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Complete List of Authors:	Hennigar, Chris; University of New Brunswick, Faculty of Forestry and Environmental Management Weiskittel, Aaron; University of Maine Allen, Howard; ProFOR Consulting MacLean, David; University of New Brunswick,
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Development and evaluation of a biomass increment-based index for site productivity

Chris Hennigar (corresponding author; 506-470-3373; chris.hennigar@unb.ca)¹, Aaron Weiskittel (aaron.weiskittel@maine.edu)², H. Lee Allen (allen.profor@gmail.com)³, and David A. MacLean (macleand@unb.ca)¹

¹ University of New Brunswick, Faculty of Forestry and Environmental Management, P.O. Box 4400, Fredericton, NB, E3B 5A3 Canada

² University of Maine, School of Forest Resources, Orono, ME, USA

³ ProFOR Consulting, 225 Winding Ridge Dr., Cary, NC, USA

Abstract

Measures of forest productivity generally rely on site index, which can be problematic for multi-cohort and mixed-species stands. Using stand growth and dominant tree height-age (i.e., site tree) measurements from ~10,900 plot locations from Maine, Nova Scotia, New Brunswick, and Prince Edward Island, a forest productivity model for the Acadian Region was developed as a function of climate, lithology, soils, and topographic metrics. Approximately 65% of variation in observed above-ground dry-biomass growth rate (BG) was explained by a Chapman-Richards function of temperature, bedrock, soil root space, slope, and depth to water in combination with stand structure and species predictors. Productivity was then defined in terms of the predicted asymptote of BG, holding structure and species constant, which was termed biomass growth index (BGI); i.e., the site-influenced component of the BG relationship. BGI was mapped on a 20 m grid throughout the region. BGI explained 0-30% of the variability in spruce (*Picea* sp.) and balsam fir (*Abies balsamea*) site index, and had similar site index predictive performance ($\pm 5\%$) when compared to existing land productivity classifications in each province. BGI provides a direct relationship between site variables and growth and can help guide forest management decisions and future research.

Keywords: Productivity, mixed species, site index, Acadian forest, biomass growth

30 Introduction

31 Determining site productivity is an important yet difficult issue for forest management
 32 and planning (e.g., Carmean 1975; Skovsgaard and Vanclay 2008, 2013). A variety of direct and
 33 indirect as well as phytocentric and geocentric measures of site productivity have been used in
 34 the past. The most common site productivity measure used today is site index, which has
 35 numerous advantages and disadvantages (Weiskittel et al. 2011b). The most important
 36 advantages of site index are a long history of development and use, as well as high
 37 interpretability; while key disadvantages are that it requires direct expensive measurements and
 38 existing equations, tree social status is not always fixed over time (Raulier et al. 2003), and can
 39 be sensitive to stand age (Fig. 3.1 in Weiskittel et al. 2011b; Fig. 3 in Goelz and Burk 1992). In
 40 particular, site index can be difficult to estimate and use in mixed-species and multi-cohort
 41 stands, especially with long histories of partial harvesting regimes.

42 In mixed-species and uneven-aged stand types, a variety of approaches have been used to
 43 determine and quantify site productivity. The most common include: (1) a modified estimate of
 44 site index (e.g., Curtis and Post 1964; Hamel et al. 2004); (2) ecological-based classifications
 45 (e.g., Monserud 1984; Wang 1998); and (3) increment-based indices (e.g., Schmoldt et al. 1985;
 46 Vanclay 1989). Like site index, these various approaches have important advantages and
 47 disadvantages, which may limit their application. For example, a composite site index for mixed
 48 species requires the construction of conversion equations (e.g., Carmean 1979; Nigh 1995),
 49 while ecological-based classifications are categorical, making additional analysis difficult and
 50 are often too coarse for management planning. Increment-based indices have been conducted at
 51 the individual tree-level using either diameter (Vanclay 1989) or height (Stage 1963), as well as
 52 with stand-level variables (e.g., Schmoldt et al. 1985; Berrill and O'Hara 2014). Although the
 53 increment-based approach offers several advantages, it generally requires permanent plots, which

may limit its robustness and applicability when those are not available. In addition, most of these methods are focused on the stand-level productivity and can make it hard to compare across broad geographic regions. Recent work has related observed site indices to climate (Weiskittel et al. 2011a), soils (Jiang et al. 2015), and modeled or observed net primary production (Swenson et al. 2005), which allows site index to be mapped across a region (e.g., Coops et al. 2011). However, mapping of increment-based measures of productivity has received less attention.

The Acadian Region is a transitional forest with a relatively large number of tree species present and complex stand structures due to past management and an abundance of natural regeneration. Consequently, there is a long history of site productivity studies in this region going back more than 50 years (AAFC 1998). However, previous efforts have largely focused on unmanaged spruce-fir (*Picea-Abies*) site index (Griffin and Johnson 1980; Vicary et al. 1984; Ker and Bowling 1991; Williams et al. 1991; Steinman 1992) and ecological land classification (MacDougall et al. 1988; Solomon et al. 1995; Zelazny et al. 2007; Keys et al. 2010). Studies have identified several climate (Briggs and Lemin 1992) and soil properties related to productivity such as drainage class and soil depth (Briggs 1994; Steinman 1992). However, a consistent, high-resolution, and robust measure of site productivity does not exist for the region. In addition, the tremendous increase in availability of high resolution and spatially explicit information including elevation, climate, lithology, soils, hydrology, and vegetative cover data offers an opportunity to examine a greater array of influential factors on productivity in this region.

