Development of a Climate–Driven Forest Vegetation Simulator

The Priest River Experimental Forest 2008 Workshop Results

Prepared for

Rocky Mountain Research Station
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Fort Collins, CO

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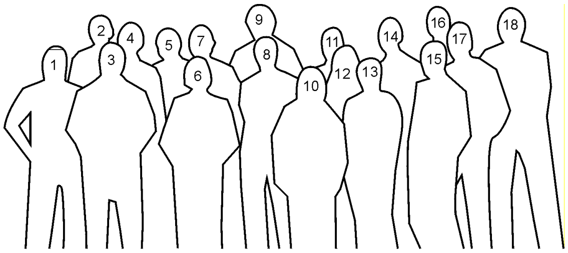

1: Brad StClair; 2 – Dennis Ferguson; 3 – Bob Monserud; 4 – Peter Gould; 5 – Doug Maguire; 6 – Erin Smith-Mateja; 7 – Aaron Weiskittel; 8 – Fred Martin; 9 – Doug Berglund; 10 – Mee-Sook Kim; 11 – Phil Radtke; 12 – Laura Leites; 13 – Megan Roessing; 14 – Colin Daniel; 15 – Glenn Howe; 16 – Dave Cawrse; 17 – Don Robinson; 18 – Nick Crookston

Missing: Kelsey Milner

1. Introduction

"Make everything as simple as possible, but not simpler." *– Albert Einstein*

This report documents the discussions and recommendations of a workshop held at the Priest River Experimental Forest from September 9-11, 2008. The purpose of the workshop was to further define approaches for building a climate-driven version of the Forest Vegetation Simulator (FVS, Crookston and Dixon 2005), building upon a similar workshop exercise in 2007. A list of the workshop participants is provided in Appendix A.

The workshop structure was based upon a process first outlined by Holling (1978) for developing interdisciplinary models in support of natural resource management. With this process, workshop participants are led through a series of exercises with the goal of specifying the bounds of the model, and provide an overview of its major components and their inter-relationships. The specific goals of this workshop were to discuss and identify:

1. the key processes that should be represented in the model;
2. the linkages between the processes using a "Looking Outward Matrix"; and
3. the candidate approaches, options and knowledge gaps for representing the key processes.

The remainder of this report is structured as follows:

- Section 2 lists the main points of talks given on the first day of the workshop, reporting research progress since the 2007 workshop.
- Section 3 briefly reiterates the results of the discussion from the 2007 workshop that considered model temporal and spatial bounding, management actions and key indicators of model behavior. The workshop participants briefly reviewed and ratified these at the beginning of the workshop.
- Section 4 describes the key processes to be addressed in a new climate-driven version of FVS – these include regeneration, tree growth, mortality, site potential and genetic adaptation.
- Section 5 lists the next steps identified by participants for developing the model.

2. Reporting

2.1 Potential change in lodgepole pine site index and distribution under climate change in Alberta

– Bob Monserud

Bob reported on work he and colleagues have done examining variation in lodgepole pine range site productivity under climate change scenarios in Alberta, Canada. They mapped smoothed SI and climate across the province and correlated SI with the Julian day when Growing Degree Days (GDD_5) reaches 100. They also correlated species range with Dryness Index (GDD_5/Annual Precipitation).

2.2 FVS-BGC a duel resolution hybrid model with physiological and biometrical growth engines

– Kelsey Milner

Kelsey reviewed a decade of research he has done to try to improve the vegetation dynamics of FVS, incorporating the BGC physiological model. The hybridization creates a climate sensitive model. The model requires daily climate data (temperature, precipitation, light) and soil information for the site. Allometric relationships are species-specific; some physiological parameters are life-form specific (grass, shrub, trees) while others are common to all life forms.

2.3 Use of simplified process-based models to improve empirical growth models

– Aaron Weiskittel

Aaron reviewed the main features of empirical and process-based models, and the efforts to create hybrid approaches to bridge gaps between them. He went on to describe the 3-PG model, which has a fairly simple structure and monthly time step. The model has had some successes but also has some fundamental problems which he is working to address.

2.4 Modeling height growth responses to change in climate of interior Douglas-fir populations

– Laura Leites

Laura spoke about research she and colleagues have done, analyzing provenance data to assess the effects of climate change on growth of Douglas-fir populations. She reviewed four previous provenance studies and went on to describe her efforts to build climate-sensitive predictive models for 228 populations using linear mixed-effects models.

2.5 Decision support tools for determining appropriate provenances for future climates

– Glenn Howe & Brad St.Clair

Glenn spoke about their efforts to develop the National Forest Genetics Data Center to provide an intellectual repository for long-term provenance and genecology studies, web-based decision support tools, and related extension training programs. He also shared recent results from BC researchers (O'Neill and others) incorporating provenance, sensitivity to site climate and future climate to predict changes in productivity.

2.6 Growth multipliers: when and why they're used and how they work

– Peter Gould

Using 3 different scenarios, Peter reviewed the use of multipliers to adjust the behavior of models like FVS and ORGANON. Multipliers can be applied to diameter-growth, height-growth and mortality and are most commonly applied when the default model parameters fail to capture changes in traits, disease or climate. Multipliers do not change overall growth patterns, maximum BA or SDI. They ***do*** alter individual trees' trajectories and can result in an individual tree (or stand) reaching an end-state sooner. This can create timing differences for self-thinning and changes in species dominance

2.7 Testing an approach for making FVS climate sensitive

– Erin Smith-Mateja

Erin described development work she and colleagues have done to begin to modify FVS to accommodate climate change: site productivity can now be changed using the SetSite keyword. She showed examples of results for the North Idaho and Central Rockies variants, where habitats were shifted by one or two zones. The models are sensitive to shifts toward warmer and cooler habitats, but not always in the same way at all locations. End-users will probably be most comfortable with climate scenarios implemented as changes in diameter growth and mortality that are created by *experts*; as most users do not feel confident enough to choose parameters on their own.

3. Model Bounding, Inputs & Outputs

This section recapitulates the results of the model bounding decisions made at the 2007 workshop (ESSA Technologies 2007). The workshop participants reviewed these boundaries briefly and found that they remained valid.

