding capacity) is a function of soil texture and stand rooting depth.

Gross primary production (PG) is calculated by multiplying $\Phi_{\text{p.a.u.}}$ by a canopy quantum efficiency coefficient (α), with a maximum value (α_c) set by the soil fertility rating (FR). It was assumed in this analysis that α_c increases linearly with FR from a minimum of 0.38 to a maximum of 3.84 g C MJ^{-1} $\Phi_{\text{p.a.}}$.

$$\alpha_c = 3.455\,\text{FR} + 0.384 \tag{2}$$

α_c is reduced when mean monthly temperatures are sub-optimal for a given species.

A major simplification in the 3-PG model is that it does not require detailed calculation of respiration. Autotrophic respiration and total net primary production (P_N) in temperate

Table 2
3-PG parameters sets and predictions that provide a close match with site-specific yield table values of stocking density, basal area, standing volume, and maximum PAI between ages 20 and 70 years[a]

Site no. and dom. species	Initial trees (ha^{-1})	Fert. rank 0–1	Quantum efficiency (g C MJ^{-1} $\phi_{\text{p.a.}}$)	Stem mass[a]	3-PG predicted max L	3-PG predicted max PAI (m^3 ha^{-1} yr^{-1})
1-DF	1112	0.29	1.37	$y = 0.048x^{2.434}$	2.2	4.6
2-PP	1112	0.45	1.92	$y = 0.025x^{2.644}$	1.8	5.8
3-DF	1112	0.55	2.30	$y = 0.019x^{2.761}$	2.6	5.6
4-PP	1112	0.55	2.30	$y = 0.200x^{2.800}$	2.2	6.8
5-DF	1112	0.76	3.02	$y = 0.022x^{3.514}$	3.9	7.2
6-DF	865	0.45	1.92	$y = 0.004x^{3.233}$	4.5	7.8
7-DF	865	0.55	2.30	$y = 0.011x^{2.980}$	7.2	15.4
8-DF	856	0.8	3.18	$y = 0.007x^{3.078}$	9.4	20.8
9-DF	856	0.85	3.35	$y = 0.005x^{3.141}$	9.4	20.8
10-DF	850	1.00	3.84	$y = 0.006x^{3.098}$	12.5	29.2

y in kg; x, DBH in cm.
[a] Derived from site-specific yield tables.

forests are recognized to be relatively constant fractions (0.53 and 0.47, SE ± 0.04) of P_G (Waring et al., 1998; Gifford, 2003). The model partitions P_N into root and aboveground biomass based on species-specific allometric relations.[2] The fraction of total P_N allocated below-ground increases from 0.2 to 0.6 as the ratio of $\Phi_{p.a.u.}/\Phi_{p.a.}$ decreases from 1.0 to 0.2.

In this study we parameterized 3-PG for Douglas-fir and ponderosa pine, the two most widely distributed species in the Pacific Northwest, so that outputs matched local yield table values for stocking, mean diameter at breast height (DBH), basal area, and standing volume between stand ages of 20–70 years (Table 2). More details on using yield tables to predict carbon balances with 3-PG are presented in Law et al. (2000) and Waring and McDowell (2002). These papers include a complete listing of parameters not presented in Table 2.

The range in max L across the region are reasonably well known based on a number of transect studies (e.g., Runyon et al., 1994; Law et al., 2004). To keep max L within reasonable bounds and to simplify the analyses, we set specific leaf area at 4.0 m² kg⁻¹ for all calibration sites. The soil fertility ranking (FR), which controls maximum quantum efficiency (a_c), was adjusted for each calibration site. By linking these two variables, stemwood production is increased through greater photosynthetic efficiency and by reduced allocation of photosynthate below ground (Esprey et al., 2004). The ASW capacity, a variable which is only seasonally important and has no affect on a_c, was set at 300 mm except on the best site (No. 10) where a value of 400 mm was required to match yield table growth rates when FR and a_c were set at maximum values (Almeida et al., 2004a).

Wood density was initially assumed constant for the calibration sites at 0.4 Mg m⁻³ for calculation of stem mass allometric equations derived from the relations between DBH and stem volume extracted from the site-specific local volume tables. However, after matching basal area growth, we found it necessary to assign a density of 0.35 Mg m⁻³ to those sites where Douglas-fir was present, in order to match max PAI. To account for regional differences in growing season temperatures we assigned a temperature optimum of 20 °C to the five more productive sites (Table 1) on the west side of the cascade range and 15 °C to those to the east side of the range.

