Development of a Climate–Driven Forest Vegetation Simulator

The Priest River Experimental Forest Workshop Results

Prepared for

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Moscow, ID

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Preface

"Every national forest will specifically deal with climate change across landscapes."

"All forests…take up enough carbon from the atmosphere to offset about 10 percent of America's carbon emissions. I propose a national effort to double that amount by 2020.

"…we could replace as much as 15 percent of our current gasoline consumption with ethanol from wood."

– September 7, 2007, Forest Service Chief Gail Kimbell[1]

"Our results join with many other's to predict a widespread disruption of native ecosystems from global warming."

– Rehfeldt and others (2006)

In the face of climate change – when forest ecosystems are being threatened – we are seeing an increase in expectations for society to derive benefits from forests. For managers, the stakes are rising simultaneously with the complexity of knowledge needed to meet demands for ecosystem services.

The Forest Vegetation Simulator (FVS, Dixon and others 2002, Crookston and Dixon 2005) is a forest dynamics model used by forest managers to simulate the effects of management. Its outputs include descriptions of species and size-class distributions. Many other indicators of forest ecosystem function are available through model extensions that represent insect and disease dynamics, fire, fuels, and carbon. The model is used for project planning at the stand and landscape levels and to support regional analyses.

The core tree growth and mortality components are modeled functions of site capacity, tree size, and competition. The measures of site capacity rely on direct observations of biological indicators like site index. Foresters simply make direct observations of how well the best trees are growing and use these observations as an indicator of the physical factors of the site that actually control tree growth. These factors include water, nutrients, light, and heat (and their interactions). There is an assumption that the trees have the genetic capability to use these resources to grow. In fact, there may be tree species, or genotypes of the same species that could make better use of the resources to grow better than the trees foresters observe.

Some major components of site quality are changing due to climate change. The most important two in the near term are water and heat, but atmospheric gas concentrations important for growth are also changing. Currently, FVS assumes that site quality will remain constant during the simulation period. To account for changing site, a modification of the model, how it is used, or both is in order.

Just how to modify the model was the subject of the workshop reported in this document. Twenty six professionals gathered together at the historic Priest River Experimental Forest in northern Idaho, to discuss ways of retooling the core growth, mortality, and regeneration establishment components of the model to properly respond to climate change. The original set of disciplines that were important to the original development of the model was enhanced to include physiologists and geneticists. This report journals their discussions.

– Nicholas L. Crookston, October 22, 2007, Moscow ID.

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[1] From "Climate change, kids and forests: what's the connection?" Address to the Society of Environmental Journalists annual conference, Stanford CA.

Table of Contents

Back row, left to right: Mike Bevers, Dave Marshall, Gary Dixon, John Marshall, Bill Wykoff, Ann Abbot, Stephanie Rebain, Robert Froese, Peter Gould, Albert Stage, Fred Martin, Dave Cawrse

Middle row: David Loftis, John Goodburn, Bob Monserud, Erin Smith-Mateja, Linda Joyce, Laura Leites, Glenn Howe, Abdel-Azim Zumrawi

Front row: Kelsey Milner, Nick Crookston, Colin Daniel, Bryce Richardson, Don Robinson, Mike Ryan

1. Introduction

The following report documents the discussion and recommendations of a workshop held at the Priest River Experimental Forest from September 5-7, 2007, the purpose of which was to define one or more approaches (or frameworks) for building a climate-driven version of the Forest Vegetation Simulator (FVS). A list of the workshop participants is provided in the Appendix.

The structure of the workshop 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. Specifically, the goal of this workshop was to discuss the following:

1. objectives of the modeling exercise;
2. indicator variables for the model (*i.e.* output variables on which management decisions are based);
3. management actions to which the model will respond (*e.g.* tree planting);
4. temporal/spatial extent and resolution of the model predictions; and
5. key processes that should be represented in the model.

