

FVS and Global Warming: A Prospectus for Future Development

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Abstract—Climate change—global warming and changes in precipitation—will cause changes in tree growth rates, mortality rates, the distribution of tree species, competition, and species interactions. An implicit assumption in FVS is that site quality will remain the same as it was during the time period observations used to calibrate the component models were made and that the site quality will not be affected by climate change. This paper presents evidence of the impacts of climate change on forests and argues that FVS needs to be revised to account for these changes. The changes include modification of the growth, mortality, and regeneration establishment models, all of which need to account for changes in site quality and genetic adaptation. Criteria for modifying the model recognize that the model's applications and uses will not diminish and need to be supported. The new process, climate change, needs to be recognized by the model because it influences all of the processes FVS currently represents. Plans are being made to address this major task.

Introduction

This paper is a call to action. A key use of FVS is to forecast the species and size distribution of forest stands over time, given proposed management regimes. This and other uses are documented by two previous symposium proceedings (Teck and others 1997; Crookston and Havis 2002) and other key documents (Dixon 2003; Crookston and Dixon 2005). Typical applications of FVS are clearly within the time span of predicted significant climate change (Rehfeldt and others 2006; IPCC 2007a).

FVS needs to be modified so that it can be useful in the face of changing climate (Monserud 2003). The key uses of FVS will be in even greater demand as forest managers try to cope with climate change in addition to ever increasing demands for wood, habitat, and other ecosystem services. How to manage forests over the rest of this century and into the next is an open question that cannot be addressed with forest growth models that are both insensitive to climate change and are designed for century long projections.

Necessary changes to FVS touch all aspects of the base model as climate change influences the processes the model represents (Crookston and Dixon 2005; IPCC 2007b). In this paper we present research that shows how one scenario of climate change is predicted to alter the climate for some important species (Rehfeldt and others 2006) and present some recent exploratory work showing how it might influence the carrying capacity of forested lands in the Western United States as measured by stand density index (Reineke 1933), one of the key variables used in FVS to predict mortality. In addition we review recent exploratory work that relates growth increment to precipitation and temperature and discuss the role genetics might play in predicting growth. After the need for modifying FVS is clearly documented and some of the exploratory work is presented, we discuss the design criteria for a new climate-based variant and discuss our ideas on how this model might take shape.

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Change In Species Distributions

Climate is the major factor controlling species distributions (Holdridge 1947). Rehfeldt and others (2006) published maps of the climate profiles for individual species and plant associations. Figure 1 depicts the current and projected locations of the climate profiles for *Pinus ponderosa*, *Larix occidentalis*, *Pseudotsuga menziesii*, and *Picea engelmannii* for contemporary climate and at three points in the future. A species climate profile is a model that predicts the presence of a species according to climate metrics. The maps were produced by relating current species distributions as recorded in the Forest Inventory and Analysis (FIA) data to the climate variables predicted using a model of the climatic normal period of 1960 to 1990 (Rehfeldt 2006). Future distributions of species' climate profiles were made by predicting the future locations using forecasted climates. The forecasted climates were based on the average of two global circulation models run for a "business as usual" scenario of 1 percent increase in greenhouse gases per year over this century. The two models are from the Hadley Center (HadCM3GGA1) (Gordon and others 2000) and Canadian Center (CGCM2_ggha) (Flato and Boer 2001).

It appears that for some species, for example *P. menziesii*, the future does not seem too bleak (yet likely understated in these figures; see the discussions in Rehfeldt and others 2006), but for others, the forecast is not very positive (*P. engelmannii*, for example). The point is that the locations of the climate profiles change, some more than others, and that the change is clearly within the period of typical one-century long FVS projections. We conclude that species composition is likely to be influenced in ways not contemplated with the current FVS model formulation and that the magnitude of the change is likely to be large and widespread.

Carrying Capacity, Maximum Stand Density Index

As part of our preliminary work on modifying FVS, we worked out a model of maximum stand density index (MaxSDI) (Reineke 1933) computed using the Western U.S. FIA data as a function of two climate measures, mean annual precipitation (MAP) and the number of degree days above 5 °C (DD5). SDI is the equivalent trees per acre (TPA) at a quadratic mean diameter (QMD) of 10 inches (there is a metric version as well that does not have an exact linear conversion), expressed as follows: $SDI = TPA (QMD/10)^{1.605}$. SDI is used in the mortality models in some FVS variants. As the tree density reaches a proportion of the maximum tabulated in the model for a site, the model increases the mortality rate so that the established upper limits of SDI are not exceeded. In this context, MaxSDI is used as a measure of the site carrying capacity. The climate-derived MaxSDI equation is:

$$MaxSDI = b_0 (1 - \exp(-(b_1 MAP)^{b_2})) DD5 \exp(b_3 DD5) \quad (1)$$

where $b_0 = 1.901$, $b_1 = 0.003489$, $b_2 = 1.861$, $b_3 = -0.000775$, with a residual standard error of 181.5 where all coefficients are significant with $P < 0.01$. Observations used to fit this model are those subplots (from the FIA data) that carry the highest SDI measurements across several climate gradients. Briefly, the procedure for one climate variable was to create 300 bins of observations corresponding to 300 fixed intervals along a climate gradient (MAP, for example). In each bin, the identity of the 99th percentile observation of SDI was recorded. This procedure was completed independently for each of 35 climate variables used by Rehfeldt and others (2006). The lists of subplot identities were then combined and all duplicates were removed.