3.1 Management actions

A new version of FVS should retain all of the currently supported management actions, including various ways of harvesting and thinning, pruning, fertilization (for some variants), regeneration (for some variants) and FFE fuel management actions. In addition, the following are possible new management actions: location of seed source provenance, specifying that seed comes from a source other than local.

3.2 Indicators

The new version of FVS should retain all of the current stand and individual tree indicators: volume, basal area, canopy cover, diameter, species, height, crown length, crown width, height increment, diameter increment, estimated background mortality, crown bulk density, fuel loading and size of carbon pools. Possible new FVS indicators include the "potential" future species composition – what could potentially grow (similar to the current FFE potential fire report) and leaf area index (LAI).

3.3 Space and time

The current *spatial resolution* of FVS is a stand or plot (*i.e.*, cluster) of trees. The current *spatial extent* of FVS is a collection of stands. Participants agreed that the current spatial extent and resolution would continue to be appropriate for a climate-driven version of FVS. For development purposes, the North Idaho model is used as the reference model, recognizing that eventually all FVS variants will need to be climate-sensitive.

The *temporal resolution* of the model is defined as the smallest unit of time over which the model will be required to make predictions for the user, while the *temporal extent* of the model is the time period over which the system should be capable of making predictions. Participants agreed that the temporal resolution, currently 5-10 years, may need to change for a climate-driven model in order to handle climate inputs. In addition, some modeling approaches might require a daily internal time step. The suggested new default temporal resolution would likely be one year. The temporal extent of the model may remain unchanged, and most participants were comfortable with a 50-100 year extent under changed climatic scenarios.

3.4 Inputs and outputs

The current model's primary input is an inventory of existing trees for a site, supplemented by location and site information. Data quantifying climate will be a new input to the model, although the actual implementation and temporal resolution (daily, monthly or annual) will depend on the temporal needs of the submodels. The primary output for the current model is a report that provides detailed species and size composition of trees at each time step of a simulation. These outputs will continue and may be supplemented by additional diagnostic output relevant to climate and adaptation, as discussed in the next section.

4. Key Processes

To introduce the effects of climate, three concepts were proposed:

1. **Species-specific site carrying capacity** will change with climate, and this will affect tree survival, since the FVS tree mortality model is (and will continue to be) sensitive to carrying capacity.
2. Climate change will modify **how well individual trees are adapted to a site**. The model will therefore modify individual tree growth rate as a function of the "distance" – measured on climatic axes – between the climate at an individual's contemporary climate ("baseline", "ancestral") seed source and the projected future climate.
3. An **individual tree's growth rate will be directly related to climate** and therefore the new model will change growth rates as climate changes, regardless of seed source.

These concepts build upon these discussions and decisions made at the 2007 workshop (ESSA Technologies 2007). The component processes and interactions defined at the 2007 workshop are represented through the Looking Outward Matrix shown in Table 1. The purpose of this matrix is to simplify a complex problem by first defining and circumscribing the component sub-processes and then defining the interactions between the components, often stated in the form:

Information X is created and passed **from** Submodel Y and given **to** Submodel Z

In Table 1, these are structured using rows ("From") and columns ("To") with the submodel processes themselves on the diagonal of the table. External inputs like climate and soil data; and external outputs like reports are also listed at the top and right side of the table.

Besides refining the Looking Outward Matrix, the workshop participants also discussed the inclusion of concepts such as large-scale disturbance and the role of understory vegetation (grass and shrubs) that may become important under novel climate regimes, especially those that might result in the loss of tree cover. Notwithstanding their possible importance, they were generally deferred.

The following sections elaborate on the possible or proposed dynamics of each of the five submodels along with a description of linkages with other submodels. The subsections are presented in the same order in which they are found in Table 1.

		To Submodel					
		Regeneration	**Tree Growth**	**Tree Mortality**	**Site Potential**	**Tree Adaptation**	
	Input to Submodel		Climate at the site	Climate at the site	Climate at the site; Soil water carrying capacity	Climate at the site and at the seed source for each tree	**Output Reports**
From Submodel	**Regeneration**	Regeneration submodel	New regeneration and seed zone of origin	Seed zone of origin			Summary of new regeneration; provenance; growth relative to potential
	Tree Growth	Stand structure, composition	Tree Growth submodel	Current density and growth rates			Summary of growth rates, size and species composition
	Tree Mortality			Tree Mortality submodel			Summary of mortality rates
	Site Potential	Competition from grasses, shrubs	Potential growth rate (site index)	Carrying capacity (*maxBA* or *maxSDI*)	Site Potential submodel		Summary of site potential
	Tree Adaptation	Species climatic zone (yes or no)?	Relative or absolute gain or loss in diameter and height growth.	Species climatic zone (yes or no)?		Tree Adaptation submodel	Summary of individual gain/loss relative to index?

Table 1 – The looking outward matrix of proposed model components and their interactions. See the preceding page for additional explanation of the matrix.

4.1 Regeneration

Prior to the 2008 workshop, a Draft Conceptual Framework (Appendix B) was circulated, in which it was proposed that Regeneration be deferred to a future round of model changes. However, the participants felt that it was important to add a more substantial place holder for this component, even if it is implemented later. Table 1 reflects this view, although the implementation details still remain to be made at a later date. The sections below note some of the probable attributes and considerations necessary to climate-sensitive regeneration models, regardless of their details.

Input from Tree Adaptation

A list of species that are potentially present at the site (or alternatively, provenances planted through assisted migration) would likely be one of the inputs to a climate-sensitive Regeneration submodel. Such lists are already used by FVS regeneration models, but are currently indexed to ecologically-based static habitat zones. As a surrogate for lists based on fixed habitat classes, the Tree Adaptation submodel could provide a list of stocking adjustment multipliers for candidate species and provenances. Along with current stand structure and the actual stream of future climate, very low multipliers might be used to condition the presence of actual surviving seedlings at the site.

Input from Tree Growth

Stand composition (stems ac^{-1} by species) is a frequent component of current regeneration models and is likely to continue to play a role in regeneration models, particularly those where the future climate is fairly similar to the current climate and locally sourced seed remains viable.