The overall goal of this analysis was to develop a quantitative, species-independent, and unified site productivity model that could be used in complex forest conditions such as the Acadian Region of Maine, New Brunswick (NB), Nova Scotia (NS), and Prince Edward Island (PEI). The specific objectives of this paper were to: 1) compare alternative approaches for

quantifying site productivity; 2) evaluate the relationship of the site productivity measure to a suite of factors including climate, bedrock, soils, drainage, and topography; 3) map productivity at high spatial precision (20 m) for forest research, planning, and management purposes; and 4) compare the performance of the developed index to existing site classification systems.

Methods

Study area

The Acadian forest region resides in the transition zone between the conifer-dominant boreal forests to the north and the broadleaf forests to the south. Three Canadian Maritime Provinces (NB, NS, and PEI) are found in the region, along with southern portions of Québec, and much of the US state of Maine. Across the region, climate estimates indicate average annual precipitation is 1,130 mm with a range of 870 to 1,750 mm, while mean growing degree days (sum of temperature >5°C) is 1625 with a range of 726 to 2292 days. Glacial till is the principal soil parent material, with soils ranging from well-drained loams and sandy loams on glacial till ridges to somewhat poorly to very poorly drained soils on flat areas between low-profile ridges.

The majority of the Acadian forest is dominated by naturally-regenerated, mixed-species stands that display either even- or uneven-aged stand structures, while some portions of NB contain intensively-managed, single-species plantations. Over 60 tree species are present in the region, and common conifer species include balsam fir [*Abies balsamea* (L.) Mill.], red spruce [*Picea rubens* (Sarg.)], white spruce [*Picea glauca* (Moench) Voss.], eastern white pine [*Pinus strobus* L.], eastern hemlock [*Tsuga canadensis* (L.) Carr.], black spruce [*Picea mariana* (Mill.) B.S.P.], and northern white-cedar [*Thuja occidentalis* L.]. Common hardwoods include red maple [*Acer rubrum* L.], paper birch [*Betula papyrifera* Marsh.], gray birch [*Betula populifolia* Marsh.], yellow birch [*Betula alleghaniensis* Britt.], quaking aspen [*Populus tremuloides* Michx.], bigtooth aspen [*Populus grandidentata* Michx.], American beech [*Fagus grandifolia*

Ehrh.], northern red oak [*Quercus rubra* L.], and sugar maple (*Acer saccharum* Marsh.).

Tree Data

Data were compiled from existing forest inventory plots where individual tree growth over time and/or site trees (with co-dominant and dominant tree height vs. age data) had been measured by government and industrial forestry organizations across Maine, NB, NS, and PEI (Table 1). While not considered part of the Acadian forest, southern Maine plots were included to provide wider climatic calibration and possibly more robust productivity estimates.

Pre-commercially thinned and planted stands were omitted. Site trees were limited to ages 20 to 100 years old. Plot measurements prior to 1990 were omitted to avoid, as much as possible, effects of the 1970-1980s spruce budworm (*Choristoneura fumiferana* Clem.) outbreak on growth estimates. Plots with basal area $>75 \text{ m}^2 \text{ ha}^{-1}$ as well as site trees yielding an estimated index height outside the range of 2 to 35 m (at breast-height age 50) were omitted because these observations are highly unlikely in the Acadian forest and probably result from data entry errors. In total, 8,460 plot locations had at least one balsam fir or spruce site tree, and 6,804 locations had at least one 3-10 year plot growth measurement period (Table 1).

Tree above-ground dry biomass was calculated for trees $\geq 9 \text{ cm}$ DBH using Lambert et al. (2005) tree biomass equations. Plot biomass growth of surviving trees (BG ; $\text{kg ha}^{-1} \text{ yr}^{-1}$) from one measurement period to the next was calculated using:

$$BG_{pm} = \frac{(BM_{pm+1} - BM_{pm})}{GS} \quad (1)$$

where BM is above-ground dry biomass of all trees in a plot p that are alive at the start of a plot measurement period (m) that remained alive at the next ($m+1$) measurement period, and GS is the number of growing seasons between m and $m+1$.

Spruce or fir site index (height at breast-height age 50) for each plot was based on the average spruce or fir index calculated for each site tree as a function of breast-height age and

total tree height (Ker and Bowling 1991). Calculated site index was strongly correlated with age and was consistently over-predicted when age was <50 and under-predicted when age was >50 years, based on comparisons with site tree index for different aged trees of the same species in the same plot. This bias was corrected with simple linear regression models of site index over age for each fir and spruce species using plots with multiple site trees.

Site Factors

Various site factors were compiled and derived including those representing climate, lithology, soils, and topography (Table 2). Monthly climate normals data (1971-2000) at 800 m resolution were obtained from McKenney et al. (2006). Lithology and soils data were obtained from various sources. Rock type classification was limited to eight broad groups (Table 3), partly due to difficulty in interpreting lithological descriptions in each jurisdiction, and also to avoid cases where the rock type was restricted to a limited range of climatic or geographic zones.

Since lithology is generally correlated to soil fertility and other site factors, a bedrock productivity index (BRI) value between 0 (worst) and 1 (best) using a combination of expert opinion (Colpitts et al. 1995) and partial dependence responses observed during preliminary analysis. The granite type (e.g., quartz, rhyolite, granite) was consistently observed, on average, to result in the worst site productivity of all rock types. Non-calcareous fine sedimentary (e.g., siltstone and mudstones) bedrock performed as well as weakly calcareous sedimentary and only slightly worse than strongly calcareous (e.g., limestone) bedrock. Low growth difference observed between non-calcareous and calcareous variants of the fine sedimentary rock type was unexpected, but may have occurred because these rock types were often spatially aggregated, and as a result of repeated glaciation, these rock types are likely to be mixed together in soil parent material. Logically, calcareous origins should lead to the highest bedrock productivity score and it was therefore set to one. Mafic (basalt, gabbro) performed slightly better than coarse

sedimentary (e.g., conglomerate, sandstone), but overall, was less than fine sedimentary bedrock.