2.3. Climatic and soil data sources for the 3-PG model

Climatic data, with a spatial resolution of 1 km, were extracted from the DAYMET climatological database for the United States (Thornton et al., 1997).[3] Eighteen years (1980–1997) of daily data were averaged to provide meteorological
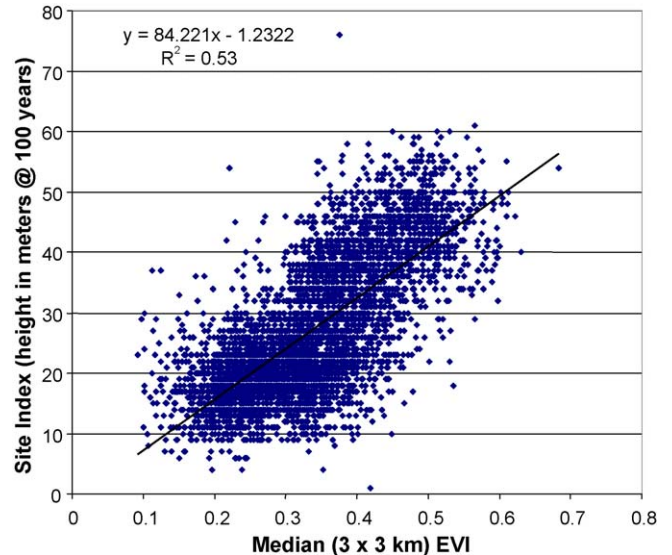

Fig. 1. The median EVI extracted from a 3 km × 3 km set of pixels in the vicinity of 5263 federal analysis and inventory plots (offset for privacy issues by 1–3 km) predicted measured site index for Douglas-fir at 100 years from a coast range yield table (McArdle, 1961) nearly as well ($R^2 = 0.53$ vs. 0.55) as a biophysical model (3-PG) that requires detailed information on climate and soils (Swenson et al., 2005).

data in the format required by the model. We assumed that climatic conditions over this period were stable enough not to affect average yields and site index estimates.

2.4. Acquisition and processing of remotely sensed data

MODIS 1 km × 1 km resolution EVI (MOD13A2) data were acquired for an 8-day period in mid-July 2003 (yearday 209–216) at or near the seasonal peak in L from tiles H08V04, H09V04, H10V04 and H11V03. These acquisitions were processed into a lambert equal area azimuthal projection using the MODIS reprojection tool. ArcInfo/ArcGrid software was utilized to reproject geographic site coordinates (Table 1) to match the projection of the raster image, to extract EVI data from the raster for each site, and to display the reprojected image.

The vegetation around some sites was recently disturbed while elsewhere riparian protected areas were undisturbed and more productive than typical sites. To minimize these variations we smoothed the raster image using a 3 km × 3 km moving window median filter and extracted EVI values from the smoothed image for each site. Similar median analyses of 3 km × 3 km grids were performed around each of the 5263 FIA survey sites in Oregon because the precise locations of plots were not provided (Fig. 1).

3. Results

The process-based model, when constrained with the set of parameters presented in Table 2, produced max PAI values in close agreement ($r^2 = 0.99$) with those generated by the site-specific yield tables (Eq. (3), Table 3). 3-PG predictions of max

