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Representing site productivity in the basal area increment model for FVS-Ontario

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ABSTRACT

The utility of site index as a predictor variable in models for complex, mixed species stands is limited because the site index concept is not well suited for these stand types. Additionally, there is no standard protocol of estimating site index for uneven-aged mixed species stands, which is evident in permanent sample plot (PSP) and co-operative (COOP) data sets available from the Province of Ontario, Canada. Under such circumstances, an alternative to site index in a basal area increment model was explored, using a combination of climate and Forest Ecosystem Classification (FEC) variables from the Ontario boreal region. Among the four candidate climate variables chosen, mean annual temperature (MAT) explained the most variability in basal area increment for the four selected tree species – trembling aspen (*Populus tremuloides* Michx.), balsam fir (*Abies balsamea* (L.) Mill.), jack pine (*Pinus banksiana* Lamb.), and black spruce (*Picea mariana* (Mill.) B.S.P.). Our results indicated that a combination of the climate variable, MAT, and FEC explained a substantially higher proportion of variation in the basal area increment than site index alone. Thus, climate and FEC variables are superior substitutes in the basal area increment model even when error-free site index values are possible to obtain.

1. Introduction

The terms *site*, *site quality*, and *site productivity* have been used interchangeably in forestry, though they are not synonymous (Skovsgaard and Vanclay, 2008). *Site* is generically considered as place or geographic location of land. However, in a forestry context, "site is an area considered as to its physical factors with reference to forest producing power, the combination of climatic and soil conditions of an area" (Frothingham, 1921). *Site quality* reflects a measure of productivity potential for a given site at a given time (Carmean, 1975; Daniel et al., 1979; Clutter et al., 1983; Vanclay, 1992). Site quality is the combination of physical and biological factors that govern the site properties (Skovsgaard and Vanclay, 2008). Vanclay (1994) and Skovsgaard and Vanclay (2008) defined *site productivity* as a quantitative estimate of the potential of a given site to produce wood/timber or biomass for a particular species. For instance, site index (SI), or the height of a specific population of dominant or co-dominant trees at a reference age, is a widely accepted measure of site quality, and is the most commonly used quantitative index of site productivity in forestry (Kayahara et al., 1998). In a forestry context, site productivity emphasizes the timber or biomass production capability as a major indicator of site, regardless of its ecosystem concept.

The concept of site classification has long and rich history in agriculture and forestry. Alternative approaches have been developed for representing site, depending on the intended purpose. For instance, plant communities, or even attributes of single plants, have been used as relative indicators of productivity potential of an ecosystem, sometimes referred as "phytometers." In forests, site index is an important proxy of site quality and has been used in many conceptual and simulation models of ecosystem dynamics. There are numerous reasons for using site index as a means for quantifying site. For example, height can be accurately measured with minimal cost. Also, site index is simple to use, widely applicable, considered free from the effects of stand density, and highly correlated with volume production in normally stocked stands (Mader, 1963; Carmean, 1975).

The concept of site index was developed for single species, even-aged stands, but over the last two decades, it has been applied in mixed species uneven-aged stands (Monserud, 1984; Huang and Titus, 1993; Peng, 2000). As a result, numerous drawbacks to site index have been identified, discussed, and reported (Monserud, 1984). For instance, site index is often not observable because free-growing and undamaged dominant or co-dominant trees may not be present; a situation that is common in degraded stands or stands managed using uneven-aged silviculture. Even if suitable trees are present, they may not be the species desirable for estimating site index. These limitations of

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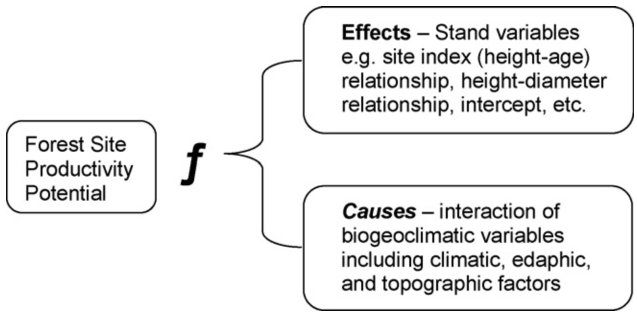

Fig. 1. Conceptual frameworks for estimating potential productivity of a given stand.

estimating site index become more and more noticeable as the scope of forest management widens towards multiple use, mixed species or uneven-aged management. Such changes in the scope of forest management have not only limited the application of site index, but also exerted pressure to explore alternate methods of evaluating site productivity.

Site productivity has been used in forestry in the context of both cause and effect (Fig. 1). For instance, site index is used as an *index* or *proxy* of potential site productivity, which integrates the effects on tree growth from numerous site variables. Alternatively, use of topographic, climate or soil variables to predict potential site productivity emphasizes a cause and effect relationship with tree growth. A shift in emphasis in forest management from yield to more holistic approach of sustainable ecosystem management favors environmental variables over site index as an alternate approach to site productivity evaluation.

It has been well-recognized that the potential productivity of an ecosystem can be characterized by an interaction of biogeoclimatic factors that include climatic, edaphic, and topographic factors (Zon, 1913; Cajander, 1926; Hägglund, 1981). A number of studies have demonstrated a relationship between the site productivity potential index and biogeoclimatic factors (Chen et al., 2002; Gustafson et al., 2003; McKenney and Pedlar, 2003; Wang et al., 2004; Monserud et al., 2006, 2008; Stage and Salas, 2007). These studies showed the application of biogeoclimatic variables while estimating productivity potential for a given tree species; however, these studies are confined to a geographical area with a large spatial heterogeneity, most particularly the western parts of the United States and Canada.