Input from Site Potential

In a working climate-sensitive regeneration model, it will also be necessary to consider the influence of other understory vegetation types (grass and shrubs) that may be predicted by the Site Potential submodel. These could condition the probability of successful germination.

Output to Tree Growth

The current FVS regeneration models separate the simulation of the net effects of germination and initial growth of regenerating seedlings from the subsequent growth of small and large trees. At the end of each model timestep, regenerating trees are promoted to the small tree model, at which time they begin to be simulated as individual trees. Barring a fundamental change in model architecture, the climate-sensitive FVS will need to accomplish the same handoff, but will need to be careful in its approach and treatment of trees before and after they make this transition, so that a consistent set of climatic sensitivities and constraints are applied before and after the handoff.

4.2 Tree Growth

Two complementary concepts – *species response* to climate and *site response* to climate – are proposed to make the Tree Growth submodel climate-sensitive. To model species response, the Tree Adaptation submodel will provide information about each provenance's current climate sensitivity relative to the population and contemporary (historic) climate for the provenance. This will result in species-based multipliers that will be applied to predicted diameter or height growth.

The concepts of location and fixed habitat class are embedded in the equations of the current North Idaho FVS tree growth models, as are coefficients fitted and indexed to combinations of species and location.

To model site response, the Site Potential submodel will provide an additional dynamic site-multiplier that will further scale predicted growth through its effect on site quality.

Creating site sensitivity could be approached through a complete refitting of the models, replacing habitat and location variables with climatic and soil variables. As a simpler first alternative though, it may be possible to introduce location-based (*i.e.*, habitat code) modifiers that bridge this gap. For each existing habitat type, these multipliers would provide a productivity-based multiplier based on the change in maximum basal area (BA, or Stand Density Index, SDI) for the location, compared to the historic site productivity for the zone. This concept is discussed in more detail below and in Section 4.4.

Species and site multipliers will be applied independently (recognizing that interactions may be present). When grown within their provenance and under historic climate, individuals will grow just the way they do in the current FVS, assuming current model forms and coefficients remain unchanged. Under warming scenarios, some climate regimes may lead to increased growth rates for some species through increased species or site multipliers, while some species may experience decreased growth rates due to one or both multipliers.

Input from Regeneration

Small trees created through regeneration will periodically be added to the list of individual trees. Their subsequent height and diameter growth and mortality will be subject to the same multiplicative species and site multipliers as all other trees already simulated by the small and large tree models. These regeneration trees will also be indexed by their provenance and will therefore follow the growth behavior appropriate to their provenance.

Input from Site Potential

The Site Potential submodel will provide a single scalar multiplier reflecting changes in growth rate under changing climate, so that changes to site productivity will adjust the growth rate of individual trees, independent (and in addition to) climate-driven changes to the individual growth rate for species or provenances.

There are alternative approaches for such guidance. One approach would be to simply use the proportional change in carrying capacity (relative to historical) as a multiplier, ultimately leaving the Mortality submodel to compensate as necessary for possible overshoot as the stand moves toward carrying capacity. A more nuanced approach could include the difference between current BA (or SDI) and climate-sensitive maximum BA to gradually constrain the growth modification multipliers (much same way as some parts of the current Mortality submodel work). This second approach would require the Site Potential submodel to pass slightly different information to the Tree Growth submodel.

Input from Tree Adaptation

The Tree Adaptation submodel will provide a set of seed-zone multipliers that will be applied to predicted diameter or height growth. The multiplier's value will be 1.0 when the provenance is grown or planted within its historic provenance under contemporary climate. Depending on the shape of the functional response and climate scenario, individual tree growth may increase or decrease for differing provenances or under changed climate regimes (see Figure 2).

The response function information (*i.e.*, its provenance and function parameters) will be maintained as a property of each tree in the simulation. Thus, even if a tree is grown at new sites with novel climates, it will "remember" its intrinsic response function and will respond appropriately to climate change.

Input from External Climate Data

Climate for the site and year will be a direct driver of response functions of the Tree Adaptation and Site Potential submodels. If individuals from multiple seed-zones are grown together, then those individuals will follow the climate response appropriate to their provenance location. A variety of climate inputs are possible, ranging from a simple stream of Mean Annual Temperature, to measures of monthly temperature and moisture and other threshold-base measures such as degree-days above ***x*** °C.

Output to Regeneration

Current stand composition of trees (including their seed-source) will be provided to the Regeneration submodel.

Output to Mortality

Stand density and individual tree growth rates are currently provided as inputs to the FVS Mortality submodel and are likely to remain so in the climate-sensitive Mortality submodel.

4.3 Tree Mortality

The current FVS Tree Mortality submodel is already sensitive to site potential – expressed as maximum basal area or stand density index – as well as individual characteristics like diameter and relative growth rate. The climate-sensitive Mortality submodel will incorporate these existing variables through the Tree Growth and Site Potential submodels, both of which will be climate-sensitive. Because the Site Potential submodel will adjust carrying capacity for novel climates, the behavior of the stand-stocking component of the Mortality model will also show climate-sensitivity.

The Mortality submodel could also incorporate information from the Tree Adaptation submodel in the same way that the Tree Growth submodel does. However, it is not yet clear whether such a direct link is necessary, since it could conceptually be double-counting effects that are already indirectly passed via the other two submodels. Sensitivity analysis may be required to resolve whether or not this linkage is needed.

A possible difficulty in implementing a new Mortality model is the frequent emphasis on average climate (e.g., MAT) as an input driver for many models, whereas mortality may be more influenced by extreme events (heat, cold and drought) that are not captured by the mean. Since most climate data sets include some measures of extreme temperature, it may be more suitable to include measures such as “minimum January temperature” to capture extremes.

Input from Tree Growth

The climate-sensitive Mortality submodel will incorporate individual diameter and relative growth rate, as well as stand attributes like current basal area and current stand density index, just as the current FVS uses them. The individual tree attributes passed to the Mortality submodel will already have been adjusted by the Tree Adaptation and Site Potential submodels.