Figure 2 illustrates the equation's response surface. At the lower end of the precipitation gradient, MaxSDI increases with increased precipitation, but at the upper end there is no increase in carrying capacity. In fact, there is some evidence that at the highest precipitations, MaxSDI falls as precipitation increases. This can be seen by inspecting the residual plot that shows that MaxSDI is over predicted at high levels of precipitation. For the purposes of this paper, we left the equation form as shown with an upper asymptote on precipitation. The response of MaxSDI to heat is different in that higher heat results in higher MaxSDI until an optimum is reached and then additional heat causes decreases in MaxSDI. The equation captures some important components of climate and plant interactions.

The quotient of DD5 divided by MAP is sometimes called annual moisture index (Rehfeldt and others 2006), but may be better referred to as an annual dryness index (ADI) because as the amount of heat increases for a fixed amount of moisture, the numeric

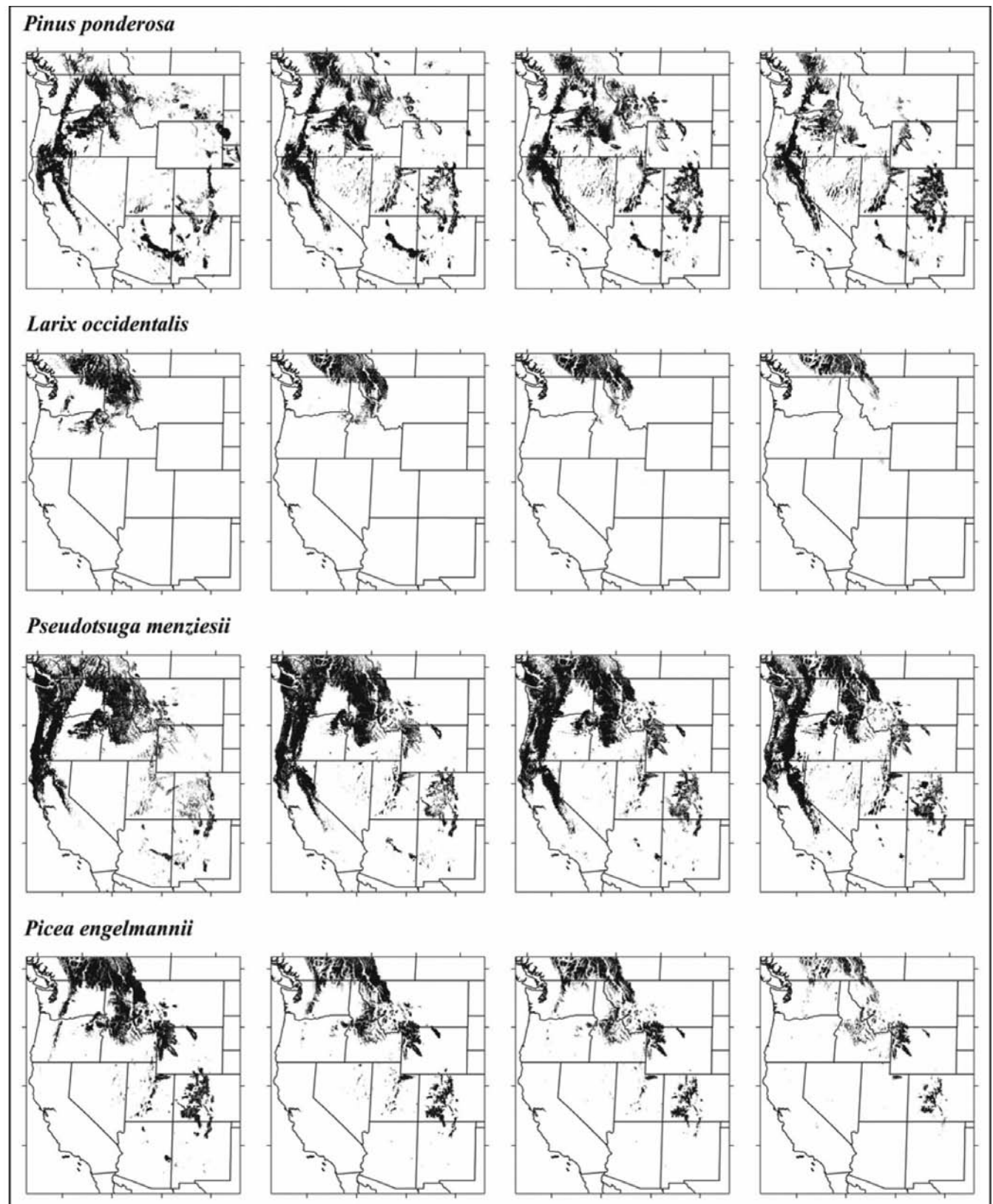


Figure 1—Modeled climate profiles of four forest tree species for the contemporary climate and for the decades beginning in 2030, 2060, and 2090 (left to right) (reprinted from Rehfeldt and others 2006, p. 1146).

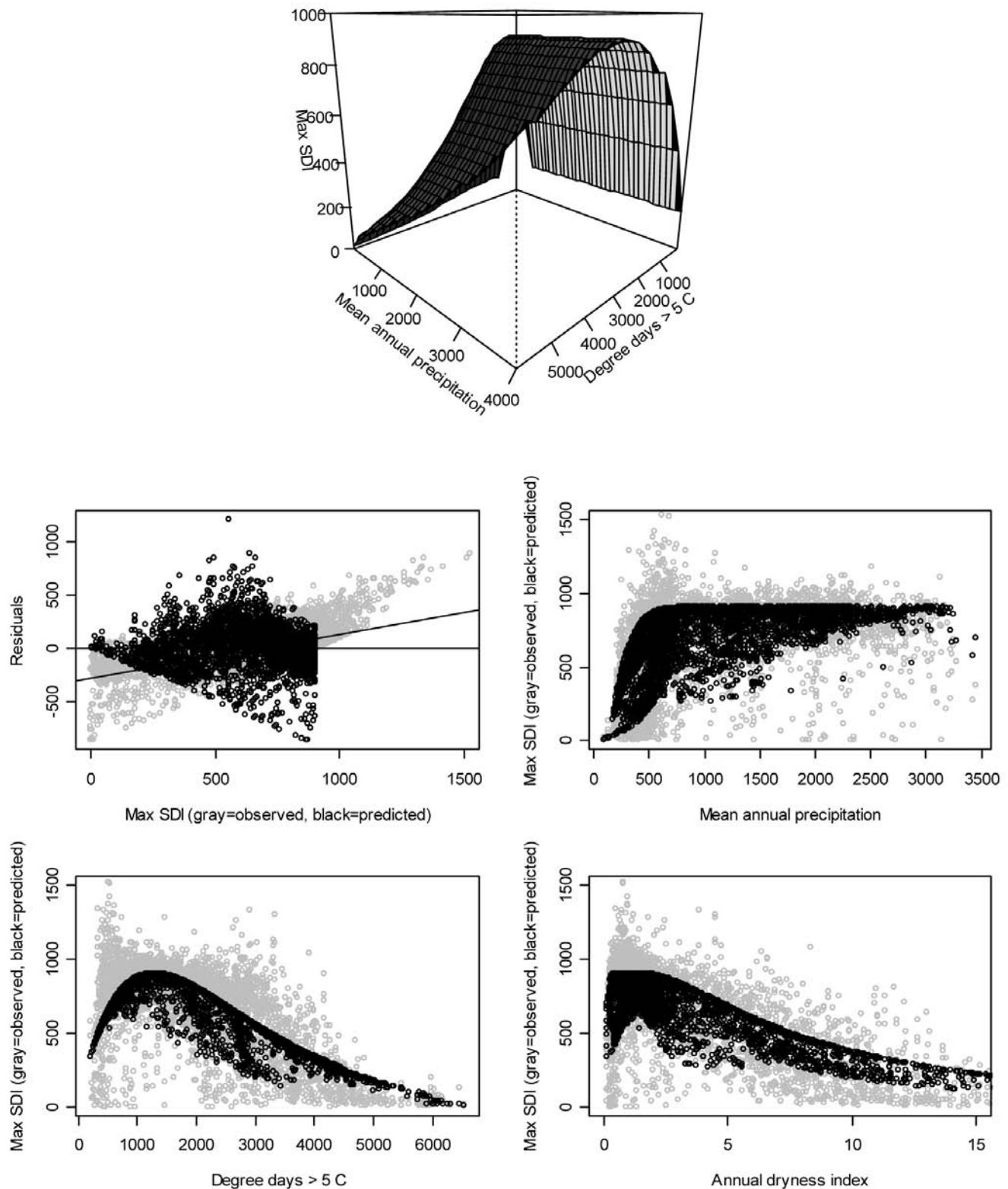


Figure 2—The top graphs predicted values of MaxSDI (Equation 1) plotted over mean annual precipitation (MAP) and degree days > 5 °C (DD5). In the rest of the panels, gray is the observed data and black is the predicted. The middle row left panel displays the residuals with a flat reference line and a diagonal line that illustrates bias. The predicted values are plotted over the predictor variables in the middle right and lower left panels. The last plot (lower right) is predicted plotted over annual dryness index (ADI) even though that variable was not included in the regression.

value of the index increases. We plotted MaxSDI over ADI to illustrate the relationship (fig. 2, lower right), but we did not directly include this ratio as a predictor.