Site characterization in the form of indices or classes has numerous advantages in forestry and forest management. An accurate characterization of site allows for efficient land use allocation, integrated ecosystem planning, evaluation of ecosystem productivity and diagnosis, and prescribed ecosystem management. As a result, the majority of research has been concentrated on estimating site productivity using causal proxies, such as climatic, edaphic, and topographic factors (Fig. 1). However, very few studies have investigated the usefulness of these factors in a diameter or basal area increment model (Wykoff and Monserud, 1988; Froese, 2003). As discussed elsewhere, site productivity is an important fundamental predictor variable in the diameter or basal area increment model. It is essential to include site productivity in the model in either form (causes or effects) in order to explain site level variation in diameter or basal area increment of an individual tree.

A flexible and robust regional aspatial individual tree diameter or basal area increment model can be developed by deliberately choosing an appropriate base function along with a model structure that can accommodate the most important predictor variables including size, site, and competition (Pokharel, 2008). In the context of the Forest Vegetation Simulator (FVS), it is increasingly important to account for geographic variability of the growing conditions as FVS is intended to cover the scope of many thousands of hectares (Crookston and Dixon, 2005; Froese and Robinson, 2007). Site index has been used as a predictor variable in many FVS growth engines developed and used elsewhere (Bush, 1995a,b; Bush and Brand, 1995). Even though site index is extensively used in growth modelling, often it has received substantial criticism when used in degraded stands or stands managed using uneven-aged silviculture. There is a need to search for an alternate to site index to represent site quality in the diameter or basal area increment model that is intended to be used at regional scale, such as FVS.

1.1. Prior representation of site effects in FVS-Ontario

Site is considered one of the fundamental factors in an increment model designed for regional use. However, its utility in the increment model depends on the consistency and reliability of its field estimation. In the case of Ontario's FVS development efforts (Woods and Robinson, 2008), incorporating site effects have always been problematic for many tree species. For instance, site index is non-significant in the diameter increment model developed by Lacerte et al. for every tree species, except jack pine and black spruce (FVS-Ontario Version 1 – Lacerte et al., 2005, 2006b). In the process of refining and enhancing the diameter increment model Woods and Penner (2007) took Wykoff's (1990) approach to selecting the base function and structuring the basal area increment model, expanded the data sets, and formulated a new model for the most common tree species in Ontario, and continued to used site index as a site quality variable. In that study, however, site index was still non-significant for most tree species.

Obtaining estimates of site index to accompany available Ontario inventory data is especially problematic. Most data sets lack identification of individual site trees, total height and individual tree age data. Often, if age is available, it is the stand age, not the breast height age of an individual site tree. While this could be corrected for using age to breast height models (USDA Forest Service, 1975), we cannot ensure that trees otherwise would meet acceptability criteria for site index estimation, such as being free of evidence of past suppression or top damage. Ignoring this issue will result in unknown bias in estimates because it is impossible to identify the population of trees for which site index prediction equations were designed.

Estimating site index is essentially impossible in the Great Lakes – St. Lawrence (GLSL) data sets. These sets include measurements of overwhelmingly shade-tolerant hardwood stands or stands with silvicultural treatments that involve selective harvesting. Thus, some past suppression of height growth is almost certain in measured trees, irrespective of the absolute or relative size of any given individual tree. Because these sets usually have height and age data available, it is possible to select a certain number of the largest trees in the plot and calculate a site index from those trees. However, such site index calculations are almost certainly under-estimates of the site index that would be expected if trees had grown without past height suppression.

Thus, while large array of data is available through the Ontario Ministry of Natural Resources (OMNR), the associated estimates of site index have limited utility in diameter or basal area increment modelling. In order to make these Ontario data sets usable, an alternative approach of including site variables in the increment model is over-due. Alternative approaches have shown promise in conceptually related studies. McKenney and Pedlar (2003) used climate and soil variables to estimate site index for jack pine and black spruce in Ontario, and Gustafson et al. (2003) used site and climate variables to generate a potential site productivity map for aspen in the Upper Great Lakes region. Both of these studies

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demonstrated that site productivity can be mapped using climate and soil variables. However, the effectiveness of climate variables in addition to Forest Ecosystem Classification (FEC) in an increment model has not been evaluated in a single empirical study. Furthermore, there is a little topographic variation across the Province of Ontario (Baldwin et al., 2000). Then again the question that arises here is: could biogeoclimatic variables explain a significant amount of variation in an individual tree diameter increment model for Ontario? Readily available of geospatial climate data allows us to test this hypothesis using data imputed to each inventory plot and plot level FEC variables.

FEC may represent or refine the site effect at a micro-level. The utility of habitat type in an increment model in the western parts of the United States has been successfully tested by appropriately introducing habitat types as a dummy variable in (Wykoff et al., 1982; Wykoff, 1990). In the case of northwestern Ontario, an earlier study by Carmean (1996a) showed a poor relationship between FEC soil type and productivity potential of trembling aspen (*Populus tremuloides* Michx.) (*QA*), jack pine (*Pinus banksiana* Lamb.) (*JP*), and black spruce (*Picea mariana* (Mill.) B.S.P.) (*BS*). The question that arises here is whether FEC, using both vegetation and soil type, possibly in combination with climate, could prove more successful.

1.2. Objectives

We posited that when the full FEC classification was used in combination with climate variables as model predictors that this approach would be superior to site index alone, which is something not explored in previous work. The specific objectives of the study were: (1) to compare and contrast the variability explained in diameter or basal area increment using site index and climate variable(s) as site proxies in addition to other size and competition variables; (2) to evaluate the contribution of FEC in explaining variability on diameter or basal area increment for the selected four tree species; and (3) to assess the contribution of FEC when coupled with climate variable(s) as an alternate to site index while explaining variability in diameter or basal area increment.

