Climate-FVS Version 2: Content, Users Guide, Applications, and Behavior

Nicholas L. Crookston

Abstract

Climate change in the 21st Century is projected to cause widespread changes in forest ecosystems. Climate-FVS is a modification to the Forest Vegetation Simulator designed to take climate change into account when predicting forest dynamics at decadal to century time scales. Individual tree climate viability scores measure the likelihood that the climate at a given location and at a given point in time is consistent with the climate recorded for species' contemporary distribution. These viability scores are input into Climate-FVS. A web-based service is available for providing this input for climate predictions generated by down scaling general circulation model (GCM) outputs run using several models and scenarios from the IPCC third (IPCC 2000) and fifth assessments (IPCC 2013). Climate-FVS contains components that modify mortality and growth rates, plus rules for establishing new trees. Commands are presented that control the model. These commands enable the users to explore the model's sensitivity to model components and parameters, to include pertinent information unknown to the model, and use the model to simulate management alternatives. Model outputs are very sensitive to the mortality component, are moderately sensitive to growth rate modifications, and are sensitive to maximum density adjustment only when a stand's maximum density is being approached. The intended model uses are to provide insights into future forest dynamics that are not otherwise evident, to provide model outputs that are relevant to forest managers, to provide a consistent way to compare management alternatives, and to do so using defensible methods.

About the author

Nicholas L. Crookston has been an Operations Research Analyst with the USDA-Forest Service since 1983. His central focus is the development and implementation of the Forest Vegetation Simulator (FVS). He also conducts scientific investigations to fill gaps in the FVS model. Recently that work has included modeling climate, climate-change, and species-climate profiles for western tree species. He has also developed software used to impute required inventory data to sites where these data are not available. He can be reached by Email at: ncrookston.fs@gmail.com

About the cover:

The cover art conveys fact that global warming is occurring, there are creditable predictions as to its magnitude, and although there are important differences in scenarios and GCM predictions, the future will not be the same as the past (the top graph is part of figure TS-15 reprinted from Stocker and others 2013, p. 89). Climate-FVS, represented by the FVS logo, integrates climate predictions to provide site-specific estimates of forest dynamics, represented by the bottom graph (fig. 17, herein).

Table of Contents

1. Introduction

Climate is changing (Hansen 2010, Stocker and others 2013) and that change is changing forests (Rehfeldt and others 2006). How this driving force is used in prognoses of forest stand development in Climate-FVS (Crookston and others 2010) is the primary purpose of this paper. Climate-FVS is an addition to the Forest Vegetation Simulator (Crookston and Dixon 2005; Dixon 2013 revision) that takes future climate projections as input and modifies the predictions for forest dynamics by including them in the calculations. To use this model proficiently requires knowledge of its scientific content and how it works.

Climate-FVS is designed to meet the same purposes as the core FVS system with the added benefit of taking climate change into account. The model's central purpose is to provide users insights into how forests will change over time given alternative management actions. Using the model provides consistent, documented, and defensible methods for producing information useful to forest managers.

Climate-FVS currently applies to the western half of the contiguous United States (herein, "the West"). There are efforts underway to build a counterpart that covers the eastern half of the United States and indeed that model will likely contain some of the same features (Phil Radtke, personal communication). However, because it will cover different ecosystems than those in the West it will have different model content, options, and supporting documentation.

Many people hold the view that there is a great deal of uncertainty in predictions of future climate and that it is therefore not feasible to consider climate change in forest growth predictions. The base FVS model, used without the climate adjustments, predicts a future that is a reflection of climates that predominated the last half of 20th Century. That time frame is coincident with most of the measurements on which the model is based. The climates of the 21st Century are predicted to be warmer; assuming that they will not change is most likely wrong (IPCC 2013). While outputs from Climate-FVS may not turn out to be correct, ignoring climate change in prognoses of future forest species and size composition would misinform forest planning and forest management decisions.

While some detailed examples are presented below (sections 4 and 5), outputs from Climate-FVS tend to exhibit some general trends. First, since FVS starts with an inventory of existing site and tree measurements, there is generally no immediate effect of climate change on predicted stand dynamics. Within a few decades, climate-change induced mortality starts to ensue; first for species that are near the edge of their ranges and then for all species (1) because the new climates are not like those where the species currently exist, (2) because the new climate is simply markedly different than the current climate, or for both reasons. Mortality opens growing space that the model can fill with species adapted to the new climate. The impact is that existing trees are replaced with regeneration.