Figure 3 maps the predicted change in MaxSDI for areas currently considered forested or woodlands (Brown and others 1998) in the Western United States using Equation 1. The period of change is from climate normal period (1961 to 1990), to the year 2060 as predicted by the climate model of Rehfeldt (2006). The projected changes are quite large and beg a question regarding how much the equation is being used to extrapolate into future climates. Figure 4 (left) is a scatter plot of the observations used to calibrate Equation 1 designed to show the range of MAP and DD5 measurements. Four example locations were picked to illustrate that in some cases, for example, in the Olympic Mountains of western Washington State the current climate is quite unique in the Western United States, with very high precipitation and low heat. Increases in DD5 and MAP indicated by the short vector do indeed suggest that the model is being used to extrapolate beyond contemporary experience. But the other three locations are within the range of data and exemplify a large percentage of the mapped changes. The right side of figure 4 charts the MaxSDI values for all four locations now and in the future. In general, increases in MaxSDI are consistent with areas that are currently cold and wet that will become warmer and still have enough precipitation to support forests. Decreases in MaxSDI are generally consistent with places that are already hot, are projected to become hotter, and any increase in precipitation will not significantly offset the increase in heat. This work does not account for changes in species composition that may be necessary to actually see any gains in MaxSDI or that might result from losses.

MaxSDI is not used in every variant of FVS as some use basal area maximum (Crookston and Dixon 2005). Note that while these two measures are not identical, they are strongly related and there is little doubt that conclusions reached by studying MaxSDI apply to maximum basal area as well.

Change in Growth Rates

Growth increment in FVS is a function of three basic factors: tree size (represented by diameter, height, age, or these in some combinations), competition (measured by stand density and basal area in larger trees), and site quality (measured as site index or habitat type, slope, elevation, and other factors). The model formulations are designed to predict increment as tree size, competition, or both change, but not designed to allow for site quality to change assuming that it will remain constant over time. As we have shown, that assumption under climate change is not defensible. Crookston and others (2007) did a preliminary analysis of the diameter increment of *P. menziesii*. They refit the increment equation in FVS (Wykoff 1990; Stage and Wykoff 1998) by replacing the static site quality measurements with mean annual temperature and precipitation. Although preliminary, plots made using the equation provide some insights (fig. 5). First, the FIA data used to calibrate the equation did not support the notion that growth will decline with temperature increases, although it will increase with increased precipitation. This result defies growth theory. Surely, as temperature increases beyond the limits of a tree to cope, the result will be lower growth. Furthermore, the adaptive response of individual trees, measured by the response for individual genotypes, determines the individual growth response to climate change (Langlet 1936; Rehfeldt and others 1999; 2002, 2003). Genetics research supports a bell-shaped curve for growth response on a temperature gradient, with different maxima for each genotype.

We conclude that a combination of information from genetics research, growth theory, and observations like those from FIA will need to be combined to realistically model growth. Proper modeling of mortality is also necessary. The growth rates of trees that recently died are normally not recorded and are therefore observations of growth for dying trees are rare in the data used to calibrate the growth model. Statistical analyses of these data lead to model parameterizations that do not reflect slowing of growth as trees die. The mortality model, therefore, also needs to be adjusted so that trees are predicted to die as conditions change from those that support growth to conditions that do not support growth.