Input from Site Potential

The climate-sensitive Mortality submodel of FVS will incorporate the concepts of maximum BA and maximum SDI, just as the current FVS uses them. However, these stand attributes will have been adjusted by the Site Potential submodel, making them sensitive to climate influence.

Input from Tree Adaptation

As noted above, information from the Tree Adaptation submodel may be used to further adjust predicted mortality the same way that relative growth rate currently contributes to mortality in FVS. This linkage will be developed if the existing indirect linkage (via the Tree Growth submodel) is not adequately reflected in changes in survival.

Input from External Climate Data

External climate data will be necessary if linkage to the Tree Adaptation submodel is required. This data would allow current climate to play a direct role in survival, probably through the same dome-shaped function, where the maximum of the dome corresponds to maximum survival.

4.4 Site Potential

Extensive discussions at the 2008 workshop were based around empirical observations (see Section 2.1) and physiological modeling (see Section 2.3) of site quality, and confirmed the necessity of including climate-mediated changes to site potential as part of the climate-sensitive FVS. Site potential in FVS – expressed as the maximum BA or maximum SDI for a habitat class – has traditionally been static during a simulation. Following discussions at the 2007 workshop a new keyword (SiteSet) was developed, which allowed habitat class (and therefore site potential) to change within a simulation. This keyword was created so that exploratory behavior analyses could begin. (see Section 2.7)

Most of the discussion at the 2008 workshop was centred on the problem of linking primary productivity estimates to more conventional measures of site productivity. If a model is able to predict annual NPP (Net Primary Productivity, g C m^{-2} yr^{-1}) and asymptotic carrying capacity (g C m^{-2}) at the site based on species attributes and functions coupled to a daily or monthly time series of light, temperature and soil moisture, how should that NPP or carrying capacity biomass be first partitioned into the carrying capacity for grasses, shrubs and trees? Assuming it can be partitioned and the carrying capacity of tree plant-forms (g C m^{-2}) obtained, a possible next step would be to create a link function relating carrying capacity and maximum BA calibrated using historical climate and historical site index over all sites used by an FVS variant. (Figure 1) That way the proportion of tree carrying capacity (*e.g.*, 85% or 110%) under the new climate regime could inform the Tree Growth submodel for the existing stand, guiding the stocking trajectory by adjusting the growth of individual trees up or down. Besides biomass (g C m^{-2}), t is also possible that LAI may be an alternative candidate for measuring carrying capacity.

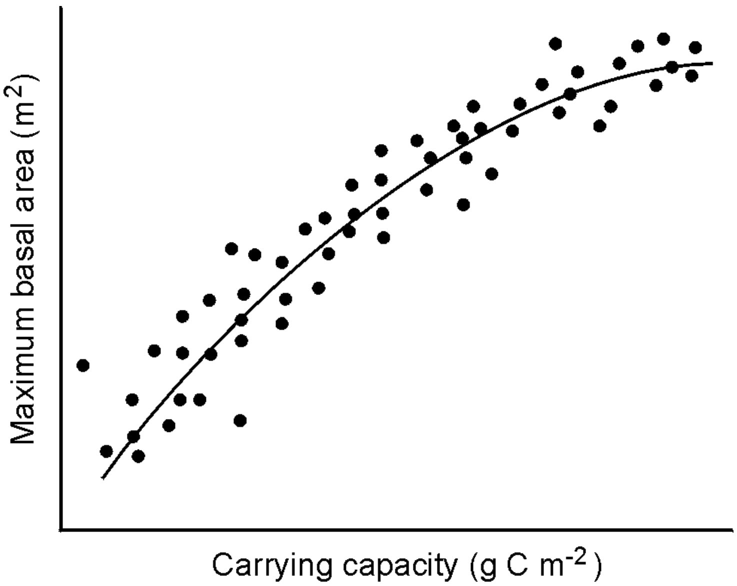

Figure 1. Hypothetical relationship between Carrying Capacity and Maximum Basal Area for each simulated calibration site in the NI-FVS variant. To work, the relationship must be strictly increasing.

Even though the participants were unable to provide a definitive specification for the Site Potential submodel, they were able to agree that it is a necessary component, and that the necessary inputs and outputs of the model can be described without yet knowing the interior structure of the submodel.

Input from External Climate Data

The exact form of climate data used by the Site Potential submodel will depend on the needs of the selected model. Some might require monthly time series of minimum and maximum temperature, precipitation and perhaps soil moisture capacity. Other models might require such data at an even finer daily time scale. The external data will need to be indexed by climate scenario, location and year

Input from External Soil Data

The need for this source of external data (indexed by location, but static with respect to year and climate scenario) will depend on the simplicity or complexity necessary for the Site Potential model that is implemented.

Output to Tree Growth

The Site Potential submodel will provide a scalar multiplier to the Tree Growth submodel, in which the climate-sensitivity of intrinsic site productivity is related to historical carrying capacity and current density. The multiplier will be 1.0 for stands grown under historical climate, but will be lower when carrying capacity is reduced and greater than 1.0 when the carrying capacity is higher relative to the historical maximum.

Output to Tree Mortality

The climate-sensitive Site Potential submodel of FVS will guide the Tree Mortality model through changes to site carrying capacity. The climate-modified maximum BA (or SDI) will therefore modify tree survival as a function of stand stocking, just as the current FVS uses static maximum BA.

Output to Regeneration

If the implementation of the Site Potential model includes the partitioning of biomass among life forms, it may be possible to use the presence of grass and shrub to condition regeneration success.

4.5 Tree Adaptation

The Tree Adaptation model is based on two key concepts: populations and climate-response. The first concept is that some tree species exist as specialists: genetic populations that are superficially identical but which have unique population traits that result in different growth traits in different geographic/climate zones. Douglas-fir was noted as having a number of such populations (geographic provenances) across its entire geographic range, while western white pine was noted as an example in which there is a single population only. Provenance 'awareness' will be introduced as a new tree characteristic in the climate-sensitive FVS model and tree growth will become sensitive to the provenance of seed stock for planting and regeneration. FVS currently uses habitat codes to incorporate site-specific differences in growth rate. Seed zones are typically much smaller than habitat zones and will therefore likely require a new set of indices to track the original seed-zone of inventoried and regenerating trees.