As will be shown below, other effects of climate change—for example those that are related to changing growth rates—are of much less importance.

The opportunities for management to adapt forests to climate change center on changing the timing of harvests and the selection of planting stock. Short rotations can be used to ensure adapted trees are on rapidly changing sites. Management actions can be timed so that the general trend of accelerated mortality is replaced by harvests and planting so that lands that can sustain forests in the future are indeed stocked with healthy growing trees.

Climate-FVS requires an input file of future climate information and accompanying tree species viability scores—a measurement of how consistent the new climate is with records of where trees of a specific species are known to exist today. Section 2, *Model Content*, includes details about where to get these data and how they are used. Section 3, *Users Guide*, covers the commands that control the model, input, and output. Section 4, *Applications*, presents examples that illustrate model use, including management approaches. Section 5, *Sensitivity*, briefly explores how sensitive the model outputs are to individual subcomponents. Lastly, Section 6, *Summary*, is a synthesis that includes identification of caveats and key findings.

2. Model Content

Crookston and others (2010) presented all of the components of the first version of Climate-FVS, hereafter called version 1. For the sake of completeness, some of that information is repeated in this report, along with model updates applicable to version 2. However, some of the discussion and scientific rationale for the approaches presented in the 2010 paper are omitted yet remain relevant.

Climate-FVS is designed to be sensitive to location. It starts with inventory information that represents conditions at a specific place. It also uses input generated from a climate model that provides estimates of climate that are specific to the location as defined by longitude, latitude, and elevation.

Key facts about the model: (1) Climate-FVS represents general trends, and (2) changes in the variance in climatic conditions are not directly represented. Climate-FVS does not attempt to model exactly what will kill trees or exactly when they will die. For example, while the model may predict the demise of lodgepole pine, it does not simulate mountain pine beetle outbreaks or fires that may indeed become the causes. There are other modules in FVS that can be used to represent these ecosystem components. While there is evidence that the extremes may have a large influence on ecosystems, this model is based solely on changes in average conditions yet it still predicts huge impacts. If forest change is in fact driven primarily by climate extremes in addition to changes in averages, then the model projections of climate-caused impacts are probably conservative.

2.1. Climate

Climate-FVS requires input that defines current and future climate. Estimates are provided using spline climate surfaces (ANUSPLIN; Hutchinson 2004) of monthly averages (called *normals*) of mean, maximum, and minimum temperature and precipitation for point locations. The surfaces are continuous functions of latitude, longitude, and elevation. They provide potentially unique values for specific combinations on these axes rather than raster grids that provide the same value for all locations within a grid cell, as done in many climate models (e.g., Daly and others 2008). The spline climate estimates (http://forest.moscowfsl.wsu.edu/climate) include algorithms to generate from monthly means 35 variables with more direct relevance for plant ecophysiology, such as mean annual temperature and precipitation, degree days above 5 °C, degree days below 0 °C, the length of the frost period, and interactions such as annual dryness index, which reflects the balance between growing season warmth and precipitation.

Contemporary climate (the 1961-1990 climate normal period) is used as a base period because (1) this period mostly predates the beginning of accelerated climate change, (2) the data needed to compute the averages for this period were readily available and (3), much of the growth and mortality data used to calibrate components of the base FVS model and the species climate relationships are coincident with this period. The future climates are based on a downscaling of Global Circulation Models (GCMs), computed using a delta method (Daniels and others 2012; also see http://forest.moscowfsl.wsu.edu/climate/future/details.php). This method essentially involves adding the change (the *deltas*) in climate predicted by the outputs for the GCMs to the observed climate values used to build the contemporary climate surface. The updated observations are then used to build new surfaces that reflect the climate change.

In version 1, climate data and GCM simulations that corresponded to seven combinations of three GCM model outputs and three scenarios from the Special Report on Emission Scenarios (SRES) identified in table 1 were provided. These GCM outputs provided the climate projections used in the 3rd assessment report of the Intergovernmental Panel on Climate Change (IPCC 2000). For version 2, new GCM outputs, those used in the fifth assessment report (AR5, IPCC 2013) are used. These GCM runs are based on a different set of scenarios called Representative Concentration Pathways (RCPs), which are four greenhouse gas concentration trajectories adopted by the IPCC. Three of the four RCPs were processed for use in Climate-FVS: rcp45, rcp60, and rcp85. They are named after the three radiative forcing values in the year 2100: 4.5, 6.0, and 8.5 W/m^2 (vanVuuren and others 2011).