2. Data and methodology

2.1. Data sets

Long-term permanent sample plot (PSP) and co-operative (COOP) data were made available through the Growth and Yield Program of Ontario Ministry of Natural Resources (OMNR). The PSP and COOP data have a short history, and are largely growth monitoring plots installed in managed and natural forests mostly in boreal regions of the Province. The data cover a wide range of growing conditions, forest ecosystems, stand structures, age, and species composition (Hayden et al., 1995; SUMAC Forest Information Services Ltd. 2005). The spatial distribution of re-measured plots with available site index, climate, and FEC variables is depicted in Fig. 2. The topography of Ontario is primarily comprised of flat plains to very low rolling uplands with relatively small relief, ridges, escarpment, and cuestas as high as 200 m above the terrain (Baldwin et al., 2000). The highest point is Maple Mountain, which is 693 m above sea level.

2.2. Inventory design

Data were collected under a range of inventory designs. PSP data were collected using a fixed area 3-point cluster design, of which the majority of plots are circular in shape and 400 m^2 in area (Hayden et al., 1995). In contrast, the COOP plot data have a single fixed area circular plot of 400 m^2 in area (SUMAC Forest Information Services Ltd. 2005).

2.3. Individual tree and stand variables

The response variable, annual diameter increment, for each tree was estimated based on an averaging method. Diameter increment and measurement period were estimated based on two successive inventory cycles for those plots that were re-measured more than once. The measured period is estimated in years; i.e. the difference between two measured dates. No monthly data are available and, as a result, there is no possibility of adjusting proportionally within a growing season. All trees that were alive at the beginning of the inventory period were included in the estimation of stand level attributes, such as stand basal area (m^2 ha^{-1}) and basal area of trees larger than subject tree (m^2 ha^{-1}) that were estimated at the subplot level. However, only trees that were alive, measured in both successive periodic inventories, and having a diameter greater than the threshold diameter as described by Woods and Penner (2007) were used in the analysis. The resulting set included hardwood tree species greater than 15.2 cm dbh (diameter at breast height), and softwood tree species greater than 7.6 cm dbh. Four tree species that are most common in the Province of Ontario (Woods and Robinson, 2008) and also had sufficient sample size were chosen for the analysis: trembling aspen (*Populus tremuloides* Michx.) (*QA*), balsam fir (*Abies balsamea* (L.) Mill.) (*BF*), jack pine (*Pinus banksiana* Lamb.) (*JP*), and black spruce (*Picea mariana* (Mill.) B.S.P.) (*BS*). Trees with negative diameter increments were assumed to have measurement error and were excluded from the analysis. The tree factor (sample expansion factor) for all trees that were alive at the beginning of the inventory period was estimated at the subplot level in order to maintain the same plot size over a wide range of inventory designs. The individual tree, stand variables, site index, and climate data are summarized for the four selected tree species in Table 1.

2.4. Climate and site index variables

Climate variables were imputed at each inventory plot location using gridded climate data sets available from Canadian Forest Service (Personal Communication Dan McKenney and Pia Papadopol March 2008; Mackey et al., 1996; McKenney and Pedlar, 2003; McKenney et al., 2007). The source was a continuous climate grid generated using the software *ANUSPLIN*, based on 1961–1990 climate data for Ontario (McKenney et al., 2007). Over five dozen derivatives representing precipitation, temperature, and growing season were generated for each plot location. Among the over five dozen derived variables, only four – number of days of growing season (days) (NGDS), mean annual temperature (°C) (MAT), total precipitation during growing season (mm) (GSPPT), and annual precipitation (mm) (APPT) – were selected as a candidate variables for the diameter or basal area increment modelling. Their choice was primarily due to their established utility in site productivity estimation elsewhere (Monserud et al., 2006), and also their high correlation with species dynamics and tree growth in Ontario (Thompson, 2000).

Site index was estimated at each plot that has a marked site tree, and also has available height, and age information using equations from Carmean et al. (2001) for *JP* and Carmean (1996b) for *BF*, *BS*, and *QA*. When only stand age was available we converted it to breast height age using equations developed by the USDA Forest Service (1975). For the COOP data, site index estimates were supplied with the plot data (SUMAC Forest Information Services Ltd. 2005). Site index conversion was carried out among the selected four tree species using corrected conversion equations from Carmean (1996b).