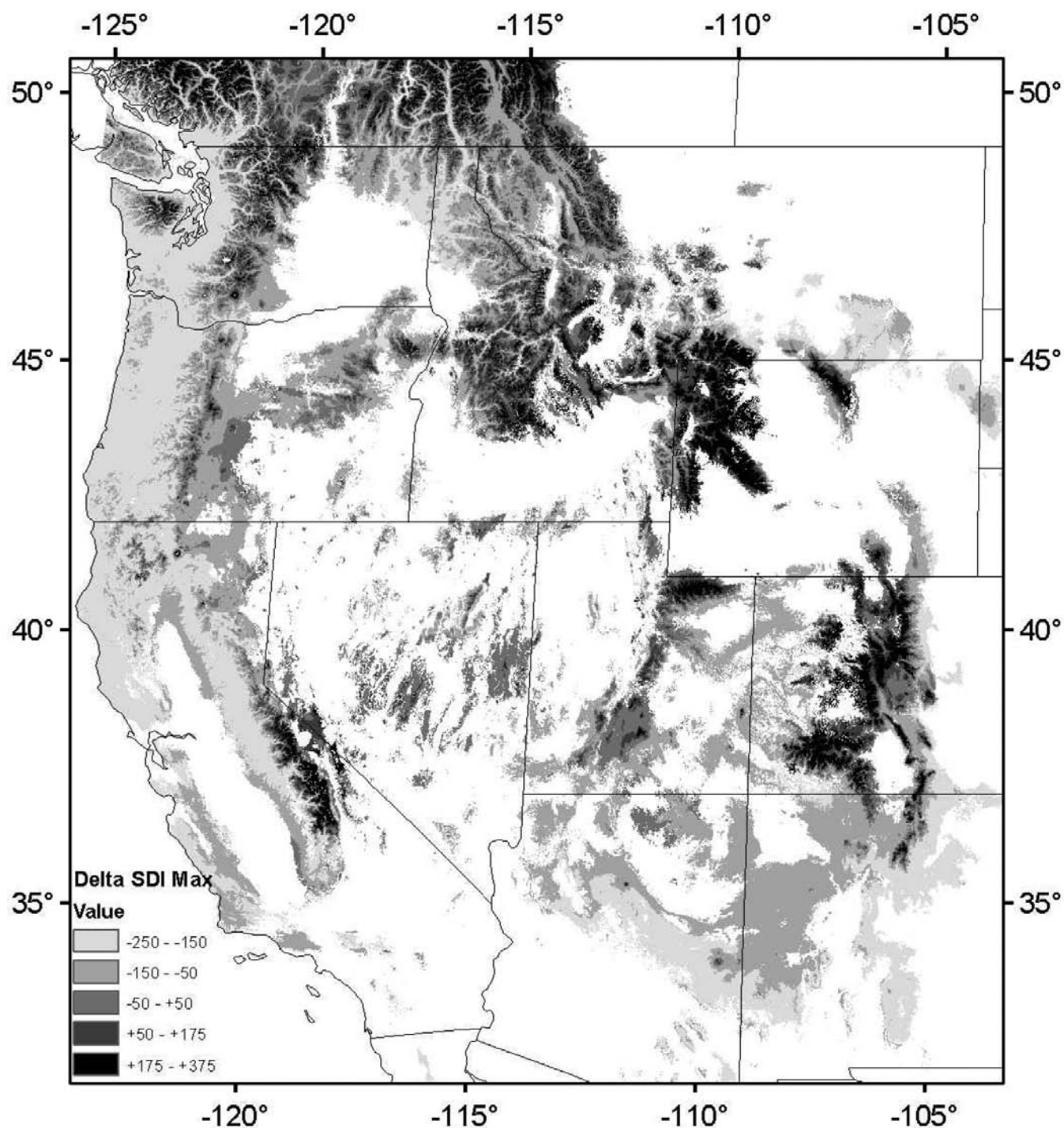


Figure 3—Predicted change in the MaxSDI for areas currently considered forest or woodlands for the 1960–1990 climate normal period to the year 2060, using the spline model of Rehfeldt (2006) and the average of the predictions of two global circulation models run under a “business as usual” scenario.