The remainder of this report is structured as follows:

- Section 2 provides an overview of the model bounds, as defined by the workshop participants – this includes model objectives, indicators, management actions, extent and resolution.
- Section 3 describes the key processes to be addressed in a new climate-driven version of FVS – this includes tree growth, mortality, regeneration and genetic adaptation.
- Section 4 lists the next steps identified by participants for developing the model.

2. Model Bounding

The most important decision in any modelling exercise is deciding what the model should and should not do – *i.e.* bounding the model. The following section provides an overview of the agreed-upon bounds for a climate-driven version of FVS, as defined by workshop participants.

2.1 Objectives

The first step in model bounding is to define the purpose of the new model. As suggested by Holling (1978), “the importance of an early statement of questions to be answered by [a modeling] exercise cannot be overemphasized… Too many models have been built with unclear program goals, resulting in too many inappropriate models”.

A number of objectives were identified by participants for a new climate-driven version of FVS, which included the following:

1. **Maintain credibility**

   This was the key objective expressed at the workshop. Participants agreed that FVS would have little value as a predictive tool if it did not continually evolve to use the best available science.

2. **Responsive to climate**

   A second objective for any future changes to FVS was that the model predictions be made sensitive to climate and by extension, climate change. More specifically:

   - Climate variables should be provided as inputs to the model – in other words, the model should not be making any climate predictions itself.
   - The new model should be able to respond appropriately to climatic inputs that exceed the historical range of variability – in other words, it should be capable of making predictions under climatic conditions that currently existing trees have not experienced.
   - FVS should account for the effect of genetic differences in adaptation to climate of different tree species and their provenances.
   - All of the climate-related inputs to FVS should be reviewed to insure that they are specified in a consistent manner. For example, fire severity inputs, which are fed into the FVS Fire-Fuel extension, should be specified in a manner that is consistent with the suite of climate inputs provided elsewhere in the model.
   - Climate inputs to the model should be optional – i.e. the model should be capable of running under a constant, “current” climate assumption as well as under climatic scenarios in which CO_2 level and patterns of temperature, precipitation vary.

3. **Flexible architecture**

   Participants agreed that the current understanding of how future climate change will affect tree growth and mortality is not well understood. As a result, any changes to the structure of FVS should allow for the model to be changed easily as new knowledge and understanding emerge. More specifically:

- The model should allow for users to test alternative hypotheses with respect to model relationships (*e.g.* importance of different climatic variables in predicting future forest conditions; the relationship between climate and growth of species and genotypes of those species).
- FVS should be capable of accommodating alternative climate change scenarios as input, as there are several competing hypotheses for future climate change.
- FVS should continue to run with the existing extensions (*e.g.* fire and fuels, root disease, pine beetle), recognizing that some extensions will themselves need to be adapted to become climate-sensitive.
- It should continue to be easy to create new FVS variants.

4. Expanded predictive capability

A climate-driven version of FVS should be capable of the following:

- predict realistic structure and composition of stands – including effects of climate – which can, in turn, be inputs to other models (*e.g.* landscape models such as VDDT and TELSA (ESSA Technologies Ltd. 2005, 2007)), as an aid to decision making;
- allow users to compare the effects of silviculture alternatives;
- guide users with respect to appropriate silviculture practices in the face of climate change (*i.e.* be able to provide simulation results that can help to answer the questions: “What will I grow?” and “How should I nurture it?”);
- predict the productivity of trees under different climate change scenarios; as a result, species may show increased or decreased growth depending on competitive and physiological responses;
- predict species ranges (and the possible alteration of ranges under altered climates) that are consistent with other research;
- predict future condition of a landscape (*e.g.* for national forest planning) – both over a 10–15 and 50 year time horizon[2]; and
- continue to support inventory update as a model use.

2.2 Management actions

Given a clear set of management objectives for the new model, the next step in the model bounding process is to define the relevant *management actions* to which the model will respond. Actions are simply those activities that managers can consider in their attempts to manipulate a system to meet goals and objectives. From the standpoint of a model, they are quantities which have some influence on the model, but which are not predicted by the model. Instead their levels are specified outside of the model, usually as a part of an overall policy or management strategy. Although management strategies are usually implemented as a suite of actions, it is important that the system be capable of varying and responding to actions individually, to gain a sense of the system’s sensitivity to particular decisions.