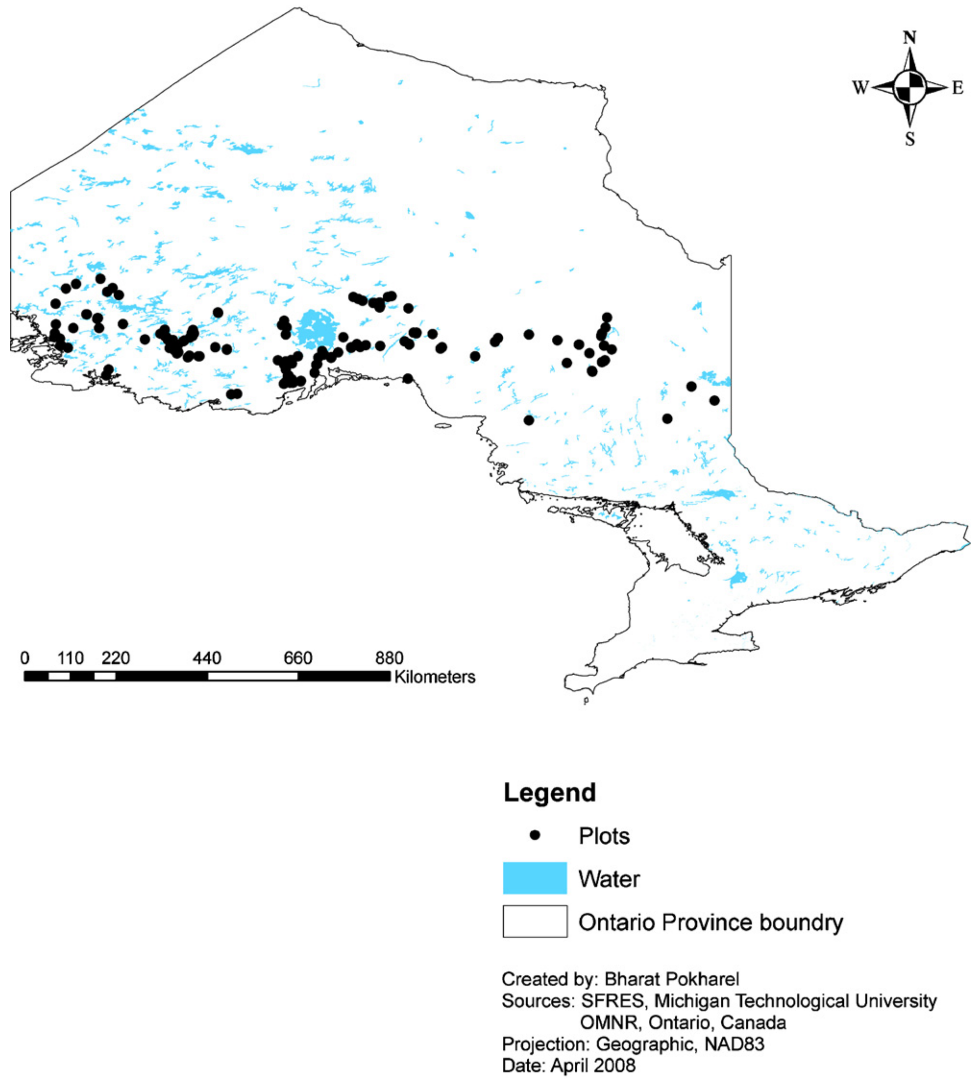

Fig. 2. The location of plots that have site index, FEC, and climate data in the Province of Ontario, Canada.

2.5. Forest Ecosystem Classification (FEC)

Site quality has been characterized as an interaction of biotic and abiotic factors (Hägglund, 1981; Skovsgaard and Vanclay, 2008); therefore, consistent sets of environmental factors and vegetation conditions may be useful to describe the productivity potential for an ecosystem. In Ontario, Hills (1959) first developed a coarse level hierarchical land classification system based on physiography, soils, climate, landforms, and vegetation. Over the last two decades, the FEC system has been developed for Ontario at a higher resolution with ecosites at spatial scale of 1:10,000–1:50,000. FEC are mapable units that have relatively uniform parent materials, soils, hydrology, and vegetation structure and composition (Taylor et al., 2000). An FEC ecosite may consist of a number of vegetation types (V-types) and soil types (S-types) (Racey et al., 1996; Taylor et al., 2000) representing the ecosystem at an operational level. The available data sets from the Province of Ontario only cover FEC from the Northeastern (MNR region 2) (Taylor et al., 2000) and Northwestern (MNR region 1) (Racey et al., 1996) regions.

Due to the small number of plots that represent each FEC in the data sets, the inventory plots were merged within and between the two regions in order to create a uniform set of FEC ecosite groups. A total of 8 FEC ecosite groups were created for the available data sets (Table 2). FEC were merged between two Northeastern and Northwestern regions based on a draft matrix of FEC translation between two MNR regions (Personal communication, April 2008; Scott McPherson, Ontario Ministry of Natural Resources). As described by Taylor et al. (2000), the nomenclature and numbering of old site types (McCarthy et al., 1994) available in the data sets were changed to the FEC number as described by the new field guide for the Northeastern region (Taylor et al., 2000). During the process of creating FEC ecosite groups, suffices of FEC such as soil texture, species richness, soil depth and soil moisture were ignored as there were not enough plots available under each of these original sub groups. Additionally, a subjective judgmental approach based on the species dominance in the plot within the data set, and also corresponding vegetation types (V-types) and soil types (S-types), were cross checked while grouping the FEC.

2.6. Basal area increment model

The base model we used was a gamma function, to produce a composite model using size, site and competition as predictor variables and difference in diameter squared (DDS) as the response variable (Pokharel, 2008). The same set of size and competition variables were included while altering the variables that explain site effects in the increment model; i.e. SI with

Table 1
Summary of individual tree, stand, and climate attributes from re-measured plots.

Variables	Unit	Tree species			
		Populus tremuloides (*QA*)	*Abies balsamea* (*BF*)	*Pinus banksiana* (*JP*)	*Picea mariana* (*BS*)
N	No. plots[a]	48	27	74	111
n	No. trees	662	702	3808	3517
dbh	cm	22.48 (15.2, 57.3)	12.05 (7.6, 36.4)	14.99 (7.6, 51.3)	13.24 (7.6, 37.5)
Δdbh	cm	0.22 (0, 2.16)	0.22 (0, 1.96)	0.17 (0, 1.22)	0.16 (0, 2.02)
BA	m^2/ha	30.90 (11.74, 61.79)	23.96 (0.41, 35.44)	24.54 (4.80, 43.13)	28.45 (1.14, 49.04)
dbhq	cm	16.83 (6.99, 31.06)	9.83 (4.03, 21.24)	12.27 (4.18, 30.00)	11.90 (5.24, 30.00)
SI	m	18.58 (6.42, 24.56)	10.96 (5.39, 22.24)	15.84 (6.13, 26.39)	12.77 (5.19, 28.08)
NDGS	days	166.36 (156, 181)	165.27 (157, 175)	171.31 (157, 182)	166.35 (156, 182)
MAT	°C	0.58 (−1.02, 2.18)	0.36 (−0.8, 1.19)	1.05 (−0.81, 2.49)	0.49 (−1.05, 2.49)
GSPPT	mm	457.09 (415.3, 500.4)	460.76 (435.8, 502.5)	462.21 (393.7, 506)	456.18 (385.5, 506)
APPT	mm	757.73 (639, 867)	778.40 (639, 867)	719.30 (621, 935)	753.78 (621, 935)