Exact bedrock class index value and rank assigned (Table 3) were somewhat subjective; however, these rankings generally resulted in improved site response trends across jurisdictions based on preliminary analysis. For PEI, a digital bedrock layer was not available. PEI has similar geological origins as eastern NB (sandstone); however, presence of siltstone overlying sandstone in PEI is more common (MacDougall et al. 1988), as is deep soils with few coarse fragments, which suggest the parent material of PEI may be of higher quality for tree growth than in eastern NB. Therefore, PEI was assumed to more closely resemble that of fine sedimentary during regional site modeling. Finally, importance of BRI in the site model during preliminary analysis slightly increased if the BRI value was spatially ‘blurred’ by calculating an average weighted BRI value using the proportion of area of each rock type within a 10 km radius of each plot location. One, 5, and 10 km radii were also explored, but the 10 km radius performed best.

Various soil attributes were also examined (pH, various horizon depth summaries, % coarse fragments, texture, soil water holding capacity, mode of deposition), but preliminary analysis indicated that only mineral soil root restriction depth (RRD; e.g., depth to hardpan or bedrock, up to 100 cm) and to a lesser extent % coarse fragments (CF) showed consistent moderate to weak correlation with site productivity measures, overall and within each jurisdiction. As these two soil attributes were highly correlated and both act to limit soil rooting volume (water, nutrients), a unified index of root growing space (RGS) was calculated as:

$$RGS = RRD * (1 - (CF_{top30} + CF_m)/200) \quad (2)$$

where CF_{top30} is CF measured in the top 30 cm of mineral soil, and CF_m is CF measured from the top of mineral soil to the lesser of root restriction depth or 100 cm. When CF was available for each mineral soil horizon (all regions except NB), mean CF was weighted by the proportional depth of each horizon in CF_{top30} and CF_m . Only categorical classes of CF were available for NB,

which were translated into numeric proportions based on class mid-point values.

RGS explained roughly the same degree of site variability compared to using RRD and CF; however, differences observed near jurisdiction borders were visually reduced compared to RRD and CF alone. RGS was mapped at 50m resolution and set to zero for areas with extensive rock outcrops or barren land and to -1 for wetlands, bogs, and other very poorly drained areas identified in available forest photo-interpreted shapefiles (1:12,500 scale) in NB, NS, and PEI. In Maine, the US National Wetland Inventory from the US Fish and Wildlife Service was used to improve resolution of wetlands and bogs in the RGS layer.

A variety a topographic variables were derived based on existing digital elevation models (DEMs) for each jurisdiction; resolution ranged from 6-90 m. Topographical variables included elevation, depth to water (DTW; Murphy et al. 2009), slope (°), solar radiation (Fu and Rich 2002), and System for Automated Geoscientific Analyses (SAGA) terrain indices (Böhner et al. 2006) such as topographic wetness, roughness, positive openness, and slope position class.

Data Analysis

BG and site index response to site factors were explored using the nonparametric ensemble regression tree algorithm, Random Forests (Breiman 2001). Site factors that showed relatively consistent effects on site in each jurisdiction were selected and refined for use in the final site model. In addition, stand structural measures (biomass, basal area, density, quadratic mean diameter) and species basal area proportions were examined as background effects likely to influence observed growth.

BG was favored over site index as a measure of site productivity because preliminary analysis indicated that: 1) tree site index was not correlated to any site factors tested in Maine, 2) BG could be estimated for a larger set of sample locations and with more trees contributing to the growth signal at each location for most jurisdictions (Table 1), and 3) stand metrics like BG

are more robust measures of site productivity than tree-based ones like site index. In addition, due to the inability of Random Forests to 1) extrapolate beyond the underlying data and 2) factor out effects of stand species structure, the final BG model was fit using generalized non-linear least squares with R package nlme (Pinheiro and Bates 2015). Influential predictors identified using Random Forests were carried forward into development of this equation to predict BG as a combination of site and stand structural and compositional metrics. Final BG model form and predictors selected were based on predictor significance and minimizing model Akaike information criterion score. Preliminary analysis indicated the best model form was a Chapman-Richards equation and 15,622 plot growth measurements were used to simultaneously fit the final model (eq. 3-7):

$$BG_{pm} = (CLIMATE_p + SOIL_p + TOPOGRAPHY_p + SPECIES_{pm}) * (1 - e^{-b_0 BM_{pm}})^{c_0 + c_1 QMD_{pm}} \quad (3)$$

$$CLIMATE_p = a_0 + a_1 FrostFreeDays_p + a_2 AvgGrowingTemperature_p \quad (4)$$

$$SOIL_p = a_3 \ln(RGS_p + 10) + a_4 BRI_p \quad (5)$$

$$TOPOGRAPHY_p = a_5 \ln(DTW_p + 0.0001) + a_6 (SLOPE_p^{s_0} * e^{-s_1 SLOPE_p}) \quad (6)$$

$$SPECIES_{pm} = a_7 POPLAR_{pm} + a_8 PINE_{pm} \quad (7)$$

where the asymptote of maximum biomass productivity was defined by a combination of site factors (CLIMATE, SOIL, TOPOGRAPHY; see Table 3 for variable descriptions) and SPECIES factors (% basal area of POPLAR and PINE) with parameters $a_0..a_8$, s_0 , and s_1 ; the growth rate parameter b_0 was influenced by plot above-ground dry-biomass (BM) at time 0 surviving to time 1; and the shape parameters c_0 and c_1 were influenced by the quadratic mean diameter (QMD) at time 0. All site variable values were bilinear-interpolated for each plot location (p), while stand

variables, including BG, were calculated for each plot measurement period (m). To address heteroscedacity, a variance power function was included in the final model.

