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Addressing climate change in the forest vegetation simulator to assess impacts on landscape forest dynamics

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ABSTRACT

To simulate stand-level impacts of climate change, predictors in the widely used Forest Vegetation Simulator (FVS) were adjusted to account for expected climate effects. This was accomplished by: (1) adding functions that link mortality and regeneration of species to climate variables expressing climatic suitability, (2) constructing a function linking site index to climate and using it to modify growth rates, and (3) adding functions accounting for changing growth rates due to climate-induced genetic responses. For three climatically diverse landscapes, simulations were used to explore the change in species composition and tree growth that should accompany climate change during the 21st century. The simulations illustrated the changes in forest composition that could accompany climate change. Projections were the most sensitive to mortality, as the loss of trees of a dominant species heavily influenced stand dynamics. While additional work is needed on fundamental plant–climate relationships, this work incorporates climatic effects into FVS to produce a new model called Climate–FVS. This model provides for managers a tool that allows climate change impacts to be incorporated in forest plans.

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1. Introduction

Climate change is expected to have pronounced ecological consequences in forested ecosystems. Projected impacts encompass a broad range of effects: the evolution of novel plant associations (Jackson and Overpeck, 2000), shifts in the spatial distribution of tree species (e.g., Iverson and Prasad, 1998), redistribution of populations adapted to local climates (e.g. Tchebakova et al., 2003), and changes in site index (Monserud et al., 2008). Studies (e.g., Bachelet et al., 2001b; Hansen et al., 2001; Melillo et al., 1995; Neilson et al., 2005; Shafer et al., 2001), in fact, have been unanimous in predicting widespread disruption of native ecosystems from the change in climate being portrayed by numerous General Circulation Models (GCM) (see IPCC, 2000). Many accounts illustrate the impact of climate change on the vegetation (see Breshears et al., 2005; Jump et al., 2009; Allen et al., 2010; Mátyás, 2010), such as the migration at high altitudes and demise and replacement at low altitudes of *Fagus sylvatica* (Peñuelas et al., 2007), or the dieback of *Populus tremuloides* due to a climate-induced stress (Rehfeldt et al., 2009).

Most forest managers use growth models to aid decision making. These models, like the widely used Forest Vegetation Simulator (FVS, Crookston and Dixon, 2005; Dixon, 2008; Stage, 1973), were developed for use in a static climate. Because many component functions describing stand dynamics are dependent on climate, growth models in general are incapable of reflecting impacts of climate change. In this paper, we describe adjustments to the predictors in FVS to take into account the effects of climate on mortality, growth, and regeneration. The modified model, called Climate–FVS, is used to simulate impacts of climate change on three climatically diverse landscapes.

FVS is an individual-tree, semi-distance-independent growth model. Inputs include an inventory of site conditions and a set of measurements on a sample of trees (e.g., tree size, species, crown ratio, recent growth and mortality rates). Outputs include summaries of tree volume, species distributions, and growth and mortality rates that are often customized for specific user needs. The Fire and Fuels Extension of FVS (FFE-FVS, Rebain et al., 2009; Reinhardt and Crookston, 2003) outputs many indicators including a report on carbon loads used herein. FVS is used to support an array of management issues spanning silviculture prescriptions, fuels management, insect and disease impacts, and wildlife habitat management. Spatial scales range from a single stand to thousands of stands. The temporal scale has traditionally been about 200 years (400 years maximum), but here we limit ourselves to ~100 years, the period covered the GCM used for simulations.

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FVS is widely used in North America for project-level analyses and forest planning. Integrating climate change and species–climate relationships into FVS provides managers a familiar tool useful for addressing climate change issues. There are several variants of FVS that share the same core technology but differ in their treatment of growth and mortality. This paper deals only with those variants in use in the western United States.

2. Methods

The components of FVS most subject to climate and therefore needing adjustment are those dealing with mortality, carrying capacity, tree growth, and regeneration and establishment. Our approach to adjusting these components is to (1) define a species-specific viability score as a function of climate and (2) develop a means to compute climatically induced changes in site quality. The final model must also recognize that stand dynamics will depend on the adaptedness of the genetic system (physiological attunement to the climate, see Rehfeldt et al., 1999) as the climate changes.

2.1. Climate estimates and projections

Our analyses use spline climate surfaces (ANUSPLIN, Hutchinson, 2004) for providing 1961–1990 monthly normals of mean, maximum, and minimum temperature and precipitation for point locations (see Rehfeldt, 2006; Sáenz-Romero et al., 2010). The surfaces are indexed by latitude, longitude, and elevation, and because the splines are continuous rather than grids, point estimates can be generated rather than gridded estimates available from raster cells in many climate models (e.g., Daly et al., 2008). The spline climate estimates, available at URL http://forest.moscowfsl.wsu.edu/climate, include algorithms to generate from monthly means 35 variables such as mean annual temperature and precipitation, degrees days above 5 °C, degrees days below 0 °C, and the length of the frost period, and interactions such as annual dryness index, which reflects the balance between growing season warmth and precipitation.