Of the available model runs (table 1), rcp60 is highlighted in this work as it roughly corresponds to SRES A2 and seems most relevant to study. Furthermore, in preparation for version 2, an ensemble of 17 GCM models were run in addition to three specific GCMs. The ability to generate predictions for specific locations is provided at http://forest.moscowfsl.wsu.edu/climate/customData/fvs_data.php.

Table 1. GCM model/scenario names.

Short name	Version	GCM group name and scenario identification
CGCM3_A1B	1	Canadian Center for Climate Modeling and Analysis, scenario A1B
CGCM3_A2	1	Canadian Center for Climate Modeling and Analysis, scenario A2
CGCM3_B1	1	Canadian Center for Climate Modeling and Analysis, scenario B1
GFDLCM21_A2	1	Geophysical Fluid Dynamics Laboratory, scenario A2
GFDLCM21_B1	1	Geophysical Fluid Dynamics Laboratory, scenario B1
HADCM3_A2	1	Hadley Center/Met Office (UK), scenario A2
HADCM3_B2	1	Hadley Center/Met Office (UK), scenario B2
CCSM4_rcp45	2	The Community Earth System Model, scenario rcp4.5
CCSM4_rcp60	2	The Community Earth System Model, scenario rcp6.0
CCSM4_rcp85	2	The Community Earth System Model, scenario rcp8.5
GFDLCM3_rcp45	2	Geophysical Fluid Dynamics Laboratory, scenario rcp4.5
GFDLCM3_rcp60	2	Geophysical Fluid Dynamics Laboratory, scenario rcp6.0
GFDLCM3_rcp85	2	Geophysical Fluid Dynamics Laboratory, scenario rcp8.5
HadGEM2ES_rcp45	2	Hadley Center/Met Office (UK), scenario rcp4.5
HadGEM2ES_rcp60	2	Hadley Center/Met Office (UK), scenario rcp6.0
HadGEM2ES_rcp85	2	Hadley Center/Met Office (UK), scenario rcp8.5
Ensemble_rcp45	2	Our ensemble of 17 AR5 model predictions, scenario rcp4.5
Ensemble_rcp60	2	Our ensemble of 17 AR5 model predictions, scenario rcp6.0
Ensemble_rcp85	2	Our ensemble of 17 AR5 model predictions, scenario rcp8.5

Three future time points are addressed: the 10 years surrounding 2030, 10 years surrounding 2060, and 10 years surrounding 2090. In Climate-FVS, points in time between those periods are linearly interpolated. As pointed out in section 1, this approach has low temporal resolution and ignores the within- and between-year fine-scale variation in weather and climate. On the other hand, the approach offers reasonably high spatial resolution whereby differences in climate along steep elevation gradients are reasonably represented.

2.2. Species Viability

Climate is the most important single factor defining species ranges. Rehfeldt and others (2006, 2009) developed methods to relate presence and absence observations derived mostly from Forest Inventory Data (FIA; Bechtold and Patterson 2005) to contemporary climate. A regression and classification algorithm called Random Forests (Breiman 2001; as implemented in R by Liaw and Wiener 2002) was used to generate sets of classification trees, where each set can be used to estimate the likelihood that the climate at a location is suitable to the species. We interpret this likelihood as a continuous zero-to-one index of the species' viability in the climate at a given location and hereafter refer to it as the *viability score*. Values near zero indicate that the climate is not suitable for the species, while values near one indicate that the climate is consistent with species presence.

Random Forest models are available for the most important forest tree species that occur in the western conterminous United States (table 2). Predictions are generated for specific locations for current conditions and for future climates using http://forest.moscowfsl.wsu.edu/climate/customData/fvs_data.php. As discussed in section 3, these data are entered into Climate-FVS along with the climate information. They are used in several ways as described below.

Table 2. Species list and summary of Random Forest predictors for Climate-FVS in the western United States.