While holding species covariates at zero, the asymptote of the BG model was calculated for all plots and also mapped across the region on a 20m grid by bilinear interpolating site variables for each x, y coordinate and termed the biomass growth index (BGI; maximum $\text{kg ha}^{-1} \text{yr}^{-1}$) as:

$$BGI_{xy} = CLIMATE_{xy} + SOIL_{xy} + TOPOGRAPHY_{xy} \tag{8}$$

Ability of the BGI model to explain variation in average spruce and fir site index observed across all plot locations was evaluated using Random Forests. The same was done for comparison purposes using current classifications of site productivity in NB (ecological land class; Zelazny et al., 2007), NS (forest photo-interpreted land capability class; NSDNR, 2015), and PEI (soils-based forestland capability class; MacDougall et al., 1988). Finally, incremental improvement of using both BGI and land classification together to explain variation in site index was also examined.

Results

Effects of climate

Most climate variables (Table 2) were moderately to weakly correlated with observed BG, but as expected, were also strongly correlated to one another (e.g., maximum vs. mean temperature). Some climate variables (e.g., summer precipitation) were strongly correlated with BG, but also with other site factors (e.g., elevation, bedrock). Variables were dropped if little or no model error reduction occurred when they were removed, or if the relationship of the variable to BG varied from negative to positive or from strong to weak when examining relationships across each jurisdiction. The only climate variables retained in the final model were average

growing season temperature and frost free days; however, May-September average temperature was a close alternative and performed nearly as well on its own. Temperature was consistently important regardless of jurisdiction and contributed significantly to the final model.

Effects of lithology and soils

Second only to temperature (mean growing season temperature + frost free days) in contribution to model error reduction was underlying lithology (rock type). Rock type was important in all jurisdictions, excluding PEI, which was assumed to have a similar rock type throughout. The continuous measure of BRI always outperformed the categorical representation of rock type in the model. Soil influence on BG was moderate-weak in NS and PEI, and weak-poor in Maine and NB. BG log-linearly declined with RGS overall and within each jurisdiction; however, RGS was not a strong relative predictor in the final model because of issues with consistent and reliable soil mapping previously discussed.

Effects of topography and drainage

BG was negatively correlated with elevation, but elevation was highly correlated with temperature. Elevation resulted in almost no model improvement when temperature was included, and therefore was dropped from the final model. Slope was the strongest and most consistent topographical site predictor across all jurisdictions and BG generally increased logarithmically with it, peaked at 5-10°, and then declined linearly thereafter. As with slope, BG also logarithmically increased with DTW, especially between 0 and 10 cm. DTW generally outperformed topographic wetness index, but only slightly, and both drainage measures only weakly improved overall BG variance explained. DTW, while important, was the least significant variable retained in the final model.

Effects of stand species and structure

BM and QMD ≥ 9 cm DBH explained more variability in BG than all other site factors

combined. Using BM and QMD alone removed most residual model bias when plotted against other stand structural metrics (basal area, density, and height) and also for most species proportions in the plot. BG was increasingly under predicted as proportions of poplar or pine increased, so these species were incorporated into the final site model.

Biomass growth model

All BG parameters were highly significant ($P < 0.0001$; Table 4) and together explained 65.2% of total BG variation across the region: 41% in Maine ($n = 4,225$), 35% in NB ($n = 4,201$), 51% in NS ($n = 7,063$), and 13% in PEI ($n = 161$). Approximately 50% of the total variance explained was attributable to site factors based on Random Forests analysis. The model under predicted biomass growth in Maine by 7.2% and over predicted growth in NS by 1.6%, in NB by 5.5%, and in PEI by 1.8%. Forty-eight percent of plots had mean residual error $< 500 \text{ kg ha}^{-1} \text{ yr}^{-1}$. Influence of site and structural variables on BG is presented in Fig. 1.

Plot mean BG residual error (observed – predicted) was spatially interpolated across the region using ordinary kriging in ESRI ArcGIS version 10.1 with a minimum of 20 plot neighbour samples and 5 km raster cell size (Fig. 2). In many cases, spatial distribution of errors suggested that areas with concentrated low productivity sites (e.g., NB lowlands/highlands, NS southeast shore) are less productive than predicted, and areas of concentrated high productivity sites (e.g., northwestern NB; southwest ME) are more productive than predicted; however, in many other cases, pockets of spatial bias are not readily explainable. Indication of diluted BG predictions at site extremes may have resulted from noisy plot data and spatial inaccuracies in site predictors. Approximately 50% of the total variance explained was attributable to site factors based on Random Forests analysis.

Biomass growth index

The asymptote of the BG model with species held constant at zero (BGI) was mapped at

20 m resolution for each jurisdiction (Fig. 3). Highest rates of BGI were predicted in parts of southern and central Maine as a function of warmer growing conditions, deep soils, and fine sedimentary bedrock origins. Reduced productivity visually corresponded with one or more of the following conditions: highlands and cool coastal areas, poorly drained local topography, or areas with poor soils and/or bedrock.