Note: Δdbh = diameter increment per year; dbhq = quadratic mean diameter (cm); SI = site index (m); NDGS = number of days of growing season (days); MAT = mean annual temperature (°C); GSPPT = total precipitation during growing season (mm); APPT = annual precipitation (mm); the values in parenthesis are the range. *N* is number of plots, whereas *n* is number of trees.
[a] Total number of plots used in this analysis are 152.

climate and/or FEC variables. Such alteration of site variables resulted in five different scenarios: (1) SI; (2) SI and FEC; (3) climate variables; (4) climate variables and FEC; and (5) FEC alone. The FEC ecosite groups were represented using dummy variables in the model. The plausible model used under five chosen scenarios for the selected tree species is:

$$\ln(\text{DDS}+1) = b_0 + b_1 \cdot \ln(\text{dbh}) + b_2 \cdot \text{dbh} + b_3 \cdot \frac{\text{BAL}}{\ln(\text{dbh}+1)} + b_4\,\text{BA} + b_5\,\text{SITE}$$

where DDS is the annual difference in diameter squared ($\text{dbh}^2_{\text{year1}} - \text{dbh}^2_{\text{year0}}$). A gamma based linear form of the model was used to describe a size effect, which is the function of dbh, the current tree diameter at the breast height (cm). Competition is represented by BAL, the total basal area of trees with larger dbh than the subject tree ($m^2\,ha^{-1}$) and BA, the stand basal area ($m^2\,ha^{-1}$). SITE is the site effects incorporated into the model by using one of the five scenarios. Then, b_0 is intercept, b_1, b_2, b_3, and b_4 are species specific coefficients, and b_5 is a vector of coefficients of relevant site effects.

The same subset of data was used while comparing the mean squared error (MSE), and the coefficient of determination (R^2) under each scenario. The fit statistics were compared among the five scenarios, and the sign and magnitude of parameter estimates were analyzed. The partial sums of squares (PSS), which accounts for the partial reduction in error sum of squares due to the addition of that variable in the full model, was calculated and compared among the scenarios for each selected tree species.

3. Results

3.1. Site index, climate and FEC variables in the basal area increment model

There was a considerable difference among the fit statistics generated under each scenario for the four selected tree species. For all five scenarios, the R^2 values were greater than 0.22. SI was

Table 2
Grouping of FEC based on the available plot within the database.

FEC groups	FEC ecosite code	Description
FEC-1ES12	1ES12	Conifer dominated stands with red, white, and jack pine, occasionally with occurrence of trembling aspen
FEC-1ES13-20-2ES2	1ES13, 1ES20, 2ES2	Jack pine dominated even-aged stands, and sometime overstorey is dominated by jack pine and black spruce
FEC-1ES14-22-2ES3	1ES14, 1ES22, 2ES3	Overstory dominated by jack pine and black spruce with mixture of white birch, trembling aspen, and balsam fir
FEC-1ES15-27	1ES15, 1ES27	Stands dominated by fir with mixture of trembling aspen and white birch
FEC-1ES19-23-29-32-2ES6-7	1ES19, 1ES23, 1ES29, 1ES32, 2ES6, 2ES7	Hardwoods, fir, and spruce mixedwood stands
FEC-1ES21	1ES21	Fir and spruce mixedwood stands
FEC-1ES25-26-2ES5-13	1ES25, 1ES26, 2ES5, 2ES13	Black spruce and jack pine dominated stands
FEC-1ES35-36-2ES9	1ES35, 1ES36, 2ES9	Black spruce dominated stands in wetlands or area with moist clayey soil

Note: In the FEC groups, prefix is MNR region i.e. 1 means northwest, and 2 means northeast, ES means ecosite and suffix number means actual ecosite number (e.g. 1ES15 means ecosite 15 in Northwest region). The 8 FEC group codes were systematically developed based on the parent FEC nomenclature from which they were derived.

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not significant for *QA*, and it also had a negative coefficient for *BF* (Table 3a and b). MAT explained an equal or greater amount of variation than the SI in the basal area increment for all selected tree species, except *BS* (Table 3). The basal area increment model that replaced SI by FEC alone also explained a greater amount of variability, and had less MSE than the model that includes SI for all four selected tree species. Among all five scenarios chosen, a combination of a climate variable, MAT with FEC explained the most variation and also had the least MSE (with a non-practical exception in the case of *BS*) (Table 3b).

3.2. Use of climate and FEC variables

Among all four chosen climate variables, MAT explained the most variation in basal area increment, and the sign and magnitude of its coefficient estimates were as expected. This result further coupled with FEC as a dummy variable in order to develop a parsimonious model. The fit statistics clearly indicated that MAT along with FEC could replace SI for the selected four tree species for the Province of Ontario (Table 3).

Partial sums of squares (PSS) were calculated for all candidate variables under two scenarios – composite model with site index and FEC, and composite model with MAT and FEC. FEC as a dummy variable reduced a considerable amount of PSS, and it was highly significant when used with either site index or MAT in the basal area increment model (Table 4). Similarly, MAT had higher partial sums of squares than site index alone for all selected tree species, except for *BS* (Table 4). A climate variable, MAT alone may not sufficiently replace site index for all tree species; however, carefully selected climate variable(s) along with FEC explained a significantly higher portion of variability in basal area increment for an individual tree as compared to the other alternate approaches evaluated here.