Species	Plant code	Common name	Number present[a]	Commission error[b]	Omission error[b]	Lower viability[c]
Abies amabilis	ABAM	Pacific silver fir	4106	0.0539	0.0008	0.5936
Abies concolor	ABCO	White fir	8692	0.052	0.0017	0.5653
Abies grandis	ABGR	Grand fir	8220	0.066	0.0008	0.5723
Abies lasiocarpa	ABLA	Subalpine fir	11294	0.0748	0.0006	0.5913
Abies lasiocarpa var. *arizonica*	ABLAA	Corkbark fir	370	0.0454	0.0013	0.5463
Abies magnifica	ABMA	California red fir	1248	0.0668	0.0018	0.5516
Abies magnifica var. *shastensis*	ABSH	Shasta red fir	600	0.0673	0.002	0.5358
Abies procera	ABPR	Noble fir	1522	0.0962	0.0014	0.5544
Acer glabrum	ACGL	Rocky Mountain maple	712	0.0818	0.0054	0.4873
Acer grandidentatum	ACGR3	Bigtooth maple	348	0.0657	0.0012	0.5544
Acer macrophyllum	ACMA3	Bigleaf maple	3616	0.1436	0.0011	0.5497
Aesculus californica	AECA	California buckeye	228	0.1804	0.0015	0.5515
Alnus rhombifolia	ALRH2	White alder	208	0.1455	0.0018	0.5487
Alnus rubra	ALRU2	Red alder	4882	0.1211	0.001	0.5594
Arbutus menzeisii	ARME	Pacific madrone	3098	0.0826	0.0008	0.5753
Betula papyrifera	BEPA	Paper birch	302	0.0789	0.0019	0.5535
Betula papyrifera var. *commutata*	BEPAC	Western paper birch	328	0.0379	0.0004	0.593
Calocedrus decurrens	CADE27	Incense cedar	4868	0.1119	0.0017	0.5508
Castanopsis chrysophylla	CHCH7	Golden chinkapin	1810	0.092	0.001	0.5654
Cercocarpus ledifolius	CELE3	Curlleaf mountain-mahogany	1192	0.0872	0.0012	0.5551
Chamaecyparis lawsoniana	CHLA	Port-Orford-cedar	6152	0.0243	0.0007	0.6056
Chamaecyparis nootkatensis	CHNO	Alaska cedar	472	0.1072	0.0024	0.5299
Cornus nuttallii	CONU4	Pacific dogwood	1050	0.1435	0.0021	0.5389
Fraxinus latifolia	FRLA	Oregon ash	206	0.1321	0.0032	0.5343
Juniperus deppeana	JUDE2	Alligator juniper	3046	0.0547	0.0021	0.5657
Juniperus erythrocarpa	JUCO11	Redberry juniper	84	0.223	0.0021	0.5607

Table 2. Continued

Species	Plant code	Common name	Number present[a]	Commission error[b]	Omission error[b]	Lower viability[c]
Juniperus monosperma	JUMO	Oneseed juniper	3866	0.0717	0.0012	0.5858
Juniperus occidentalis	JUOC	Western juniper	3152	0.0574	0.0007	0.5681
Juniperus osteosperma	JUOS	Utah juniper	9262	0.0804	0.0017	0.5573
Juniperus scopulorum	JUSC2	Rocky Mountain juniper	3378	0.1297	0.0019	0.549
Larix lyallii	LALY	Subalpine larch	102	0.1178	0.0033	0.524
Larix occidentalis	LAOC	Western larch	9094	0.051	0.0006	0.5996
Lithocarpus densiflorus	LIDE3	Tanoak	2158	0.0622	0.0009	0.5643
Olneya tesota	OLTE	Tesota-Arizona ironwood	110	0.0941	0.0046	0.5206
Picea breweriana	PIBR	Brewer spruce	348	0.0419	0.0014	0.5581
Picea engelmannii	PIEN	Engelmann spruce	10460	0.0847	0.0007	0.585
Picea pungens	PIPU	Blue spruce	328	0.1264	0.0032	0.5261
Picea sitchensis	PISI	Sitka spruce	946	0.0932	0.0021	0.5262
Pinus albicaulis	PIAL	Whitebark pine	3112	0.0491	0.0005	0.5876
Pinus aristata	PIAR	Bristlecone pine	162	0.0791	0.0004	0.5771
Pinus attenuata	PIAT	Knobcone pine	388	0.0943	0.0011	0.5464
Pinus contorta	PICO	Lodgepole pine	15386	0.0863	0.0005	0.5902
Pinus coulteri	PICO3	Coulter pine	116	0.1476	0.0012	0.5473
Pinus edulis	PIED	Pinyon pine	9102	0.0736	0.0015	0.5729
Pinus flexilis	PIFL2	Limber pine	1938	0.0982	0.001	0.5623
Pinus jeffreyi	PIJE	Jeffrey pine	2394	0.0898	0.0015	0.5542
Pinus lambertiana	PILA	Sugar pine	4032	0.1099	0.0013	0.5565
Pinus monophylla	PIMO	Singleleaf pinyon	3430	0.0531	0.0005	0.595
Pinus monticola	PIMO3	Western white pine	3726	0.0894	0.001	0.5612
Pinus ponderosa	PIPO	Ponderosa pine	24280	0.0802	0.0014	0.5671
Pinus strobiformis	PIST3	Southwestern white pine	560	0.0663	0.0065	0.4381
Populus deltoides ssp. *monilifera*	PODEM	Plains cottonwood	76	0.1343	0.0009	0.5776
Populus tremuloides	POTR5	Quaking aspen	6196	0.0804	0.0014	0.5527
Prosopis sp.	PROSO	Mesquite	264	0.1343	0.0011	0.5623
Prunus sp.	PRUNU	Cherry	724	0.0876	0.0015	0.5446
Psuedotsuga menziesii	PSME	Douglas-fir	39490	0.0788	0.001	0.58
Quercus agrifolia	QUAG	Coast live oak	440	0.1054	0.0024	0.5412
Quercus chrysolepis	QUCH2	Canyon live oak	3310	0.1242	0.0011	0.558
Quercus douglasii	QUDO	Blue oak	778	0.1368	0.0017	0.5419
Quercus emoryi	QUEM	Emory oak	758	0.092	0.0012	0.555