Observed range of BG measured across the region was between 0 and 15,380 kg ha⁻¹ yr⁻¹ and averaged 2,541±1,299 SD kg ha⁻¹ yr⁻¹; however, samples were not equally distributed across the region. BGI predictions (kg ha⁻¹ yr⁻¹) in each jurisdiction ranged from: 0-5,872 (mean 3,975±688 SD) in Maine; 797-5,320 (mean 3,498±524 SD) in NB; 2,086-4,841 (mean 4,111±429 SD) in PEI; and 328-4,908 (mean 3,239±626 SD) in NS.

Comparison to spruce and balsam fir site trees

For Maine plots, there was no correlation between predicted BGI and plot spruce or fir site index, though spruce or fir site index in Maine was not correlated to any site predictors tested either. In Maine plots, only a single site tree is collected in a clustered plot design, this tree is sometimes outside of the plot, and age is often determined in the field, which can be problematic for species with slow growth, periods of suppression, or difficult to discern tree rings. These factors combined likely contribute to substantial noise in the Maine site tree data used.

For Maritime Canada, BGI explained low amounts of variation (<35%; Fig. 4) in spruce or fir site index depending on region and dataset, but was generally comparable to the level of site index explained by existing provincial site productivity classifications (Table 5). Our results for spruce site index slightly outperformed the NB ecological land classification, and slightly to moderately underperformed the NS and PEI land capability classification. Interestingly, for NS and PEI, 1-10% more absolute site index variation was explained when both the BGI and provincial site productivity layers were used together to predict site index (Table 5). For NB,

there seemed to be little value in using the mapped ecological land classification, alone or in combination with BGI, to predict site index.

Discussion

An ideal measure of site productivity should be integrative, independent of species, easy to measure or assess, and robust to various factors like changes in stand age. Site index meets many of these metrics, but has important limitations and can be difficult to apply in mixed-species and multi-cohort stands. Consequently, this analysis sought to develop a new biomass increment-based index of productivity, compare it to existing measures of site productivity, and map it across the entire region at a high spatial resolution.

Overall, BGI relationship to various site factors like climate, soils, and topography was logical, consistent when examined independently in each region, and the measure generally outperformed existing approaches to site productivity in the region. BGI performed well as the effects of species composition and stand structure were effectively removed, a relatively strong relationship between various site factors like climate, soils, and topography was observed, and the measure generally outperformed existing approaches to site productivity in the region. By incorporating background stand structure and species factors explicitly in the BG equation, and then holding those variables constant while predicting BGI, we removed, as much as possible, those background effects. However, because we do not possess data covering all combinations of site and stand conditions, and because stocking is often positively correlated with site quality (e.g., tree bogs and rock outcrops have non-stockable area), we wanted to be sure that BGI was not somehow confounded by this unbalanced dataset. When site variables used in the BGI model were used to predict spruce site index with Random Forests, little additional site index variability (<1%) was explained compared to using only BGI. This result suggests that BGI, despite

somewhat confounding modelling issues of stand structure and species, is capturing important aspects of soils, landform, bedrock, and climate with respect to forest productivity. Consequently, BGI should prove useful for future research and forest planning and management efforts.

Stand-level, increment-based approaches such as the one used in this analysis are likely an improvement to tree-level ones since finding undamaged, free to grow trees can be difficult (e.g., Nigh and Love 1999) and tree dominance can vary through stand development (e.g., Raulier et al. 2003). Plus, individual tree diameter and height increments are influenced by a broader range of factors when compared to stand-level increments (Weiskittel et al. 2011b), which could make determining the most influential site factors more difficult. A similar issue may also be present at the stand-level as Berrill and O'Hara (2016) recently found that stand dominant height and basal area were responsive to different site factors in mixed conifer forests in California, USA. In this analysis, stand-level biomass increment was used as it was believed to be a better measure of site productivity for mixed species stands because it considered differences in species wood density, compared to previous stand-level increment-based productivity indices that have used either basal area (Berrill and O'Hara 2014) or volume increment (Schmoldt et al. 1985). However, these analyses had fewer species present when compared to the current analysis so the correlation between basal area, volume, and biomass was likely stronger. Importantly, the species-specific biomass equations used in this analysis were a function of both DBH and height unlike most DBH-only biomass equations.

Like Jiang et al. (2015), climate was found to be a much better predictor of site productivity when compared to soils variables after accounting for differences in stand composition and structure. Unlike Jiang et al. (2015), temperature variables like frost free days and growing season temperature were most influential in our analysis, whereas precipitation and

its interaction with temperature were much more important in the other analysis. This is likely related to the spatial scale of the assessment as Jiang et al. (2015) were assessing at a much broader scale by focusing on the eastern US and consequently, precipitation would likely vary more dramatically than it does within a single region. Regardless, there is a large range of climate conditions in the Acadian Region due to the mixture of coastal and mountainous areas, so it is logical to expect climate to be a primary predictor of productivity. In fact, seven climatically distinct regions exist just in Maine (Briggs and Lemin 1992) and the range of variation observed is equivalent to the variation observed across 20° of latitude in Europe (Jacobson et al. 2009).

Climate, lithology, and soils vary considerably in the Acadian Region when compared to other regions. Consequently, their importance was expected to be greater than what was observed in Jiang et al. (2015). Although this was generally the case in this analysis, the degree of improvement was relatively marginal. For example, soil influences were moderate to weak in NS and PEI, and weak to poor in Maine and NB, which suggests that more effort is needed to accurately and more precisely map soil attributes that drive productivity in the Acadian forest region. In NB, soil types are assigned to broad polygons throughout the province and only qualitative descriptions of attributes by soil type, regardless of polygon location, are available (Colpitts et al. 1995). In Maine, soil polygon profiles sometimes vary more across township borders than within townships. For all jurisdictions, adjacent polygon differences in soil depth and other attributes are often extreme, suggesting considerable mapping error. These soil polygons often include more than one soil type with proportions stated, but not mapped. A shift toward mapping gradations in rooting depth, % coarse fragments, % sand, etc. at high resolution (20 m) as a function of topographic metrics, rather than the current approach of broadly mapping collections of associated soil types in polygons tied to hard breaks in drainage, landform, and

slope class, would probably help to improve soil predictions at fine scales.