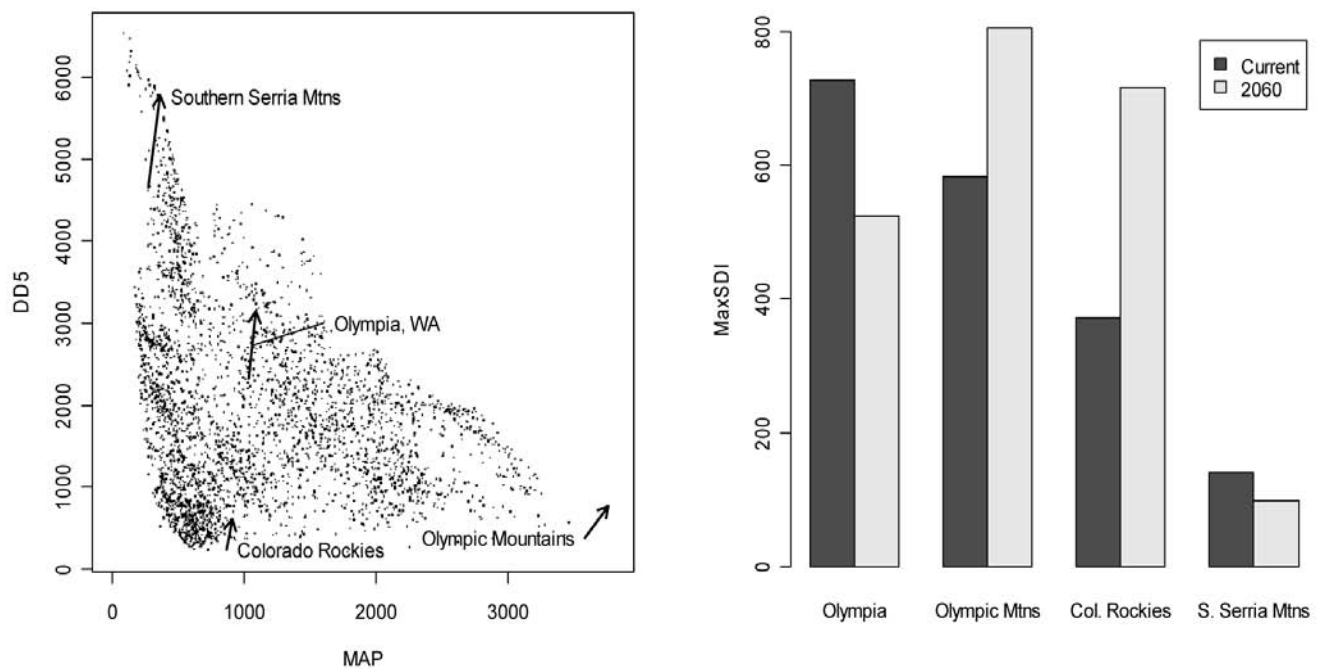


Figure 4—The left side is a scatter plot of the observations used to calibrate Equation 1 with the predicted change in MAP and DD5 from current climate to 2060 indicated with short vectors for four example locations. The bar chart on the right shows the predicted change in MaxSDI for the four locations. Changes predicted for the Olympic Mountains are slightly beyond the range of the data while the others are within the range of observations.

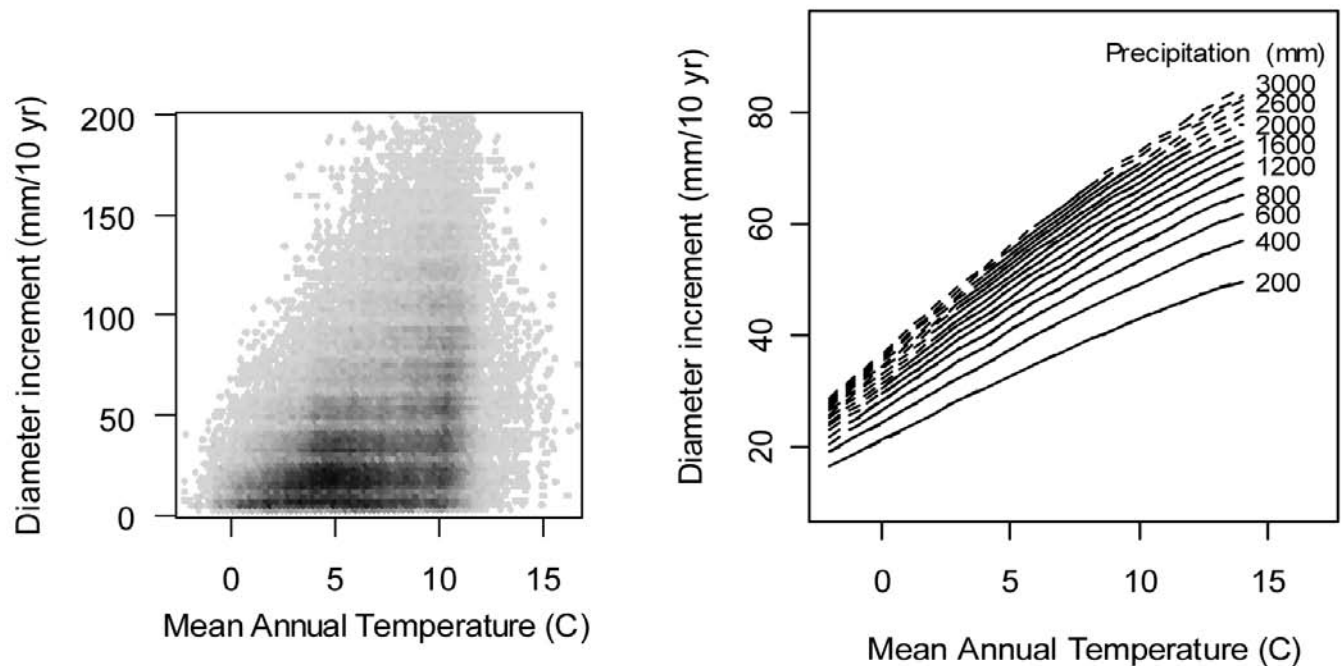


Figure 5—The left side is a scatter plot of the observations used to calibrate a diameter increment equation and the right side is the response of increment to mean annual temperature (MAT) and MAP (from Crookston and others, in press).