Table 2. Continued

Species	Plant code	Common name	Number present[a]	Commission error[b]	Omission error[b]	Lower viability[c]
Quercus gambelii	QUGA	Gambel oak	4118	0.0609	0.001	0.5732
Quercus garryana	QUGA4	Oregon white oak	1116	0.116	0.0017	0.5528
Quercus hypoleucoides	QUHY	Silverleaf oak	218	0.07	0.0027	0.54
Quercus kelloggii	QUKE	California black oak	3500	0.0982	0.0013	0.5513
Quercus lobata	QULO	Valley California white oak	150	0.1847	0.0025	0.5232
Quercus oblongifolia	QUOB	Mexican blue oak	106	0.146	0.0028	0.5283
Quercus wislizeni	QUWI2	Interior live oak	752	0.1478	0.0019	0.5332
Robinia neomexicana	RONE	New Mexico locust	294	0.1152	0.0153	0.3716
Salix sp.	SALIX	Willow	456	0.081	0.0024	0.5359
Taxus brevifolia	TABR2	Pacific yew	2106	0.1073	0.0014	0.5397
Thuja plicata	THPL	Western redcedar	6816	0.117	0.0006	0.574
Tsuga heterophylla	TSHE	Western hemlock	9992	0.0893	0.0012	0.5602
Tsuga mertensiana	TSME	Mountain hemlock	2796	0.0709	0.0013	0.5569
Umbellularia californica	UMCA	California-laurel	1034	0.1162	0.001	0.5601

[a] The number of observations where the species was present.
[b] Commission error is predicting the species is present when it is absent while omission error is predicting that it is absent when it is present.
[c] 99.5 percent of the viability scores are larger than this number among observations where the species is present.

2.3. Site Index

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

Because FVS uses site quality, often measured by site index, to estimate tree growth, Climate–FVS requires a function relating site quality to climate that is applicable to all forest types and their ecotones and to non-forest across all of the western United States. To provide such a function, we defined S to be the proportionate change in site index caused by a change from one climate (called C_1) to another (called C_2), where C_i is a vector of climate metrics like those used to measure the viability scores.

Let f be a function of C_i that predicts the site index, or at least a number that is proportional to the site index; then $S = f(C_2)/f(C_1)$. Note that $f(C_1) > 0$ because FVS is initiated with sites that are suitable for forests. To construct f, we used the FIA collection of site trees for the western United States, in which 82,649 observations of height and age are spread over 21,553 plots in forested lands. Approximately 39 percent of the observations in this dataset were Douglas-fir (PSME), but the remainder included 61 other species. Calibration data consisted of a random sample of 40,000 observations drawn without replacement from the full data set. To represent climates where there are no trees, 5000 points were randomly selected from lands in the western United States that are not capable of supporting forests.

Estimating site index for each tree was hampered by the several disparate regional models that use different base ages and a variety of model forms. This problem was circumvented by using Monserud's (1984) model that was calibrated for Douglas-fir to estimate a site index for each tree (Crookston and others 2010). This equation was used for all species despite the well-known differences in growth rates among species. Because Climate–FVS uses the ratio S instead of actual site index, bias introduced from using a single site curve for all species is alleviated, while the noise associated with disparate site curves and underlying techniques is avoided.