Despite these findings, both BRI and RGS proved to be significant predictors and can likely be improved upon. Although BRI was a subjective measure developed in this analysis, it was more effective than using lithology as a categorical variable and provides a logical link to soil fertility (e.g., Colpitts et al. 1995). For example, siltstone is not necessarily considered nutrient rich, but it weathers relatively quickly and often results in deep silty loams. In contrast, basalt, which contains higher concentrations of calcium and magnesium, weathers more slowly and often results in shallower soils with moderate to high percentages of coarse fragments. In contrast, granite is often associated with low productivity because it 1) weathers slowly, 2) has low concentrations of calcium and magnesium, 3) occurs frequently in high-elevation environments (cold) in the Acadian forest region, and 4) because soils derived from granite tend to be sandy and rocky. These correlations and interactions make it challenging to capture the true relationship between rock type and productivity, as illustrated in this analysis. Briggs (1994) found that soil root depth was an important variable in his analysis of site factors in Maine, which is consistent with the use of RGS in this analysis. In contrast, Steinman (1992) found that chemical soil variables were generally better predictors than physical soil variables in predicting both spruce-fir site index and mean annual increment in Maine. Interestingly, RGS slightly outperformed derived soil water holding capacity, which would capture differences in soil texture. Both RGS and BRI are interesting variables and should be further explored in future analyses in this region.

Topographic indices have performed well in previous site productivity analyses (McNab 2010; Stage and Salas 2007) and were expected to be important in this region given the range of topographic complexity present. In this analysis, slope and DTW were the most effective predictors among the numerous topographic indices tested. The importance of slope has been

reported in previous studies (e.g., Grant 2004; Weiskittel et al. 2007), but generally it is in conjunction with aspect as it influences the amount and type of incoming radiation (e.g., Stage and Salas 2007). In the Acadian Region, slope is often related to soil drainage given a high proportion of low-lying flat areas whose wetness can negatively impact tree growth. DTW often approaches zero in very poorly drained flat black spruce bogs, but can also approach zero near a gently sloping stream bank or near a productive alluvial terrace. Interestingly, large topographic-related declines in site productivity were only observed to occur when both slope and DTW declined to zero.

To a certain extent, slope and DWT interacted, and helped to differentiate between low DTW on sloping terrain (good productivity) and flat terrain (poorly drained), although direct variable interactions were not significant in the final model. Underlying errors and the large range in spatial resolutions used in this analysis are speculated to have reduced the true value of topographic variables since a minor rise of only 25 cm elevation can drastically improve site productivity on otherwise flat terrain where drainage is a limiting factor. Future DEM improvements via LiDAR (light ranging and detection), and perhaps through new algorithms that can measure the stagnancy of the water table, are likely to improve the prediction importance of topographic measures explored here.

Site index remains the primary means of estimating and evaluating site productivity, but its application in mixed-species and multi-cohort stands is problematic. Our biomass increment-based index of site productivity offers several advantages over both site index and ecological land classification systems. In particular, BGI provides higher spatial resolution of site productivity, is a continuous measure, and can therefore be readily used in tree and stand growth and yield modeling. Often, productivity differences within an ecological land classification class are higher than between classes (e.g. Fig. 3.3 in Weiskittel et al. 2011b) and some classes may

lack sufficient plot data to parameterize growth models for each class. Site index can be highly variable based on stand age (as observed in this study), generally requires multiple measurements per stand, and depends on having a robust, well-constructed site index equation. The lack of strong relationship between site factors and observed site index in Maine is likely related to only one site tree being measured at each plot location, the age determined in the field, and the selected tree not always being located on the plot. In contrast, biomass increment-based indices of site productivity, particularly stand-level ones, will be less variable, show a stronger link to site factors, and be more integrative of the site conditions, but require the effects of stand composition and structure be removed as highlighted in this analysis. In addition, the approach outlined in this analysis needs only one plot growth measurement rather than multiple repeated measurements needed to estimate a plot-level asymptote in yield (e.g., Schmoldt et al. 1985).

Conclusions

After accounting for differences in species composition and stand structure, a combination of climate, lithology, soils, and topography was found to be influential on biomass growth rate; with temperature, soil depth and fertility, and slope being the most important. The model explained 65.2% of the original variation in BG, suggesting potential for additional improvement. Mapping predicted BGI (defined as the maximum BG) across the region produced logical trends that were generally consistent with existing site productivity estimates. BGI predictions for each region (Fig. 3) can be downloaded at www.forusresearch.com/bgi.php. Continued measurement of permanent plots as well as improvements in the estimation of the underlying variables, particularly with respect to advancements in digital elevation and soil attribute mapping with LiDAR and other satellite remote sensing information, should provide additional opportunities to improve this index.

Overall, BGI predictions should prove useful for future research and forest planning and management efforts in the Acadian Forest region. More importantly, this general approach to modeling a biomass-increment productivity index can be implemented with short-term inventory plot growth information, and therefore can be readily adapted to other forest regions.

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642 rn/pdf/en/ForestsCrownLands/ProtectedNaturalAreas/OurLandscapeHeritage/ForewordIn-
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644 **Table 1.** Acadian forest inventory data used for model development and evaluation.