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[2] The allocation equations include branches and bark. To get a more accurate estimate of stem mass the included proportion of these components would be subtracted. These proportions are estimated from empirical relationships, which indicate that they compose 15–20% of stem biomass (See Sands, 2003). The site-specific yield tables and 3-PG simulations may be downloaded from the web site: http://www.fsl.orst.edu~waring under the heading "current research".
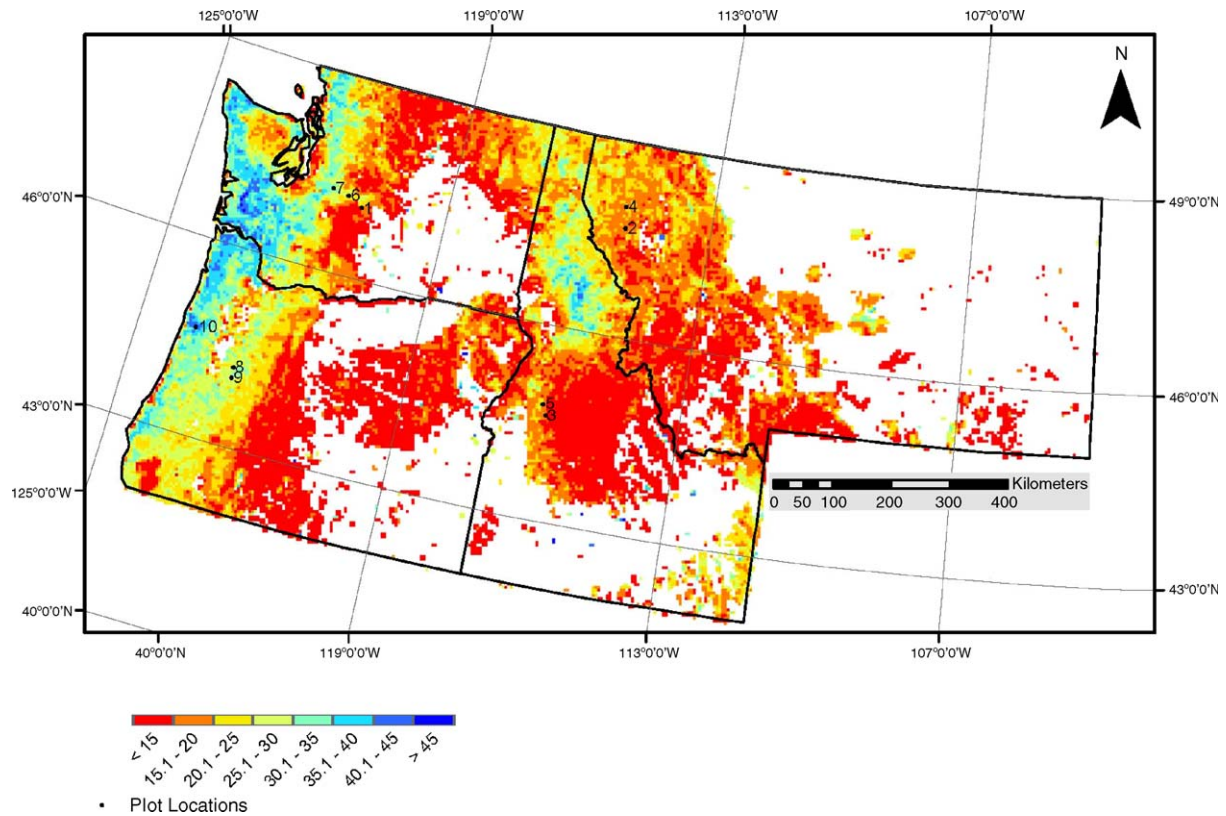
[3] http://www.daymet.org.

Fig. 2. Map depicting spatial variation in Douglas-fir site index (SI) across the Pacific and Inland Northwest was generated from mid-summer (2003) MODIS imagery of EVI by way of a linear correlation established at 10 calibration sites, $r^2 = 0.83$ (Table 3, Eq. (7)). The general pattern for Oregon is similar to that shown from the 5263 FIA survey plots (Waring et al., 2002).

Table 3
Functions derived from 3-PG simulations and mid-summer median EVI (3 km × 3 km grid) that predict yield table maximum periodic increment (YT max PAI) and site index (SI)

Equation no.	Function (x)	Predict (y)	Equation	R^2
3	3-PG max PAI	YT max PAI	$y = 1.04x$	0.99
4	3-PG max L	YT max PAI	$y = 2.302x$	0.98
5	Median EVI	3-PG max L	$y = 32.952x - 7.977$	0.86
6	Median EVI	YT max PAI	$y = 75.960 - 18.357$	0.82
7	Median EVI	SI	$y = 93.893 - 11.862$	0.83

Median EVI also predicts 3-PG simulations of max L ($N = 10$).

L, as expected from the structure of the model, were closely correlated ($r^2 = 0.98$) with max PAI (Eq. (4), Table 3).

The relationship established between median EVI and SI obtained at the 10 calibration sites (Eq. (7)) was used to predict SI values derived from McArdle's (1961) yield tables at 5263 FIA survey plots locations in Oregon (Waring et al., 2002). With agreement comparable to that attained in a previous analysis using 3-PG (Swenson et al., 2005), we felt justified to map estimates of Douglas-fir SI across 630,000 km^2 in the Pacific and Inland Northwest at a spatial resolution of 1 km (Fig. 2).