4. Discussion

Our results show that climate variables alone may replace site index for three out of four selected tree species in this analysis. This result generalizes the model within the domain of climate and geography and relieves model users from the need to determine accurate SI values for target populations in model application, which is a considerable advance. Furthermore, we demonstrated that addition of FEC along with climate variables makes the choice superior over the scenario that uses site index alone. Incorporation of climate and FEC allows the model to simulate tree growth from those inventory data that lack site index information. Such flexibility allows use of the entirety of the existing long-term re-measured data sets from the Province of Ontario, likely further increasing generality of the diameter increment model to the target population.

Climatic factors such as rainfall, temperature, radiation, and wind affect the growth rate and survival of trees. These are considered essential site factors (Hägglund, 1981; Avery and Burkhart, 2002). To represent these factors in an increment model, four climate variables – number of days of the growing season, mean annual temperature, precipitation during the growing season, and annual precipitation – were chosen deliberately. Indeed, these factors were also used for climatic index by Paterson in late 1950s to predict maximum growth potential for a site (Paterson 1956 cited in Johnston et al., 1967). Looking at the growing conditions in those stands selected from forest inventory plots across Ontario, MAT explained the most variation among the four climate variables examined.

In the case of growing season precipitation, the coefficients are negative for all tree species (results not shown), which might be interpreted as counterintuitive. However, this could be because soil moisture is not a limiting factor in Northeast and Northwest Ontario. Baldwin et al. (2000) documented that surface water runoff is abundant across Ontario, except in the extreme western and southern regions. None of these inventory plots were from the extreme western and southern regions; therefore, it may be that increasing growing season precipitation actually hinders tree growth by leading to saturated soils or indicating cooler or cloudier conditions than average. In other words, it may be sensible that the sign of coefficient estimates for the growing season precipitation are negative for all tree species. This hypothesis should be explored further in future work.

It is not unusual to use surrogate and proxy variables in natural resource modelling because they have either low measurement error or they can be easily obtained with low cost from the routine forest inventories. For instance, site variables such as aspect, slope, and elevation have been demonstrated as useful surrogates for radiation, precipitation, and temperature effects on tree growth (Hägglund, 1981; Avery and Burkhart, 2002; Stage and Salas, 2007). Surrogate and proxy variables are imperfect substitutes for the actual effect (Froese, 2003). If there is a reliable estimate of predictor variables that have casual effects on tree growth, then there is no need to use surrogates. Therefore, site variables such as slope, aspect, and elevation can be replaced by their actual causal effect climate variable, MAT. A comparative analysis of a composite model with and without these additional site variables would certainly complete this analysis. However, one was not conducted due to lack of sufficient inventory plots for each selected tree species. This hypothesis should be explored further.

The model calibration and use are dictated by the limitations of sufficient quality, and geographically and temporally representative data (Vanclay, 1995). In the case of the Ontario data, neither reliable site index information, nor a standard method of estimating site index from the inventory data are available. Despite these numerous limitations associated with site index, a conservative approach was taken while selecting plots that have site index information. The source of error while selecting site trees was minimized in order to make a fair comparison between site index and climate variables or FEC.

The inventory data are also a major limitation in this study. The Beckwith–Roebbelen (B&R) set is one of the major data sets that has a significant number of re-measured plots, yet lacks FEC data. Also, a majority of trees that have height available in the PSP and B&R data sets are not identified as site trees. In the PSP data set, 269 of 290 plots have height and age for some trees. However, site trees are specifically identified in only 107 of these 269 plots (40%). This could be due to the lack of acceptable site trees available in those plots or that the height of those trees may have been measured for purposes other than estimating site index. Estimating site index by selecting a certain number of the largest trees in the plot by dbh as site trees could be an option (The Technical Advisory Committee, 1998; Mailly et al., 2004); however, it violates the assumptions of site index – dominant or co-dominant trees that have never been suppressed in their height growth trajectory. In order to avoid bias introduced from the data sets, a conservative approach was used by which only those plots that have marked site index trees were selected and used. A standard process of site index estimation was used in order to minimize measurement error associated with site index. This allows a fair comparison between site index, and climate and FEC variables.

Our results add evidence to the hypothesis that site index has performed poorly in FVS-Ontario not because it is inferior over climate or other variables, but because its estimation has numerous drawbacks. Earlier studies by Lacerte et al. (2004, 2006a) also identified inconsistency in model prediction due to the use of the site index as an input variable in Ontario.

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Table 3
A comparison of MSE, R^2 and parameter estimates with site index, climate and/or Forest Ecosystem Classification (FEC) variables (all parameters were significant at $\alpha = 0.05$).