Besides growing according to the population or habitat coefficients for contemporary climate, individuals will also possess their population's genetic traits for climate response. Climate response relationships are often conceptualized using Mean Annual Temperature (MAT) as the independent variable, and it is possible that MAT may be used for this purpose in the Tree Adaptation submodel. However, it is also possible that alternative or additional variables may be necessary, depending on the predictive need they support. For example, it is possible that important traits such as photoperiod response, cold tolerance, drought tolerance (or even disease resistance) may prove to be important to the proper characterization of growth or to the presence or absence of a species on a particular site.

Using such a scheme growth rate can be modified by creating unique functional response curves for the populations of each species. When a population is grown within its provenance using contemporary climate (*i.e.*, ΔMAT °C = 0) it will have a growth rate multiplier of 1.0 by definition. Because populations may have different responses to MAT relative to their provenance, changing the actual site climate from the contemporary (historical) climate will either increase or decrease the multiplier depending on the growth curve parameters (Figure 2). We anticipate that the functional response will be based upon a dome-shaped (single maximum, but not necessarily a simple quadratic) function, normalized to a value of 1.0 for ΔMAT °C = 0. (see Section 2.4; Wang et al. 2006)

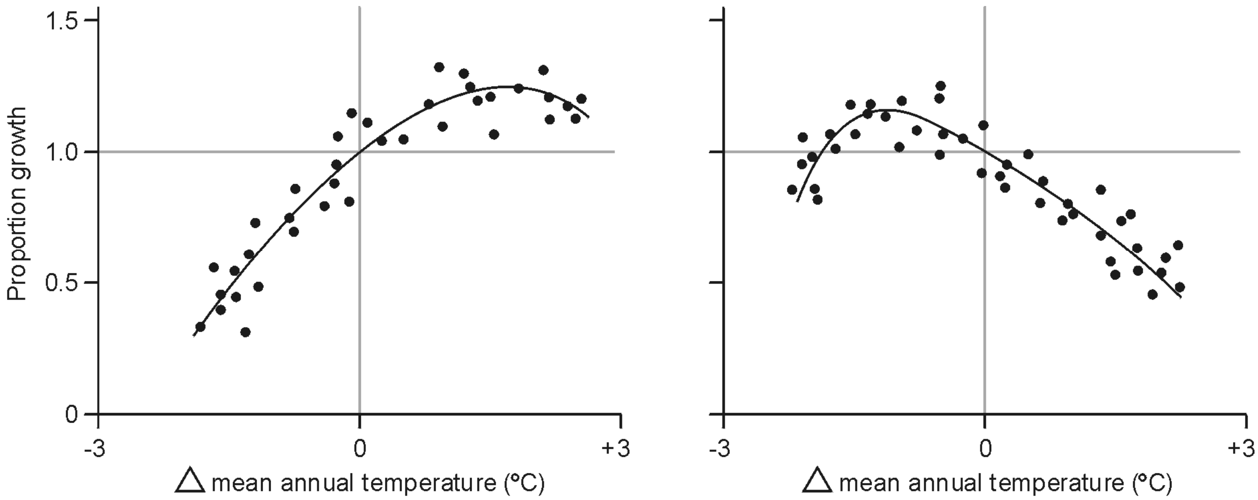

Figure 2c. Example response functions showing the response to changes in MAT for two different populations (left could be at cool end of distribution; right could be at warm end). Response functions have been rescaled so that they have a value of 1.0 at their contemporary climate.

The predictions of the functional response curves of the Tree Adaptation submodel should generally agree with presence-absence maps (Rehfeldt et al. 2006, Iverson et al. 2007) based on contemporary climate. That said, the modelled linkage between contemporary climate and species presence is confounded by the persistence of long-lived trees that can no longer reproduce through seeds (Section 4.1). Upon further analysis and comparison with species maps it may be desirable to select a low cut-off for the functional response curves (*e.g.*, set survival to zero when the response function's growth multiplier is less than 20%). Alternatively, it may be possible to create an analogous link to the Site Potential submodel in which low NPP creates a zero-survival cut off for the species distribution. Regardless of any actual implementation of linkages between functional response curves, climate envelope maps and physiological performance, it should be possible to develop functional response curves that are consistent with maps and productivity estimates produced by physiological models. There is no expectation that the match will be perfect, but the patterns should be consistent.

Output to Regeneration

The Tree Adaptation submodel will provide a set of growth rate multipliers for the climate stream in use by FVS. The Regeneration submodel will use these inputs (along with its own logic) to produce predictions of actual seedlings. Species or provenances with low growth rate multipliers would presumably be less likely to contribute to stand regeneration.

Output to Tree Growth

The Tree Adaptation submodel will provide a set of growth rate multipliers for the climate stream in use by FVS. The Tree Growth submodel will use these inputs to modify the predicted height- and diameter-growth of trees.

Output to Tree Mortality

The Tree Adaptation submodel will provide a set of mortality rate multipliers for the climate stream in use by FVS. The Mortality submodel could use these multipliers to condition the survival of individuals, in the same way that relative growth rate currently contributes to mortality in FVS.

5. Next Steps

The workshop participants developed a list of short and longer-term priorities to allow model development to move forward.