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[2] This shorter time horizon is made recognizing that the current modeling time horizon can extend 150-200 years.

Workshop participants agreed that a new version of FVS should retain all of the currently supported management actions. Current FVS management actions include:

- thinning various ways (includes harvesting);
- pruning;
- regeneration (for some variants);
- fertilization (for some variants); and
- FFE fuel management actions.

In addition, the following were identified as possible new management actions:

- location of seed source, specifying that seed comes from a source other than local; and
- management of understory vegetation.

2.3 Indicators

The third step in bounding a model is to specify its *indicators*. Model indicators are those quantities which allow the user to observe and evaluate the performance of the system in response to changes in management actions. As different users will rely upon different measures to evaluate system performance, it is important to include a diverse and comprehensive set of indicators.

Workshop participants agreed that all of the current FVS indicators should be retained. Some of the current FVS indicators include:

- volume;
- basal area;
- canopy cover;
- diameter, species, height, crown length, crown width, height increment, diameter increment, estimated background mortality;
- bulk density and fuel loading; and
- carbon loads.

Possible new FVS indicators include:

- "potential" future species composition – what could potentially grow (similar to the current FFE potential fire report); and
- leaf area index (LAI).

2.4 Space and time

To complete the bounding exercise for a model, decisions have to be made concerning the extent and resolution, both spatially and temporally, over which the model will operate.

The *spatial resolution* of the model is defined as the smallest spatial unit over which the model will make explicit predictions for the user. Currently the spatial resolution of FVS is a stand or plot (*i.e.* cluster) of trees. In addition, any model of a physical system is necessarily confined to make predictions over some *spatial extent*; 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.

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. At present the default temporal resolution of FVS is 5 or 10 years (which corresponds to the observation interval for the diameter increment measurements used to fit the FVS large tree submodel) but is under user control and can be as short as one year, while the maximum extent is approximately 200 years. Participants agreed that the temporal resolution may need to change for a climate-driven model in order to handle variations in climate inputs. The suggested new default temporal resolution would likely be one year, although a physiological submodel may need to operate on a finer timestep. The temporal extent of the model should likely remain unchanged, although it may be difficult for the model to provide credible predictions over a full 200 year horizon, and most participants were more comfortable with a 50 year extent under changed climatic scenarios.

3. Key Processes

Having bounded the model, the next step in the workshop was for participants to identify the key processes (sometimes referred to as *submodels*) that should be represented within the model. Participants identified 4 key processes that would need to be recognized by a climate-driven FVS: individual tree growth, individual tree mortality, regeneration and genetic adaptation of tree species to climate. Three of these processes are already explicitly considered within the current version of FVS, but will require modifications to the way in which they operate. The fourth process, genetic adaptation, is not currently considered by FVS but will be an important driver in predicting the forest dynamics under a changing climate.

3.1 Growth

Three possible approaches were considered for adapting the current FVS growth submodel such that it would be responsive to future changes in climate:

- a physiological approach, in which existing physiological models are used to predict tree growth as a function of climate;
- an empirical approach, in which historical plot data is used exclusively to define the relationship between climate and tree growth; and
- a hybrid approach, in which a physiological model is used to predict the potential productivity of a site, while empirical relationships are used to translate this potential productivity into tree growth.

Each of these options is outlined briefly below. While participants felt that all three approaches had merit, the consensus was that the hybrid and empirical approaches showed the most promise and should be explored first (see Section 4 for additional details).

1. Physiological approach

With this approach an existing model of tree physiology, such as BIOME-BGC (Running and Hunt 1993) or 3-PG (Landsberg and Waring 1997), would be used by FVS to predict the net primary production (NPP) every year for a given location (*e.g.* stand), given the location's climate and topographic characteristics (*e.g.* slope and aspect). The physiological model would also be responsible for predicting the change in above-ground biomass each year, which FVS would in turn need to convert into a corresponding change in diameter and height for the year using pre-defined allometric relationships for each tree species.