Site index is not the only determining factor of growth and therefore S is not used directly as a multiplier. The function depicted in figure 1 is used to scale S to compute a site-index related growth multiplier. This multiplier is used to represent shifts in site productive potential and is used in all variants, even those that do not directly use site index to measure productivity.
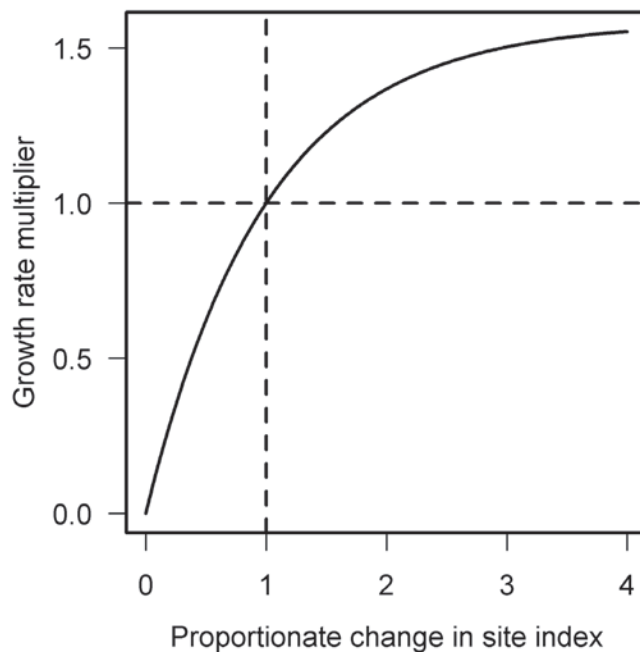

Figure 1. The site-index growth multiplier as a function of S, the proportionate change in site index.

2.4. Carrying Capacity

In FVS, carrying capacity is measured as a stand maximum basal area and as a maximum stand density index (Reineke 1933)—an internal formula converts one to the other so that both are always defined. Changes in these maximum stand densities are computed by FVS over time by calculating a weighted average maximum density among the species growing in the stand. Each species is given a default maximum density used in this calculation. Weights used in the calculation of the weighted average are the basal areas of the species present. This weighted average establishes the stand maximum in effect at a given point in simulated time.

Climate-FVS modifies the maximum carrying capacity computed by FVS by calculating a proportional change from two weighted average maximum densities. For the first of the two values, denoted D_1, the weights equal the species viability scores at the beginning of the simulation period. For the second value, D_2, the weights are the viability scores computed for the specific point in simulated time to which the modifier applies. As for computing S (section 2.3), D_1 is always greater than zero because FVS is initiated with data from sites that can support forests. The proportional change in carrying capacity is $r = D_2/D_1$.

According to this logic, maximum stand density will increase when the site becomes more suitable for species that carry high densities, but will decrease when the climate favors species that carry lesser density. This approach leaves two contingencies to address: the weighted average maximum density and the proportional change in density.

First, the weighted average maximum density (D_2) could be high even though viability scores are all low. For example, if viability scores of all species were less than 0.2 but their maximum densities were high, then the weighted average maximum density would be high because weighted averages are relative to the sum of the weights. To address this issue, an additional entry was made into the calculation of the weighted average maximum density to represent non-forests. This entry was given a carrying capacity of zero and a weight of one minus the maximum viability among the species. Secondly, the proportional change in density (r) could become extraordinarily high if the denominator in the ratio is very small compared to the numerator. To circumvent this potential problem, the magnitude of r is limited to 1.5.

The modified carrying capacity is used by FVS in its usual mortality calculations. As a stand approaches maximum density, density-dependent mortality ensues. It is also often used in specifying rules for thinning whereby a thinning is scheduled based on the stand density relative to the maximum. In Climate-FVS, the automatic establishment feature is also sensitive to this value (section 2.7).