Jurisdiction	Dataset*	Number of Spruce and Fir Site Index					Growth Plots [†]	
		Trees					Plot Locations	5-year growth measurements
		Plot Locations			Trees			
		Total	Spruce	Fir	Spruce	Fir		
NB	DNR PSP	758	532	384	974	741	1,587	3,960
	DNR TSP	3,042	1,617	1854	2,186	2,527	-	-
	AT PSP	12	8	5	28	13	97	213
NS	DNR CFI	2,177	1,633	1082	5,028	2,863	2,540	7,063
	DNR ELC	488	423	103	868	194	-	-
PEI	FFW PSP	108	92	25	807	101	44	161
	FFW CFI	409	208	163	400	204	-	-
Maine	FIA CFI	1,393	784	619	795	624	2,536	4,225
	JDI TSP	81	45	39	51	43	-	-

* Dataset descriptions:

- NB DNR PSP – NB Dep. Nat. Res. provincial permanent sample plots for tree growth research.
- NB DNR TSP – NB Dep. Nat. Res. provincial co-dominant and dominant height-age trees collected in temporary sample plots for stand and forest inventory estimation.
- NB AT PSP – Acadian Timber Inc. permanent sample plots in northwestern NB.
- NS DNR CFI – NS Dep. Nat. Res. provincial continuous forest inventory plots.
- NS DNR ELC – NS Dep. Nat. Res. ecological classification temporary sample plots.
- PEI FFW PSP – PEI Dep. Forest, Fish and Wildlife permanent sample plots for tree growth research.
- NS FFW CFI – PEI Dep. Forest, Fish and Wildlife continuous forest inventory plots.
- Maine FIA CFI – State continuous forest inventory plots; Forest Inventory and Analysis Unit, USDA For. Serv.
- Maine JDI TSP – J.D. Irving, Limited co-dominant and dominant height-age trees collected in temporary sample plots for stand and forest inventory estimation in northern Maine forests.

[†] Growth observations were limited to after 1990 to avoid confounding effects of the last spruce budworm outbreak in the region

659 **Table 2.** Various site predictor variable descriptions, spatial resolution, key references, and data providers used in the analysis.

Predictor	Resolution	Used	Reference / Data Provider
Climate			
Mean growing season temperature normals 1971-2000	800 m	Yes	McKenney et al. (2006). Custom climate normal predictions at 800m resolution for the region courtesy of Dr. Dan McKenzie and his staff, Nat. Res. Canada. Transferred in 2014.
Frost free days normals 1971-2000	800 m	Yes	
Other tested climate normals 1971-2000*†	800 m	No	
Annual mean wind speed at 30 m elevation	200 m	No	Courtesy of Dr. Yves Gagnon, Wind Energy Institute of Canada and PEI, NB, and NS governments; EOEEA via True Wind Solutions, LLC for Maine (accessed online, fall 2015)
Lithology and soil			
Bedrock Index (BRI) derived from rock type observed regional effect on site	Sampled to 50 m	Yes	Shapefiles: Maine (2015), Keppie (2000), NBDNR (2008), MacDougall et al. (1988)
Root Growing Space Index (RGS) derived as a combination of maximum root depth and % coarse fragment	Sampled to 50 m	Yes	Shapefiles: USDA (2015), MacDougall et al. (1988), Colpitts et al. (1995), CANSIS (2014). Wetland and rock outcrop enhancements using NBDNR (2015), PEIFFW (2015), NSDNR (2015).
Other tested soil attributes*‡		No	
Topography derived from digital elevation models (DEM)			
Elevation	20 m	No	DEM for PEI was based on LIDAR at 6 m resolution. DEM for Maine and NS used SRTM at 90m, and NB used SRTM at 30m. DEM and DTW (Murphy et al. 2009) were provided by the University of New Brunswick Forest Watershed Research Center in 2015.
Depth to water (DTW) predicted at 10 m resolution from DEM and mapped water features.	20 m	Yes	
Slope in degrees	20 m	Yes	

Terrain wetness, roughness, and openness index	30 m	No	SAGA (Böhner et al. 2006)
	30 m	No	Derived in ArcGIS using Fu and Rich (2002)

- 660 * Dropped from final model due to correlation with stronger variables or weak site influence.
- 661 † All climate normals (Table 1 in McKenney et al. 2006) were explored.
- 662 ‡ Other soil attributes explored where available: % sand, % clay, depth of organic layers, % organic matter in mineral soil, bulk
663 density, pH, alternate soil profile layer depth summaries, mode of deposition, and calculated soil water holding capacity using Saxton
664 and Rawls (2006).

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665 **Table 3.** Bedrock type groups, examples, and bedrock productivity index (BRI). Higher BRI values
 666 correspond to higher site productivity.

Bedrock type group	Examples of dominant rocks in each group	BRI
Felsic	Granite, rhyolite	0.00
Intermediate felsic	Granodiorite, mixed felsic/mafic	0.10
Coarse sedimentary	Sandstone, conglomerate, gneiss, coarse meta-sedimentary	0.25
Intermediate mafic	Diorite, mixed mafic/felsic	0.50
Mafic	Gabbro, basalt	0.60
Fine Sedimentary	Mudstone, siltstone, fine meta-sedimentary	0.75
Weakly calcareous	Calcareous concentrations present in fine or coarse sedimentary	0.85
Calcareous	Limestone, dolomite, marble, strongly calcareous concentrations	1.00

667

Table 4. Biomass growth model variables with plot data range and Random Forests importance scores (RFI), and non-linear model parameter estimates for eq. 3.