Two strengths of this approach are that (1) it uses the best available science to predict the future productivity of a site under alternative climates, and (2) a prototype application of the approach has already been implemented in the FVS-BGC extension (Milner and others 2002). A possible weakness of the approach, however, is that it is presently quite challenging to convert predicted NPP into predicted individual tree growth by species across the distribution of trees within the modeled stand. Soil hydrology effects might also be difficult to incorporate into a hybrid model.

2. Empirical approach

A second approach for predicting growth would involve using existing plot data to determine an empirical relationship between climate and tree growth. Existing plot data, with measurements of tree growth, would be compared to past climate data in order to develop relationships between climate (as measured at that location) and tree growth for different species (Monserud and others 2006). Historical climate at each plot location would be estimated from a surface fitted to historical weather station measurements.

The strength of this approach is that it would provide simple, data-driven estimates of the effect of climate on tree growth (Monserud and others 2007). The weakness of this approach, however, is that the empirical relationships developed would be limited in predictive capability to the range of variability in climate observed historically over the plot locations.

3. Hybrid approach

The last approach proposed by participants was a hybrid (physiological-empirical) approach (Weiskittel 2007). Here an existing physiological model would be used to predict the future standing biomass for a given year and location, as a function of climate and site characteristics. This predicted standing biomass effectively becomes a dynamic site index in FVS. Predicted changes in maximum LAI would be related to standing biomass over a range of climatic variables (current and future scenarios under permutations of water, temperature and CO_2). The predicted change in standing biomass for a particular location and year would then be distributed across all trees in a stand, and then across parts of the tree using allometric relationships. Empirical relationships could be developed using existing plot data, between changes in standing biomass and tree growth for each tree species. At the species level this would result in a set of species-level growth modifiers, a concept that is part of the current FVS model.

The strength of this approach is that it uses the best available science, as encapsulated in current physiological models, to predict overall changes in productivity as a function of climate (Valentine and Mäkelä 2005). It also builds upon historical plot data to estimate empirically the effect of such changes in productivity on tree growth. A weakness of the approach is its limited ability to extrapolate beyond the range of historical climate and species and genotypes. Empirical relationships developed between tree growth and historical climatic variation may not be sufficient to represent the range of future variation in climate for many species. More importantly, historic climate variability within a species' range would be used to predict the effects of climate change on a particular population in a particular location. Thus, potentially important climate-genotype interactions would be confounded by restricting such a model to empirical observations.

3.2 Genetic adaptation

A major consideration in predicting the effects of climate change on different tree species is that different provenances of particular species are differentially adapted to climate and may respond differently to changes in climate (see Rehfeldt and others 1999, 2001, 2002).

A limitation of the approaches presented thus far for modifying the FVS growth and mortality submodels is that none of these options account for this genetic variation in adaptation to climate. As such, the approaches presented above are only appropriate when examining small changes in climate (*e.g.* over 10-25 years), and could not be expected to provide meaningful estimates of forest dynamics over time horizons longer than this.

One could estimate the range in climatic variability over which the effect of this genetic variation might be small, and FVS could effectively ignore genetic dynamics below this distance scale. This distance could be approximated as the average (or minimum) range of climatic variation that has been observed historically within the range of a distinct population within a species. Seed zones, which have helped to avoid planting maladapted trees in the past, may be a convenient way to delineate these populations.

When using FVS to predict tree dynamics under scenarios in which the predicted future climatic variation is sufficiently large to warrant consideration of genetic adaptation, workshop participants proposed that *adaptiveness multipliers* be calculated by the model to adjust growth and mortality at the species level. These adaptiveness multipliers would represent the change in growth and/or mortality, as a function of one or more climatic variables which would be expected for each species' provenance. Such relationships would be derived empirically from existing plot data outside of FVS and provided as inputs. Data currently exists in the literature to determine these adaptiveness multipliers for lodgepole pine, and possibly also for Douglas-fir and ponderosa pine. However further analysis will be required to determine these relationships for other species.