2.5. Mortality

In Climate–FVS, mortality is a function of species viability scores described in section 2.2 and denoted as M_V and change in climate denoted as M_{dC}. The logic supporting M_V is that if viability scores drop below those at which the species occurs currently, mortality rates increase, eventually resulting in extirpation. Figure 2a illustrates the relationship between viability and mortality, plotted in the figure as survival. Experience in developing climate profiles of various species (e.g., Rehfeldt and others 2006) has shown that species rarely occur when viability scores are less than 0.5. Indeed, most sites where Pacific silver fir (ABAM) occurs receive viability scores greater than 0.9 (fig. 2b), while essentially no trees occur at viability scores less than 0.4. Table 2 shows that the histogram for Pacific silver fir is typical of many species; of the sites in which a species is present, about 60 percent had viability scores above 0.9 and 99.5 percent had viability scores above 0.55.
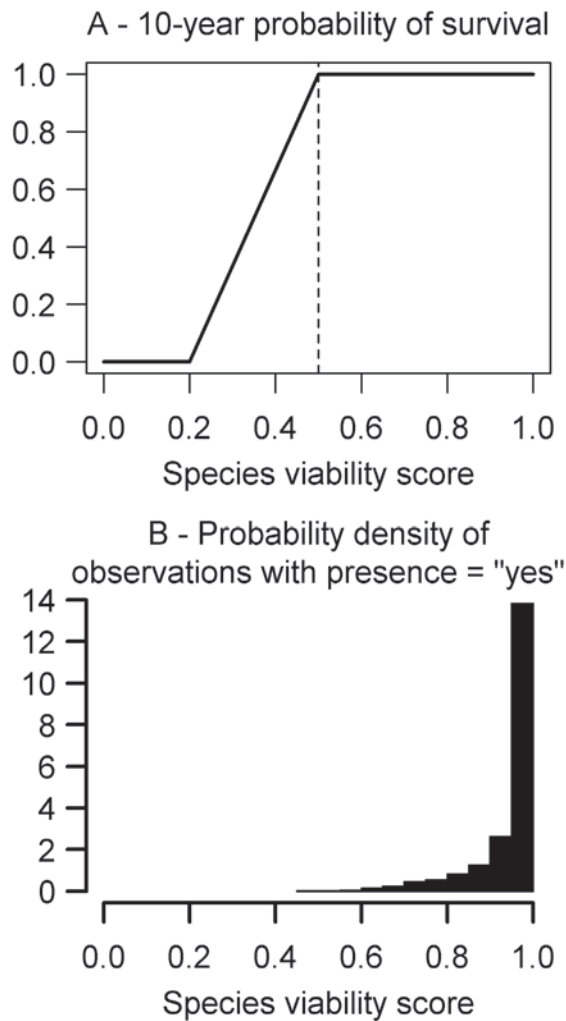

Figure 2. Representation of the logic governing a rule-based relationship between species viability scores and 10-year survival (A), and a histogram of the observations in which Pacific silver fir is present that supports the logic (B).

For Climate–FVS, we assume that at viability scores less than 0.2, a species is absent and, therefore, survival is zero. For lack of information to the contrary, we use a linear relationship to describe the decline in mortality between scores of 0.5 and 0.2 (fig. 2a). A comparison of figure 2a with figure 2b suggests that the mortality function in figure 2a overestimates survival. Note that no attempts are made to apportion mortality into causes, such as insect outbreaks, diseases, or climate-induced stress.

Experience using version 1 has led to improvements in version 2. In some cases, the Random Forest models that predict species viability commit errors of omission. They predict extremely low scores given contemporary climate even though the input tree inventory data indicates that a species is indeed present. To address this issue, an additional feature was added to scale the relationship of figure 2a. The scaling logic essentially slides the curve to the left such that 100 percent survival is predicted for the viability score computed using contemporary climate. Mortality estimated using this model, therefore, ensues if and when species become less viable in the future. The component of the model dealing with carrying capacity (section 2.4) is not adjusted.