Short Term Priorities

1. Develop a top-10 list of species from a genetic point of view, including bibliography of genetic studies, data, people (Brad StClair, Glenn Howe)
2. Develop a top-20 list of species that need to be modeled (Erin Smith-Mateja, Dave Cawrse)
3. Develop a list for necessary physiological parameter and approaches to carrying capacity, to guide immediate model exploration
4. Continue exploratory work with physiological models (Nick Crookston, Aaron Weiskittel)
5. Identify working data sets – published climate and soils, suitable for use with NI variant initially, along with availability and design scheme for integration into FVS

Longer Term Priorities

1. Develop concepts for including uncertainty (e.g., Monte Carlo, climate scenarios) in model predictions
2. Support for gathering, compiling and carrying out genetic provenance testing and growth studies

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Appendix A – Workshop Participants

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Appendix B – Draft Conceptual Framework

A Conceptual Framework for Modifying the Forest Vegetation Simulator (FVS) to be Sensitive to Climate and Climate Change

Background Document for the 2008 Priest River Workshop

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Summary

The purpose of this draft conceptual framework is to communicate the approaches being tried to modify FVS for climate change. It is intended to provide a plausible starting point for discussions and decisions about how to adapt FVS for climate and climate change. It is not an ending point (!) and readers will notice that while it offers a fairly consistent set of ideas and approaches, it leaves many of the "how-to" issues and problems unresolved. Discussing, debating and filling in those ideas and suggested solutions will be a key outcome of the upcoming workshop. After reviewing this framework (and possibly modifying it), the next steps will then include building the component sub-models, linking them together and testing the model on a variety of conditions.

Key Concepts

We present a conceptual framework for modifying the Forest Vegetation Simulator (Crookston and Dixon 2005) so that it can take climate change into account in its predictions, thereby addressing a major concern of model users.

As shown below, most of the model inputs, processes, and management actions are the same as those currently associated with FVS. The key new process controlling predictions is climate itself.

	Inputs	**Processes**	**Management**
Current	Inventory, Site	Growth & Mortality	Thinning & Planting
New	+ Climate data	Same or Similar + Climate effects	Same or Similar + Seed source

Data quantifying climate are also a new input, and establishing trees from specified seed zones is a new management action. Inputs, outputs and management actions for the current model are generally not altered beyond some additional outputs that are useful for understand how climate is influencing model predictions. The current model's primary input is an inventory of existing trees for a site and information measuring the site characteristics and location. The primary output is a report detailing the species and size composition of the trees at each time step in a simulation. Management actions are centered on silvicultural options: thinning, harvesting, planting, and related activities.

To introduce the effects of climate, we propose three key concepts:

4. Species-specific site carrying capacity will change with climate, and this will affect tree survival, since the FVS tree mortality model is (and will continue to be) sensitive to carrying capacity;
5. Climate change will modify how well individual trees are adapted to a site. The model will therefore modify individual growth rate as a function of climatic "distance" between the individual's "ancestral" seed source and the current climate, where the distance is measured on climatic axes; and finally
6. An individual tree's growth rate will be directly related to climate and therefore the modified model will change growth rates as climate changes, regardless of seed source.

Regeneration

We further propose that modification of the FVS regeneration establishment model be deferred to another round of model changes.

Most regional variants of FVS already rely on user-input to define the species, number per acre, and size of regenerating trees. In those variants therefore, is really no "model" of the regeneration process to modify for climate change. In variants where there is such a model, notably those covering the inland northern Rocky Mountains, model formulations could be altered to represent changes in regeneration success due to climate change. The approach used in those establishment models is to quantify the "net-result" of many processes and factors that influence these processes. Currently, the inherent assumptions are that future climate will be suitable for species that are currently growing and that there are seed sources of trees adapted to the site that are also present at or near the site. How to alter these assumptions – and it seems unavoidable – is unclear at this time. Therefore, our proposed approach is to model the establishment of new trees by having users specify what will be present, as is done now for most variants.

An expert system is being developed by Brad StClair and Glenn Howe (PNW and OSU) that will help users understand what species to plant and were to get the seed. In the longer term, we envision linking to that expert system so that this information can be used by the growth models.

This approach does not mean that we will ignore the issues of growth and survival of newly planted trees. We do plan to include seed source information as a tree-level state variable. If a user specifies planting with a seed source that isn't appropriate, then the mortality can kill those trees, or the growth model can affect their growth rate. If no seed source is specified, then the assumption is local seed source.

Temporal & Spatial Resolution

FVS's temporal scope is often 200 years; but our climate change predictions are for this century so for this modeling work we set the time scope to 100 years. Temporal resolution is generally 10 years but sometimes 5-year intervals are used. Spatial resolution is a "stand" of trees and scope is a collection of stands of some practical size. The fundamental sampling unit and simulation unit is an individual tree.

Approach

A modeling exercise like this one benefits from steps developed by C.S. Holling (1978) as described in *Adaptive Environmental Assessment and Management*:

1	Describe the stakeholder issues and concerns
2	List management actions that address the issues
3	List indicators (model outputs) by which alternative actions are judged
4	List processes that are affected by the actions and change the indicators
5	Identify models that represent processes
6	Define the linkages between the processes
7	Identify missing linkages and processes and conclude that those missing linkages and processes might need to be filled if the stakeholder issues are to be addressed
8	Define how the identified processes (5) function, making use of their inputs and generating their outputs

The first four of these steps have been addressed in the introduction. Here, we revisit Step 4 and go on to address the other steps.

Processes (Holling Step 4)

Several fundamental processes inherent in forest dynamics are already represented in FVS. These include the birth of new trees, growth, mortality, and disturbances (including those caused by human activities, fire, insects and pathogens). Here we identify the processes that need to be addressed in Climate-FVS.

Climate and Climate Change

Current and future climates will be input into the model from external data sources. An example of the climate data we intend to use is at http://forest.moscowfsl.wsu.edu/climate. Other data sources could also provide valid climate inputs as long as they follow the format described below.

Regeneration Establishment

As noted on the previous page, FVS will rely on external data for this information.

Tree Growth

FVS grows trees in height and diameter and broadly includes three factors: individual tree size, competition, and site. For small trees, height growth is estimated first and then diameter is predicted as a function of height, and perhaps other variables. For large trees, diameter growth is estimated first and height is predicted as a function of diameter and other variables. Variants of FVS differ by how they represent site potential some are based on habitat type or plant association and others are based on site index. Other factors that measure attributes of site potential such as slope, aspect, and elevation, are commonly included. In all cases, the current FVS assumes that trees are reasonably well adapted to the site on which they are growing, and that records of how trees have grown on the site in the past, plus how they compete with other trees, adequately represent how these factors determine future growth.

The height diameter relationship is used in estimating small tree diameter growth and climate may effect this relationship. Some discussion is needed on modeling this effect, and some way is needed internally for FVS to modify this relationship through time.