Once a relationship between climate and adaptiveness had been established, FVS would then calculate, for every simulation year and location, how far the predicted future climate deviated from current climate for each provenance. This change in climate would then be used to predict the adaptiveness multiplier for each provenance of a tree species. The multipliers, in turn, would be used to adjust the predicted future growth and mortality of each tree.

Two possible approaches were discussed by participants for developing the empirical relationships between climate and adaptiveness: long-term projects where trees are moved across different environments and short-term projects where climate has varied historically at a single location.

3.3 Mortality

With respect to predicting tree mortality under a changing climate, workshop participants agreed that it would be difficult to predict future tree mortality using only physiological models, as such models are not presently designed to make such predictions, even though it might be possible to use changes in estimated respiration from physiological models to develop such a predictive relationship (Monserud 2003).

The proposed alternative to using only a physiological model was, once again, to develop a hybrid physiological-empirical approach. A proposal was made to calculate a *vigor index* each year for each tree in FVS, and use this index to infer the level of tree mortality each year. One possible approach for predicting this index would be to relate the Leaf Area Index (LAI), as predicted each year by physiological models, to tree vigor for each tree species using historical plot data. Having developed this relationship, FVS could then predict the future vigor index of trees under alternative climate scenarios, and modify the level of tree mortality as a function of this index.

An approach based on a vigor index would need to continue to incorporate the competition and space-limitations embodied by the current drivers of SDI and maximum basal area. In addition, the revised mortality model would need to be linked with the adaptiveness multipliers developed as part of a model of genetic adaptation.

3.4 Regeneration

Discussions regarding the FVS regeneration establishment model first recognized that there are two major styles of this submodel. The "full" model predicts the species, density, and size of newly established trees at about 10 and 20 years after a harvest or other major disturbance. There are "full" establishment models for FVS variants that cover western Montana, Idaho, and southeast Alaska. For the rest of the country, model users must create and implement their own regeneration rules using FVS keywords. Even where the “full” establishment is available, many users prefer to specify their own rules, particularly when the analysis has a narrow spatial scope where the user’s own experience is the best source of information.

Since most FVS users were already modifying the existing regeneration submodel to fit their own needs, and because workshop participants did not identify a clear path to modifying the existing model to incorporate climate, participants agreed that in the short term a climate-driven version of FVS should not include a new, generic, climate-aware regeneration submodel, but rather should continue to allow users to specify the regeneration dynamics in the model. The proposed solution was to provide relevant information to users in order to assist them in incorporating climatic considerations into their development of regeneration rules.

The supporting information would address two basic types of regeneration – natural and planted – and would include the following:

1. An indication of the range of climatic conditions over which the provenances of different tree species could successfully regenerate – this would provide users with information on where alternative provenances could be successfully planted in the future.
2. A map showing the current distribution of alternative provenances, along with information on the distance over which each provenance could successfully migrate over time – combined with the climatic limits from #1 above, this would be used to limit where natural regeneration could successfully occur in the future.

4. Next Steps

Based on the initial ideas developed over the first two days of the workshop, participants spent some time on the last morning assimilating their ideas and proposing a series of steps to be followed in order to actually create a climate-driven version of FVS. The following section provides a brief overview of these proposed next steps. Note that in some cases, the participants felt that steps should be done in parallel.