FVS Components and Ideas for Change

Design Criteria

In contemplating the design of a new FVS methodology that is sensitive to climate change, several factors come to mind.

- The overall needs met by current FVS variants will remain; sensitivity to climate change must be added.
- There should be no “built in” climate change scenario. FVS must be programmed to use the outputs produced by these models and users need the ability to choose the climate change scenario they wish to run.
- The model should be consistent with current variants when run under a no climate change scenario. While this is an important goal, it will be hard to reach as differences in predictions are inevitable.
- Research indicates that genetics play a major role in determining the growth of trees when site conditions change. Some species, for example *P. menziesii*, are genetic specialists where sub populations of the species are closely tuned to the climatic regime to which they are adapted. FVS will need to take into account the climate associated with the sub-population of a species; it will not be sufficient to account for climate at the species level.
- There are several extensions to FVS that represent insect pests, pathogens, and notably fire and fuels (for an overview, see Crookston and Dixon 2005, p. 64). These extensions make use of many of the same static measures of site quality, notably habitat type/plant association and forest type, used by the base model. Any changes in the base model that represent changing site quality should be made in a way that the extensions can use the results.

Meeting these design criteria is a tall order and likely beyond the scope of first versions. Here are our speculative ideas on how to proceed.

Diameter and Height Increment

The preliminary analysis of increment presented above offers suitable direction to take for every species in FVS, however, it is likely that different climate variables will be important among species. We plan to compile and analyze contemporary observations of growth on individual trees using currently known methods to represent competition and size while introducing new methods to represent site through climate. (see Froese 2003 for a first attempt at this work). While this approach promises to capture the effect of climate on increment, it will not capture the effect of changing CO₂ or other resources that control tree growth.

Some species have strong genotypic adaptation to narrow portions of the environmental range evident for the species as a whole and that this variation is directly related to growth (Monserud and Rehfeldt 1990). Almost all of the available observations of growth record the species of the tree, not the genotype. Crookston and others (2007) addressed this issue and offered a possible solution for *P. menziesii* that would work for other species where sufficient data are available from common garden experiments. While a structure that accommodates these kinds of relationships can be included, data to calibrate the relationships are not generally available for many species. Including what is known about these relationships must be an objective of this work.

Mortality

Many current mortality models in FVS use MaxSDI as a key driver. The preliminary analysis described above holds some promise that climate can be used to predict MaxSDI. Warming temperatures and changes in precipitation can then have direct influences on mortality rates. In addition, the recent work of Rehfeldt and others (2006), plus some as yet unpublished results, indicate that species' realized niche space can be predicted using climate. We believe that climate changes can be translated into changes in the likelihood that a species can exist at a given location. Reductions in the probability that a species exists would increase the probability of mortality, and *visa versa*. This approach leaves unanswered the role of interspecific competition. Currently growing trees (trees that provide us with contemporary evidence) generally have potential niche spaces that

are significantly larger than those evident in inventory data. An empirically calibrated model like the one we envision would miss this factor. We see no solution to this issue other than to press on and push for the installation of the necessary field studies that would allow us to measure the difference between realized and potential niche. In cases where the relationships are already known, they can be taken into account in the model. Other cases will need to wait for the necessary evidence.

Regeneration Establishment

This model component predicts the number and species of newly established trees on a site. A model that purports to appropriately represent climate change in forecasts of forest species and size composition must contain a reasonable establishment model. We intend to use the same general information used to model mortality, but in a complimentary way. Stands that are under stocked will be restocked with species that have high probability of existing in the climate regime. The current methods used in FVS to model establishment contain two approaches. In the so called “full establishment” model, the model predicts the number, size, and species of trees one would expect to find at a given time past a disturbance of known character. In the other, users specify this information thereby simulating what they expect to occur. Our first step will be to include the partial model but our longer term plan is to provide a full establishment model. An important assumption of this effort is that when trees of a given species are established, they will be of proper genetic characteristics for the climate to which they are established.

Conclusions

Climate is changing (IPCC 2007a); climate affects birth, growth, and mortality of trees; FVS represents those processes, and therefore FVS must be adapted to use climate measures as predictor variables. Otherwise, FVS will lack relevance to forest managers that it has had in the past. The lack of relevance will be directly tied to the fact that FVS will be ignoring a key process (climate change) that directly influences key processes the model is designed to represent. Furthermore, we understand this to be the case, so modification of the model is essential if FVS is to be viewed as containing the scientific evidence relevant to its purposes and uses. Therefore, plans are being made to rebuild FVS so that forest managers will continue to have this important tool for aiding their management planning and activities. It will help inform foresters and other natural resource managers about the implications climate change will have on the ecosystems they are charged with managing.