To estimate future climates, weather data used in developing the contemporary climate surfaces were updated using output from three GCM and three scenarios of the Special Report on Emissions Scenarios (SRES, IPCC, 2000) (Table 1). Downscaling from the GCM grids to the point locations of the weather stations used a weighted average of the monthly change for the GCM cell centers lying within 400 km of a weather station (see Sáenz-Romero et al., 2010). The inverse of the square of the distance from the station to the cell center was used for weighting. Monthly climate surfaces for average, minimum, and maximum temperature and precipitation were then fit anew for each GCM and each scenario for each of three 10-year periods, nominally, 2030, 2060, and 2090.

Table 1
General circulation models (GCM) and special report on emission scenarios (SRES) used herein.

GCM name	Center name
CGCM3	Canadian Center of Climate Modeling and Analysis
HADMC3	Met Office Hadley Centre (UK)
GFDLCM21	Geophysical Fluid Dynamics Laboratory (Princeton University, NOAA Research)
SRES scenario	**Description**
A2	High emissions, regionally diverse world, rapid growth
A1B	Intermediate emissions, homogeneous world, rapid growth
B2	Lower emissions, local environmental sustainability
B1	Lowest emissions, global environmental sustainability

2.2. Species-specific viability scores

As an index to viability, we use a species-specific estimate of the likelihood that the climate is suitable. The estimate is derived from the climate profile, a multivariate description of the climatic niche. The profiles are developed from bioclimate models, that is, regressions of the presence or absence of a species on climate variables. Modeling techniques generally follow Iverson and Prasad (1998) but most closely parallel Rehfeldt et al. (2006), described in detail in Rehfeldt et al. (2009).

To develop the climate profile, we used a data from permanent sample plots largely from Forest Inventory and Analysis (FIA, Bechtold and Patterson, 2005) but supplemented with research plot data to provide about 117,000 observations (see Rehfeldt et al., 2006, 2009) describing the presence and absence of numerous species. The Random Forests classification tree of Breiman (2001), implemented in R by Liaw and Wiener (2002), was then used to predict the presence or absence of species from climate variables. The Random Forests algorithm outputs statistics (i.e., vote counts) that reflect the likelihood (proportion of the total votes cast) that the climate at a location would be suitable for a species. We interpret this likelihood as a viability score: values near zero indicate a low suitability while those near 1.0 indicate a suitability so high that the species is nearly always present in that climate.

Random Forest classification trees were built for 74 tree species of the western United States (Table 2), about 70% of the species in the FIA database. Although the culling of species was somewhat arbitrary, those eliminated generally occurred at fewer than 50 plots. The statistical power of the analyses is reflected in the number of available observations, as many as 39,000 for *Pseudotsuga menziesii* and as few as 76 for *Populus deltoides* ssp. *monilifera*.

The climate profile was built on 3–30 forests, each with 100 trees. Protocols for selecting the sample of observations used in each forest and the stepwise variable elimination process followed Rehfeldt et al. (2006, 2009). The approach has been shown to be robust, working superbly for a variety of widely distributed species as well as the endangered spruce taxa of Mexico (Ledig et al., 2010).

2.3. Site Index and climate

Site index is a commonly used measure of the ability of a site to produce wood (Monserud, 1984). Ideally, it is a species-specific height at a base age reached by dominant trees that have always grown without competition. Site index is known to be a function of climate (see Monserud and Rehfeldt, 1990) which explained ∼25% of variation in site index of *Pinus contorta* var. *latifolia* in Alberta, Canada (Monserud et al., 2006, 2008). In general, high site indices are correlated with long growing seasons and warm temperatures, provided that moisture is sufficient. The results show unequivocally that *P. contorta* site indices are altered by a change in climate.

Because FVS uses site quality to estimate tree growth, Climate–FVS requires a function relating site quality to climate applicable to all forest types and their ecotones to non-forest in all of western United States. This function, however, need not be species-specific because Climate–FVS used species viability scores to judge site suitability. To provide such a function, we defined S to be the proportionate change in site index caused by a change from one climate (called C_1) to another (called C_2), where C_i is a vector of climate metrics like those used to measure the viability scores.

Let f be a function of C_i that predicts the site index, or at least a number that is proportional to the site index, then $S = f(C_2)/f(C_1)$. Note that $f(C_1) > 0$ because FVS is initiated with sites that are suitable for forests. To construct f, we used the FIA collection of site trees for the western United States, in which 82,649 observations of height and age are spread over 21,553 plots in forested lands. Estimating site index for each tree, however, was hampered by