Parameter estimates	Scenarios				
	SI	SI + FEC	Climate	Climate + FEC	FEC
(a) *Populus tremuloides* (*QA*)					
Intercept	−1.0671	−1.2807	−1.3602	−1.7068	−1.2807
ln(dbh)	1.1197	1.1645	1.1411	1.1666	1.1645
BAL/ln(dbh)	−0.0719	−0.0661	−0.0656	−0.0611	−0.0661
SI					
MAT			0.3421	0.3831	
FEC-1ES13-20-2ES2		−0.8166		−0.9461	−0.8166
FEC-1ES14-22-2ES3		0.0171		−0.1212	0.0171
FEC-1ES19-23-29-32-2ES6-7		0.0752		0.2649	0.0752
FEC-1ES21		−0.1714		0.0124	−0.1714
FEC-1ES25-26-2ES5-13					
DF	659	655	658	654	655
MSE	0.5557	0.5343	0.5172	0.4900	0.5343
R^2	0.25	0.28	0.30	0.34	0.28
(b) *Abies balsamea* (*BF*)					
Intercept	0.7181	0.1601	−0.2449	−0.1294	0.1601
ln(dbh)	0.7672	0.8435	0.9874	0.9444	0.8435
BAL/ln(dbh)	−0.0467	−0.0311	−0.0297	−0.0286	−0.0311
BA	−0.0184	−0.0277	−0.0234	−0.0270	−0.0277
SI	−0.0234				
MAT			0.5170	0.3112	
FEC-1ES14-22-2ES3		−0.0821		−0.0508	−0.0821
FEC-1ES15-27		−0.0441		0.0529	−0.0441
FEC-1ES19-23-29-32-2ES6-7		0.4718		0.2770	0.4718
FEC-1ES21					
DF	697	695	697	694	695
MSE	0.3331	0.2601	0.2628	0.2453	0.2601
R^2	0.36	0.50	0.50	0.53	0.50
(c) *Pinus banksiana* (*JP*)					
Intercept	0.6897	0.4115	1.1479	0.5427	0.6143
dbh	−0.0228	−0.0358	−0.0125	−0.0321	−0.0324
ln(dbh)	0.6015	0.8773	0.4609	0.8343	0.8598
BAL/ln(dbh)	−0.1123	−0.1044	−0.1120	−0.1040	−0.1015
BA	−0.0126	−0.0159	−0.0074	−0.0126	−0.0151
SI	0.0272	0.0159			
MAT			0.0599	0.0807	
FEC-1ES12		−0.3538		−0.4111	−0.3932
FEC-1ES13-20-2ES2		−0.0345		−0.0250	−0.0262
FEC-1ES14-22-2ES3		0.0461		0.1121	0.1135
FEC-1ES19-23-29-32-2ES6-7		0.2154		0.1881	0.1712
FEC-1ES21		0.0375		0.0891	0.0559
FEC-1ES25-26-2ES5-13					
DF	3802	3797	3802	3797	3798
MSE	0.2980	0.2852	0.3010	0.2837	0.2867
R^2	0.36	0.39	0.36	0.39	0.38
(d) *Picea mariana* (*BS*)					
Intercept	0.3762	0.2981	0.8071	0.5467	0.5466
ln(dbh)	0.3265	0.6295	0.4939	0.7113	0.7213
BAL/ln(dbh)	−0.0400	−0.0250	−0.0237	−0.0171	−0.0163
BA	−0.0181	−0.0275	−0.0224	−0.0306	−0.0310
SI	0.0737	0.0349			
MAT			0.1940	0.0492	
FEC-1ES12		−0.0900		−0.1752	−0.1891
FEC-1ES13-20-2ES2		0.1266		0.1233	0.1492
FEC-1ES14-22-2ES3		0.0990		0.1558	0.1680
FEC-1ES19-23-29-32-2ES6-7		0.1951		0.3162	0.3181
FEC-1ES21		0.2972		0.3362	0.3328
FEC-1ES25-26-2ES5-13		−0.0360		−0.0681	−0.0729
FEC-1ES35-36-2ES9					
DF	3512	3506	3512	3506	3507
MSE	0.3860	0.3286	0.4430	0.3383	0.3391
R^2	0.32	0.43	0.22	0.41	0.41

It is noted that a prominent effect of measurement error of predictors in regression model development is Type II error; namely, failing to reject the null hypothesis (of no effect) in significance tests of model coefficients (Stage and Wykoff, 1998; Carroll et al., 2006; Fuller, 2006). In other words, measurement error introduces variability in the predictor that can, if large enough, overwhelm the explanatory power of the predictor in fitted regression models. McRoberts et al. (2000) argued that it is

Table 4
A comparison of partial sums of squares of error using SI and FEC, and climate and FEC while fitting the composite basal area increment model.

Parameters	Partial sums of squares by species under two scenarios							
	Populus tremuloides (*QA*)		*Abies balsamea* (*BF*)		*Pinus banksiana* (*JP*)		*Picea mariana* (*BS*)	
	SI + FEC	Climate + FEC	SI + FEC	Climate + FEC	SI + FEC	Climate + FEC	SI + FEC	Climate + FEC
dbh	0.3 (0.452)	0.09 (0.6706)	0.2 (0.3795)	0.22 (0.3459)	6.02 (<0.0001)	4.87 (<0.0001)	1.04 (0.0757)	0.36 (0.3037)
ln(dbh)	0.63 (0.2796)	2.45 (0.0257)	3.65 (0.0002)	4.26 (<0.0001)	13.37 (<0.0001)	12.09 (<0.0001)	8.49 (<0.0001)	7.63 (<0.0001)
BAL/ln(dbh)	15.36 (<0.0001)	17.49 (<0.0001)	2.3 (0.003)	2.05 (0.0039)	197.07 (<0.0001)	198.69 (<0.0001)	11.52 (<0.0001)	5.59 (<0.0001)
BA	0.35 (0.4159)	0.31 (0.4299)	16.62 (<0.0001)	15.57 (<0.0001)	24.84 (<0.0001)	14.88 (<0.0001)	99.86 (<0.0001)	125.77 (<0.0001)
SI	0.13 (0.6253)		0.31 (0.2731)		6 (<0.0001)		37.85 (<0.0001)	
MAT		29.35 (<0.0001)		10.56 (<0.0001)		11.73 (<0.0001)		2.99 (0.003)
FEC	14.87 (<0.0001)	20.02 (<0.0001)	51.79 (<0.0001)	13.14 (<0.0001)	49.77 (<0.0001)	76.12 (<0.0001)	201.39 (<0.0001)	368.48 (<0.0001)

Note: Values in parentheses are *p*-value for *F*-test. FEC were grouped into 8 categories. Each species has different number of groups: *QA* has 5 groups, *BF* has 4 groups, *JP* has 6 groups and *BS* has 7 groups each.

better not to include a variable that has a large measurement error that propagates uncertainty into the model prediction. It seems plausible to conclude that error in site index is limiting the utility of this predictor in Ontario modelling efforts. In the case of Ontario, it is worth switching to climate and FEC variables rather than developing new site index equations at the local level and estimating site index from the existing permanent sample plots in the field.