Tree Mortality

Trees routinely die in FVS. When fire, insect, or pathogen extensions are used, trees may die in episodes or faster then they would otherwise. Survivors of these episodic mortality factors die from density-dependent mortality as the density approaches site carrying capacity.

Site Potential

Currently, FVS assumes that the site is static over time, yet changes in temperature and moisture regimes will change both the carrying capacity of a site and the time it takes for trees to reach that capacity.

Tree Adaptation

As stated above, FVS assumes that tree adaptation is static and that the degree of adaptation is evident in the historical growth data used to calibrate the model.

Linkages Between Processes (Holling Step 6)

Figure 1 combines four of the processes just described, and their interactions, into a “looking outward matrix”. Generally, the processes are listed as columns and rows, with diagonal elements (darker gray) describing what happens internally within the process. The two exceptions are: (1) the first row is for information that is input from outside the model, and (2) the last column is for outputs. Each off-diagonal element identifies information passed ***from*** one process ***to*** another process or to the model output.

		***To* Submodel**				
		Tree Growth	**Tree mortality**	**Site Potential**	**Tree Adaptation**	
	Input to Submodel	Climate at the site	Climate at the site	Climate at the site Soil water carrying capacity	Climate at the site and at the seed source for each tree	**Output Reports**
***From* Submodel**	**Tree Growth**	Tree Growth Submodel	Current density and growth rates			Summary of growth rates, size and species composition
	Tree Mortality		Tree Mortality Submodel			Summary of mortality rates
	Site Potential	Potential growth rate (site index)	Carrying capacity (*maxBA* or *maxSDI*)	Site Potential Submodel		Summary of site potential
	Tree Adaptation	Relative or absolute gain or loss in diameter and height growth.	Species climatic zone (yes or no)?		Tree Adaptation Submodel	Summary of individual gain/loss relative to index?

Figure 1 – The looking outward matrix to illustrate the model components and their proposed interactions.

Missing Processes and Linkages (Holling Step 7)

As stated previously, climate change is expected to impact regeneration processes, a key element in forest dynamics. We have deferred working on this component other than allowing users to specify the species and seed sources of regeneration.

Process Functions (Holling Step 8)

Inputs – Information Provided to FVS

The primary new input is climate data, and soil data may be needed depending on how other components of the model are built. A database-oriented tabular template for climate data has been developed, where the columns are climate attributes and the rows are 10-year decade averages for the "current" time and at future decades up to the 100 year limit of the temporal scope. The column data currently include the following (some are simple interactions, and other interactions are also possible; see Rehfeldt 2005):

1	Mean annual temperature
2	Average temperature in the coldest month
3	Minimum temperature in the coldest month
4	Average temperature in the warmest month
5	Maximum temperature in the warmest month
6	Annual precipitation
7	Growing season precipitation: April – September
8	Summer-winter temperature differential (Variable 4 – Variable2)
9	Degree-days >5 °C
10	Degree-days <0 °C
11	Minimum temperature of degree-days <0 °C
12	Julian Date of the last freezing date of Spring
13	Julian Date of the first freezing date of Autumn
14	Length of the frost-free period
15	Accumulated degree-days >5 °C within the frost-free period
16	Julian Date when the sum of degree-days >5 °C reaches 100
17	Annual dryness index: Ratio of Variable 9 to Variable 6
18	Summer dryness index: Ratio of Variable 15 to Variable 7

Not shown in the table, each row in the database is also indexed by location, year (decadal) and the general circulation model (GCM) and climate change scenario upon which the projection is based. Currently, seven combinations of models and scenarios are available for analysis (http://forest.moscowfsl.wsu.edu/climate), and predictions from other climate interpolation approaches could also be used, so long as they follow the formatting described here. Finally, when seed sources from locations other than the stand are used in regeneration, the climate data for those locations must be present in these data.

We anticipate that data like those described above would be generated on a central server prior to running a simulation. These data would then be distributed to the user's computer in a data table that can be directly queried by FVS.

Lastly, some might question whether decade-level averages are defensible, compared to annual or even more temporally-fine climate (or weather) data. Our proposal is based on the belief that GCMs are best suited to portray trends in climate change rather than exact yearly forecasts. Furthermore, FVS growth models are generally designed to make periodic growth estimates. Thus, using decade-long average climate estimates coincides with the FVS temporal resolution.

Tree Growth Submodel

Currently, growth rate in FVS is a function of three factors: tree size, competition, and site potential. We intend to leave tree size and competition components unchanged. In the simplest cases, changes in site potential can be model by adjusting the intercept term in the growth equation: move the intercept up a bit to represent an increase in growth and down a bit to represent an overall decline. The amount of change in growth due to site changes can be computed as a function of the difference in site. As an example (and this is an extreme case), consider the equation that predicts change in squared diameter (DDS) that is used in the Central Rockies variant for some species (it is borrowed from the Central Idaho variant). The equation is:

$$\ln(DDS) = \beta_1 + (\beta_2\ \sin(ASP) * SL) + (\beta_3 * \cos(ASP) * SL) + (\beta_4 * SL) + (\beta_5 * SL^2) + (\beta_6 * \ln(DBH)) + (\beta_7 * DBH^2) + (\beta_8 * BAL) + (\beta_9 * CR) + (\beta_{10} * CR^2) + (\beta_{11} * \ln(BA)) + (\beta_{12} * PCCF) + (\beta_{13} * BAL / (\ln(DBH + 1.0))) + (\beta_{14} * PBAL / (\ln(DBH + 1.0))) + (\beta_{15} * \ln(CCF)) + (\beta_{16} * CCF) + (\beta_{17} * SI) \qquad [1]$$

where:

DDS is the squared inside bark diameter
ASP is stand aspect
SL is stand slope
DBH is tree diameter at breast height
BAL is total basal area in trees larger than the subject tree
CR is crown ratio expressed as a proportion
BA is total stand basal area
PCCF is crown competition factor on the inventory point where the tree is established
PBAL is point basal area in trees larger than the subject tree
SI is stand site index
$\beta_1 - \beta_{17}$ are species-specific coefficients