Variable	Units	Plot data		RFI [†] (%)	Equation 3 parameters (P)		
		Range	Mean ± SD		P	Estimate	SE
Intercept	-	-	-	-	<i>a0</i>	-7335.78	327.696
Frost free days	Days	81 – 172	123 ± 17.3	3.24	<i>a1</i>	8.194	0.6891
Mean growing season temperature	° Celsius	10.9 – 14.6	12.9 ± 0.70	14.8	<i>a2</i>	568.436	18.8332
Root growing space*	cm	-1 – 100	42.0 ± 15.1	1.17	<i>a3</i>	327.218	31.3813
Bedrock index	-	0 – 1	0.42 ± 0.22	4.12	<i>a4</i>	1205.979	56.2682
Depth to water	cm	0 – 150	7.10 ± 11.3	2.14	<i>a5</i>	55.823	6.4501
Slope	Degrees	0 – 40	3.72 ± 4.03	3.88	<i>a6</i>	705.452	160.4658
					<i>s0</i>	0.594	0.1383
					<i>s1</i>	0.111	0.0274
Percentage basal area <i>Populus</i> spp.	%	0 – 100	3.70 ± 11.5	4.28	<i>a7</i>	19.08	0.9206
Percentage basal area <i>Pinus</i> spp.	%	0 – 100	5.11 ± 15.0	1.06	<i>a8</i>	8.687	0.7799
Biomass	t ha ⁻¹	1 – 250	107 ± 19.2	88.6	<i>b0</i>	0.013	0.0007
Quadratic mean diameter	cm	9.5 – 60	19.2 ± 4.58	10.31	<i>c0</i>	0.145	0.0357
					<i>c1</i>	0.045	0.0035

* -1 for tree bogs and marshes

[†] Random Forest variable importance measured as the % increase in model mean squared error resulting from random alterations in the subject variable observed values during prediction.

Importance value and variable rank varied by about ± 3 each time the model was trained.

Table 5. Site tree (spruce, balsam fir) index variation explained by provincial land class (LC), biomass growth index (BGI; eq. 8), and combined (LC+BGI) site predictors with Random Forest; best species site index model is shown in bold.

Jurisdiction	Dataset*	Error explained (Random Forest; out of bag r^2) [‡]					
		Spruce site index model			Fir site index model		
		LC	BGI	LC+BGI	LC	BGI	LC+BGI
NB	DNR PSP	1	3	-3	2	1	-
	DNR TSP [†]	5	9	8	4	5	6
NS	CFI	25	18	33	17	17	26
	TSP [†]	19	9	26	11	27	35
PEI	PSP	39	31	43	-	-	-
	CFI [†]	26	26	27	3	3	1

* See Table 1 for dataset description and site tree sample size.

[†] Dataset (locations and inventory methods) independent of data used to fit BGI model.

[‡] Based on observations randomly held out (out of bag) during decision tree construction to provide a pseudo estimate of model performance on unseen data. ‘-’ indicates no error explained.

682 **List of Figures**

683 **Fig. 1.** Biomass growth rate (BG; eq. 3) predicted asymptote ($\text{kg ha}^{-1} \text{yr}^{-1}$) resulting from changes to
684 mean plot values (black dots) across the observed range of A) climate, B) topography, and C) soil
685 predictor variables, and D) predicted asymptote growth multiplier values across the range of plot
686 dry-biomass and quadratic mean diameter values.

687 **Fig. 2.** Biomass growth model (eq. 3) residual error ($\text{kg ha}^{-1} \text{yr}^{-1}$; plot mean observed rate minus
688 predicted rate) interpolated at 5 km resolution with kriging.

689 **Fig. 3.** Biomass growth index (BGI; $\text{kg ha}^{-1} \text{yr}^{-1}$; eq. 8) estimated at 20 m resolution; i.e., asymptote
690 of the biomass annual growth model (eq. 3) with stand species composition and stand structure
691 variables held constant at zero.

692 **Fig. 4.** Observed average plot spruce and fir site index over biomass growth index (BGI; $\text{kg ha}^{-1} \text{yr}^{-1}$;
693 eq. 8) with lowess trend lines and Random Forest r^2 for each species and dataset (a-f) listed in
694 Table 5.

Fig. 1. Biomass growth rate (BG; eq. 3) predicted asymptote ($\text{kg ha}^{-1} \text{yr}^{-1}$) resulting from changes to mean plot values (black dots) across the observed range of A) climate, B) topography, and C) soil predictor variables, and D) predicted asymptote growth multiplier values across the range of plot dry-biomass and quadratic mean diameter values.

Fig. 1

172x170mm (300 x 300 DPI)

Fig. 2. Biomass growth model (eq. 3) residual error (kg ha⁻¹ yr⁻¹; plot mean observed rate minus predicted rate) interpolated at 5 km resolution with kriging.

Fig. 2
146x90mm (300 x 300 DPI)

Fig. 3. Biomass growth index (BGI; $\text{kg ha}^{-1} \text{ yr}^{-1}$; eq. 8) estimated at 20 m resolution; i.e., asymptote of the biomass annual growth model (eq. 3) with stand species composition and stand structure variables held constant at zero.

Fig. 3

154x101mm (300 x 300 DPI)

Fig. 4. Observed average plot spruce and fir site index over biomass growth index (BGI; $\text{kg ha}^{-1} \text{ yr}^{-1}$; eq. 8) with lowess trend lines and Random Forest r^2 for each species and dataset (a-f) listed in Table 5.

Fig. 4
199x222mm (300 x 300 DPI)