1. **Obtain advice from experts on the use of various physiological models for predicting "potential" productivity of sites as a function of climate and site conditions**
    - Candidate models include: BIOME-BGC, 3-PG, FVS BGC variant.
    - Begin by reviewing Aaron Weiskittel's (2007) thesis work using 3-PG.
2. **Prepare historical plot data**
    - Organize current inventory data.
    - Identify plot data for a range of locations and species.
    - Possible sources of plot data include:
        - FIA - Nick Crookston has already compiled this for the Western U.S.; note however that locations of FIA data are not publicly available.
        - Stand exam data – note that the quality of this data is highly variable and it is difficult to know which examine data were carefully collected; however the FIA height/growth data is often not that good, so stand exam data may be preferable.
        - Other research data.
    - It is recommended that only the FIA data be used for the initial analysis, as it is already well formatted and thus will not require significant time or resources to prepare.
3. **Prepare historical climate data**
    - Acquire climatic data for a network of weather stations corresponding to the geographic range of historical plot data.
    - Generate surfaces for historical climate variables of interest (as required by the physiological models) – this will allow the past climate to be predicted for any plot location within the range of historical weather stations.
4. **Develop and apply candidate empirical growth-climate relationships**
    - One proposed approach (see Section 3.1.2) to developing empirically modeled growth relationships was to match long term historic weather records to increment data to develop growth-climate relationships. The strength of this approach is that it is grounded in observations, but two possible drawbacks are (a) the limited range of historical climate experienced by the inventory data: future climate scenarios may move outside the range of the past century; and (b) the possible censoring of the increment data by climate-related mortality.
    - A second proposed approach was to use common garden experiments to generate the necessary empirical data. The strength of this idea is that common garden plots implicitly

include all the complexities of climate, rather than only the selected (few) indicators chosen by forest scientists. The data to support such an approach may be limited to a few species, however.

- Develop empirical relationships between climatic variables and tree growth for each tree species.
- Generate an FVS diameter growth adjustment multiplier (and possibly also a height adjustment multiplier) in order to scale the FVS diameter growth (and height) predicted at each plot location as a function of one or more climatic variables.[3]
- Generate stand-level estimates of multipliers for each species.

5. **Develop and apply candidate physiological growth-climate relationships**
    - Gather and generate the necessary climate and site data required to run the physiological models (see Sections 3.1.3) at the sample plot locations. For example, the 3-PG model requires temperature, soil texture and soil depth for each location. In the absence of adequate soil data it might be necessary to adopt a default value and study outlier patterns after model fitting to generate regional soil-analogues.
    - Run each physiological model to predict past values of potential productivity (*i.e.* under current climate).
    - Gather any additional site variables required to run FVS at the sample plot locations.
    - Generate an FVS diameter growth adjustment multiplier (and possibly also a height adjustment multiplier) in order to scale the FVS diameter growth (and height) predicted at each plot location as a function of potential productivity.
    - Generate stand-level estimates of multipliers for each species.

6. **Compare empirical and physiological approaches for incorporating climate into FVS predictions**
    - Take the results of Step 5 (using one or more physiological models to modify the growth predictions in FVS), and compare them to the results from Step 4 (using direct relationships between climate variables and growth); assess which method shows the most promise for use with FVS.

7. **Repeat Step 4–6 using individual tree relationships**
    - Based on the results of Step 6, incorporate knowledge taken from the species-level relationships to re-estimate an individual tree model that includes climate drivers in addition to the current suite of FVS diameter growth variables (with the exception of current site productivity and regional variables).

8. **Determine historical range of climatic variation within the seed zone of each tree species**
    - Examine provenance maps and find the range of climatic variation in each provenance; if possible, reduce the climate variables (temperature by month, precipitation by month) to a few key measures.

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[3] Gary Dixon reports that users will soon have the ability to explore “what-if” scenarios created by altering site quality through keyword control within a simulation.

- For each tree species, calculate the average variation in key climatic variables across all seed zones – this provides an indication of the range of climatic variation over which the model can be used without explicitly accounting for genetic variation in tree species.
- Climate variables that relate to changes in potential productivity need to be aligned with the climatic variables that explain genetic differences – for example, if cold-hardiness is important to the provenance limits, this should somehow be consistent with the climate variables that determine the species growth multipliers.

9. Generate relationships for each tree species relating growth to climate for each provenance

- Identify existing sources of data to develop such relationships.
- Follow the example of Rehfeldt and others (1999, 2001) working with lodgepole pine data, extending this approach to other species.
- The end result would be an "adaptiveness" multiplier for each provenance, expressing the change in growth rate as a function of one or more climate variables.

10. Identify future genetic studies

- Additional experiments, both short and long-term, are urgently required in order to better understand the relationship between climate and growth of difference provenances.

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Appendix – List of Workshop Participants

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