Note that only the site index term in this equation is directly sensitive to climate change. Let's say we wish to compute a modifier *m* to scale DDS_1, the unchanged value to get a new estimate of growth that carries the site component. We desire to know *m* in

$$DDS_1 = DDS_2 * m. \qquad [2]$$

It is straight forward to show that

$$\ln(m) = \beta_{17} * (SI_2 - SI_1) \qquad [3]$$

Fantastic, one might say, except to note that β_{17} is equal to zero for all except one species. In this extreme case, the site effect is rather flat! Fortunately this situation is not always as extreme as noted here. However, this approach to modifying growth to account for changes in site only accounts for general trends in the growth data to which FVS is calibrated. Note that site potential is often confounded in these data. Often, elevation is a component (not in this case) and it is strongly correlated with climate. Even tree size is correlated with climate as we generally only get large trees (note the DBH term) and large basal areas (note the BA terms) on better sites.

A second way to modify growth rate to account for climate change will include a new factor to represent genetic adaptation (see "Tree Adaptation", below).

Tree Mortality Submodel

Currently, mortality rate in FVS includes a *background* mortality rate, a factor that measures relative growth rate, where slower growth trees have a higher chance of dying, and a *density-dependent* component that predicts higher mortality as stands mature and eventually approach carrying capacity. Carry capacity changes will therefore influence tree mortality, as discussed below under the Site Potential Submodel.

Site Potential

Traditional FVS accepts site potential measures as input and assumes that it remains constant over time. There are two measures of site potential. One is ***carrying capacity***, measured as the maximum basal area (*maxBA*) or the maximum stand density index (*maxSDI*) that the site can support. The other measure of site potential measures how fast trees grow, the best single example being ***site index***. Many foresters believe these two measures – carrying capacity and site index – are independent at the species level. Accordingly, for a given species *maxSDI* is essentially a constant across environmental gradients while site index is not. Ecologists and other foresters, on the other hand, believe that carrying capacity and site index are related. Both ideas are present in FVS, although not in the same variants.

We propose to model *maxBA* and *maxSDI* by species as a function of climate and to predict changes in these measures as functions of changes in climate. These changes would are then used to modify the corresponding FVS maxima. As shown in Figure 1, the effects of these maxima would be felt in the mortality model.

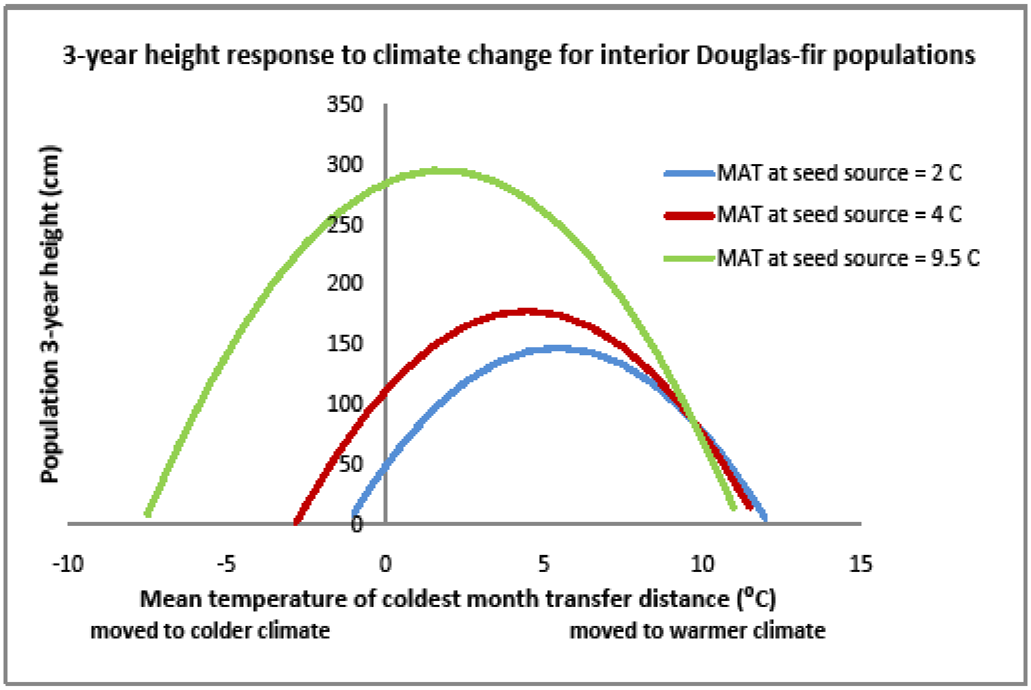
Another measure of site potential is the likelihood that a species can even exist at a site. Procedures for computing this likelihood have been developed by Rehfeldt et al. (2006) and are available for many species for the same future times and GCM model runs as described above for climate inputs. Adjustments to the site potential for a species could be made using these likelihood scores as well as the estimates of maximum carrying capacity. Alternatively (or additionally) species-presence maps could interact with FVS through a future regeneration system.

Tree Adaptation Submodel

There are at least two general ways to think about tree adaptation. One way has to do with how populations of trees evolve; in which individuals in the population express traits that make them more or less successful on a site. This process is not being modeled in this round of model changes under the assumption that this adaptation process is to too slow to influence stand dynamics within our temporal scope.

A second way to incorporate adaptation is to represent how existing trees will respond to climate change, based on the traits they already have. Figure 2 (Laura P. Leites' PhD work) illustrates how trees currently growing near the optimum climatic regime for their populations will experience negative impacts on growth with very moderate amounts of warming, yet trees that are currently growing in suboptimal conditions for the population will experience significant increases in the growth for the same moderate amounts of warming. Yet, current growth of trees growing in suboptimal conditions is much lower than trees growing near their optimum.

Equations similar to the one illustrated in figure 2 can already be calibrated for several species, and can be used to estimate a relative change in growth due to the difference in climate at the seed source for the trees, compared to the current climate. Functions like these can also be used to represent management actions designed to change the genetics of trees at a site by planting trees from different seed zones.



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