References

- Brown, D.E.; Reichenbacher, F.; Franson, S.E. 1998. *A classification of North American biotic communities*. Salt Lake City, UT: University of Utah Press. 141 p.
- Crookston, N.L.; Dixon, G.E. 2005. The forest vegetation simulator: A review of its structure, content, and applications. *Computers and Electronics in Agriculture*. 49:60–80.
- Crookston, N.L.; Havis, R.N., comps. 2002. Second Forest Vegetation Simulator conference; 2002 February 12–14; Fort Collins, CO. Proc. RMRS-P-25. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 208 p.
- Crookston, N.L.; Rehfeldt, G.E.; Warwell, M.V. 2007. Using Forest Inventory and Analysis Data to Model Plant-Climate Relationships. In: *Proceedings of the seventh annual forest inventory and analysis symposium*; 2005 October 3–6; Portland, ME. Gen. Tech. Rep. WO-77. Washington, DC: U.S. Department of Agriculture, Forest Service: 243–250.
- Dixon, Gary E., comp. 2003. *Essential FVS: A User's Guide to the Forest Vegetation Simulator*. Internal Rep. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Forest Management Service Center. 193 p.
- Flato, G.M.; Boer, G.J. 2001. Warming asymmetry in climate change simulations. *Geophysical Research Letters*. 28:195–198.
- Froese, R.E. 2003. Re-engineering the prognosis basal area increment model for the Inland Empire. Moscow: University of Idaho. 113 p. Dissertation.
- Gordon, C.; Cooper, C.; Senior, C.A.; Banks, H.; Gregory, J.M.; Johns, T.C.; Mitchell, J.F.B.; Wood, R.A. 2000. The simulation of SST, sea-ice extents and ocean heat transport in a version of the Hadley Centre coupled model without flux adjustments. *Climate Dynamics*. 16:147–168.
- Holdridge, L.R. 1947. Determination of world plant formations from simple climatic data. *Science*. 105:367–368.

- Intergovernmental Panel on Climate Change. 2007a. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Summary for Policymakers. http://www.ipcc.ch/WG1_SPM_17Apr07.pdf
- Intergovernmental Panel on Climate Change. 2007b. Climate change 2007: Impacts, Adaptation and Vulnerability Working Group II Contribution to the Intergovernmental Panel on Climate Change Fourth Assessment Report Summary for Policymakers. <http://www.ipcc.ch/SPM13apr07.pdf>
- Langlet, O. 1936. Studies on the physiologic variability and their relationship with the climate. Meddelelser Statens Skogsförsöksanstalt. 29:217–470. [In Swedish].
- Monserud, R.A. 2003. Evaluating forest models in a sustainable forest management context. FBMIS 1:35–47. Online: http://www.fbmis.info/A/3_1_MonserudR_1
- Monserud, R.A.; Rehfeldt, G.E. 1990. Genetic and environmental components of variation of site index in Inland Douglas-fir. Forest Science. 36(1):1–9.
- Rehfeldt, G.E. 2006. A spline model of climate for western United States. Gen. Tech. Rep. RMRS-GTR-165. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research. 21 p.
- Rehfeldt, G.E.; Crookston, N.L.; Warwell, M.V.; Evans, J.S. 2006. Empirical analyses of plant-climate relationships for the Western United States. International Journal of Plant Science. 167(6):1123–1150.
- Rehfeldt, G.E.; Tchebakova, N.M.; Milyutin, L.I.; Parfenova, E.I.; Wykoff, W.R.; Kouzmina, N.A. 2003. Assessing population responses to climate in *Pinus sylvestris* and *Larix* spp. of Eurasia with climate-transfer models. Eurasian Journal of Forest Research. 6(2):83–98.
- Rehfeldt, G.E.; Tchebakova, N.M.; Parfenova, Y.I.; Wykoff, W.R.; Kouzmina, N.A.; Milyutin, L.I. 2002. Intraspecific responses to climate in *Pinus sylvestris*. Global Change Biology. 8:912–929.
- Rehfeldt, G.E.; Ying, C.C.; Spittlehouse, D.L.; Hamilton, D.A. 1999. Genetic responses to climate in *Pinus contorta*: niche breadth, climate change, and reforestation. Ecological Monographs. 69(3):375–407.
- Reineke, L.H. 1933. Perfecting a stand-density index for even-aged forests. Journal of Agricultural Research. 46:627–638.
- Stage, A.R.; Wykoff, W.R. 1998. Adapting distance-independent forest growth models to represent spatial variability: effects of sampling design on model coefficients. Forest Science. 44(2):224–238.
- Teck, R.; Moeur, M.; Adams, J., comps. 1997. Proceedings: Forest Vegetation Simulator Conference; February 3–7, 1997; Fort Collins, CO. Gen. Tech. Report INT-GTR-373. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 222 p.
- Wykoff, W.R. 1990. A basal area increment model for individual conifers in the Northern Rocky Mountains. Forest Science. 36(4):1077–1104.