4. Discussion

The close relationship between mid-summer EVI and the model-generated max L ($r^2 = 0.86$; Eq. (5)) supports the contention that EVI is more sensitive to high values of L than indices based only on red and near-infrared reflectance (Huete et al., 2002). Increases in L are also coupled in the calibration component of this study with increases in a_c. Rahman et al. (2005) reported a linear correlation between EVI and P_G, which suggests that both L and a_c are probably incorporated in the vegetation index, the latter perhaps via sensitivity to changes in leaf chlorophyll concentrations (Waring et al., 1995).

The spatial distribution of SI values produced in Fig. 2 for Oregon are similar to those presented in maps referencing FIA survey plot (Fig. 2b, Waring et al., 2002). SI is consistently underestimated, however, where intensive management reduces vegetative cover associated with frequent thinning, clear cutting, and brush control activities as evidenced around the boundary of the Olympic National Park in northwestern Washington and in portions of the Oregon coast range where soil fertility is high and max L can exceed 10 (Swenson et al., 2005). By comparing EVI patterns over a decade, one should be able to distinguish recently disturbed sites for estimation of SI.

There are a number of difficulty faced in validating spatial estimates of SI using biophysical models across broad regions: (1) FIA survey plots may not be representative of the km^2 area in which they are located (or assumed to be located); (2) extrapolation of climatic conditions may be in error; and (3) soil data may be unrepresentative. Although mid-summer EVI is

not dependent on climate or soil data, we emphasize that EVI may underestimate the productive capacity of a square kilometer if the area has been recently disturbed.

In our calibration, we were fortunate to be able to utilize FPS generated site-specific yield tables, whereas in the Oregon study, McArdle's (1961) yield tables were extrapolated beyond the coast range for which they were developed. In addition, the approached used in constructing the tables compared stands of different ages on similar sites. This introduced artifacts into the prediction of PAI that are absent from modern growth and yield models based on growth functions associated with SI.

The extent to which the max L values generated by 3-PG in this study apply to a wide range of coniferous species is not known. In regions where interannual variation in L is large or the duration of display varies, averaging or integrating EVI for the entire growing season may be more appropriate.

Close inspection of Table 2 indicates that ponderosa pine (on sites 2 and 4) grows at slightly higher rates than do Douglas-fir at equivalent L values (sites 1 and 3). The max L of pure ponderosa pine stands in the Pacific Northwest rarely exceeds 3.0 (Coops et al., 2005), which relegates this type to the lower range in productivity. As a result, whether the less productive forests in the region are composed of ponderosa pine or Douglas-fir does not affect the general relation between Max L and Max PAI.

One might question our decision to use a constant relation between leaf area and leaf mass ($4 \, \text{m}^2 \, \text{kg}^{-1}$), but a linear relation between foliage mass and productivity would still exist. We further assumed that allometric relations between DBH and foliage production developed in Oregon and Washington apply across the entire range of both species. DeLucia et al. (2000) indicate that a reduction in the ratio of foliage to stemwood production should be expected in some pine species as the harshness of the environment increases. The inland variety of Douglas-fir is also known to support less foliage area for a given cross-sectional area of sapwood than the coastal variety (Waring et al., 1982). Nevertheless, max L has been documented to increase with productivity across steep environmental gradients in Oregon and Washington (Schroeder et al., 1982; Waring et al., 1978; Runyon et al., 1994). The fact that both EVI and max L are linearly related to max PAI (Table 3) support this inference although EVI may also respond to variation in canopy quantum efficiency.

Without detailed knowledge of soil fertility and soil water holding capacity at all of the sites, we linked quantum efficiency to a range in soil fertility and set soil water storage at a fairly high value (≥ 300 mm) for the 3-PG simulations. This decision did not greatly affect the fraction of NPP allocated below-ground, which varied from 33% to 50% as SI decreased (data not shown), but it could change the seasonal pattern in photosynthesis (Waring and McDowell, 2002).

This research documents an important relationship between SI and max PAI that applies to all of the generated site-specific yield tables (Eq. (1)). Because of this general relationship, 3-PG simulations could be matched, max L estimated, and a linear relationship with SI established. We encourage the further testing of mid-summer EVI as a surrogate for site index across regions where evergreen conifers dominate. Because EVI estimates are expected to respond to changes in regional climate, maps derived from this vegetation index could confirm the extent to which changes in forest growth potential are in concert with those predicted by biophysical models.

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