The effect of habitat types in describing productivity potential has been well-recognized in the western parts of the United States and Canada. Wykoff (1990) included habitat type in the Prognosis increment model (Wykoff et al., 1982), knowing that habitat type classified land based on expected climax vegetation. Similar to habitat types, FEC is an ecosystem classification framework developed in order to map a consistent set of environmental factors and vegetation conditions across the landscape in Ontario (Racey et al., 1996). FEC collectively describes the ecosystem as a common assemblage of abiotic and biotic factors. Inclusion of FEC in an increment model seems likely to explain a micro-site level variability in moisture and nutrient availability. For example, FEC as a dummy variable alone has been able to explain a greater degree of variability than site index in the basal area increment model for all four selected tree species. Similarly, FEC alone has a lower MSE and higher R^2 for *JP* and *BS* than inclusion of climate variables. A combination of FEC and climate variables has the highest R^2 and least MSE for all four selected tree species. R^2 values compare favorably to other studies involving individual tree models (e.g. Andreassen and Tomter, 2003), indicating that our model has captured core explanatory variables. Furthermore, FEC alone has the largest partial sums of squares than the site index for all four tree species, and climate variables, except for *QA* (Table 4).

FEC not only characterizes environmental factors, but also includes vegetation conditions. It may explain the variation in basal area increment due to species mixture and composition, despite the fact that its effects on growth models are unknown. The intended effect from FEC entirely depends upon grouping of FEC with a desired resolution. FEC grouping in this case acts like stratified sampling in which delineation of strata is driven by the objectives of sampling. Therefore, a combination of FEC grouping within and between regions should be based on the objectives of FEC to be represented in an increment model. The FEC grouping at the ecosite resolution in this study has demonstrated a significant effect on the basal area increment of an individual tree. Further refinement will likely increase the utility of FEC as an important predictor in the basal area increment model.

The results discussed here are slightly different than what had been reported by Carmean (1996a) for *QA*, *BS*, and *JP* in Ontario. He used only the FEC soil type data from northwestern Ontario to describe the productivity potential, while the approach in this paper uses FEC classification based on both vegetation and soil types. Soil alone may not adequately represent site quality variation across Ontario. FEC describes site as a total effect to produce vegetation from ecological perspectives as discussed by Hills (1960a,b) and Spurr and Barnes (1980). The interacting relationship between plant communities and environmental conditions has been expressed as an indicator of site quality under FEC.

The utility of a model is largely dependent on its end users. Various factors such as the cost of acquiring data and the technical skills required executing the model play a key role in making the model a useful tool. Users analyze the cost and benefit of using a model in order to meet their specific objectives. Since, Ontario has a well-established FEC system, which has been attached with its ongoing periodic inventory program, inclusion of FEC in the basal area increment model of FVS-Ontario is feasible without additional cost and planning. The climate grids are readily available from Canadian Forest Service for the entire Province of Ontario. Therefore, it is feasible to operationalize the outcomes of this study in FVS-Ontario.

The use of FEC and climate variables in an increment model has numerous advantages. A site index variable is no longer needed and almost all inventory data can be used given that spatial coordinates are available. As the sample size increases, our point estimates consist of a narrow band of confidence interval and smaller uncertainties provided that climate estimates from *ANUSPLIN* are unbiased and have acceptable levels of precision. Use of FEC and climate variables in an increment model not only helps to forecast resource availability; it is also capable of estimating growth and yield for a bare land. As a result, our strategic planning to meet future demand for forest and forest products will be more robust and reliable using the existing inventory information.

The role of climate factors in tree growth and development has been well-acknowledged in the forestry literature. More recently, a substantial portion of research effort has been devoted to climate change. As the climate changes over a period of time, the distribution of trees, growth, and mortality rates are also changing, and there is a need to incorporate that knowledge in our growth and yield models (Crookston et al., 2007; ESSA Technologies Ltd., 2007). Inclusion of climate variables such as temperature, precipitation and number of days in the growing season could accommodate some of the effect of these changes on tree growth and development. However, since the climate data for this study were 30-year averages for the Province of Ontario, they only represent the average role of climatic factors on tree growth. Tuning parameter estimates using yearly or short periodic climate data would increase the resolution and allow testing the effects of climate variability on individual tree growth.

5. Conclusions and recommendations

The climate variable MAT and the ecological variable FEC together explain a larger proportion of the variation in the basal area increment than the site index alone for the Province of Ontario, Canada. The results show that FEC explains micro-level variation likely related to soil moisture and nutrient status and is statistically significant for all four selected tree species. Since Ontario has well-established FEC system under its ongoing inventory program, inclusion of FEC and climate variables into an increment model for FVS-Ontario is feasible with little to no additional cost.

FEC should be aggregated into about 10 groups for the entire Province. Climate estimates were generated based on a 30-year normal (1961–1990); therefore an uncertainty analysis of these climate variables in an increment model would build confidence among model users. Similarly, the final diameter or basal area increment model should be validated using data from geographic regions other than the Province of Ontario, Canada.

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