The second factor M_{dC}, also new in version 2, is independently computed for each tree, and is based on climate change. The proposition is this: if climate changes at a location more in magnitude than is equivalent to changing elevation 300 m (~1,000 ft), then trees start to die, even if their viability score stays high. This mortality factor is herein called the *dClim* rule because it is based directly on changing climate. The rule ramps up the 10-yr mortality rate to a maximum of 90 percent; it reaches 50 percent when the magnitude of change is equivalent to twice as much climate change as expected in 300 m (fig. 3) of climate change.
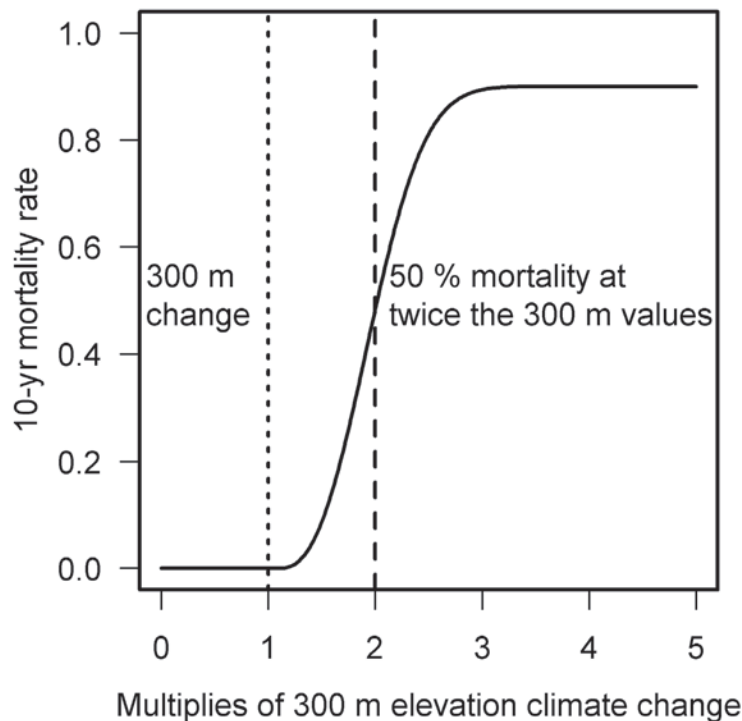

Figure 3. Ten-year mortality as a function of climate change that is equivalent in magnitude to changing elevation 300 m.

The choice of 300 m is made because it is roughly the elevation range of a seed zone (Rehfeldt 1994); trees growing beyond their adaptive range experience higher mortality rates. Model outputs from a landscape located in the western Cascade Mountains, Washington (presented by Crookston and others 2010) motivated the addition. Those simulations allowed Douglas-fir to persist on the landscape in the face of large changes in climate. Indeed, the climate remained within that tolerance for Douglas-fir as a species, but not for the population of Douglas-fir that was adapted to the site at the beginning of this century.

The magnitude of climate change is computed by comparing the value of six climate metrics for the year a given tree was born to those that correspond to a specific year in a simulation. Trees entered into the model without ages are all tagged as being born when the simulation starts. Trees established during the simulation are tagged with the birth year according to rules set in the Regeneration Establishment Model (see Dixon 2013 revision). This logic implies that trees that become established are adapted to the climate of the stand at the time of establishment.

The average of the proportionate change in the six variables measures the magnitude of change in figure 3. The six variables are: mean temperature of the warmest and coldest months, degree days above 5 °C ($dd5$), degree days below 0 °C, mean annual precipitation times $dd5$, and summer dryness index computed as $(gsdd5/gsp)^{.5}$ where $gsdd5$ is $dd5$ computed for only a few months during the summer and gsp is precipitation in the corresponding period.

The two estimates of mortality M_V and M_{dC} are reconciled with the rate FVS computes assuming no climate change (except for changing carrying capacity, section 2.4). If the estimate from FVS is higher than that computed by Climate-FVS, then the rate from the base model is used instead. This can happen when one of the other extensions is being used, such as the Fire and Fuels Extension (Rebain and others 2009) or one of the insect or disease extensions, which sometimes estimates very high mortality rates.

2.6. Growth

To address the effects of a changing climate on growth rates, Climate–FVS modifies the growth estimate of FVS. The modifier is multiplicative and is denoted as P_S, where the subscript indicates species specificity. There are three parts to the logic used to compute this modifier. The first part addresses the change in site quality, S, as defined in section 2.3. The second part addresses the expectation that living trees whose viability is decreasing should exhibit declining growth rates (see Rehfeldt and others 1999, 2001). For these trees, we added a species-specific viability, denoted by V_S and set equal to the survival rate for the species (fig. 2a). The third part (G_S) codes the adaptedness of trees as the climate changes and reflects intraspecific responses to a change in climate. Of these three effects, G_S requires elaboration before deriving P_S from S, V_S and G_S.

2.6.1. Genetic effects

It is well known from provenance tests conducted for most of the world's widespread tree species that trees grown from various seed sources exhibit different growth rates, but the expression of these differences depends on the local environment. These tests provide the best source of data for estimating change in growth associated with a change in the climate.

Re-analyses of common garden data (see Rehfeldt 1989) by Leites and others (2009, 2012) quantified Douglas-fir height growth as a function of climate metrics at the seed source and the difference in climate between the planting site and seed source. An update to version 1 replaces the earlier Douglas-fir climate-transfer model (Leites and others 2009) with the final model published by Leites and others (2012; fig. 4, left). This model was fit to height growth data from common gardens and predicts 3-year height growth as a function of mean temperature in the coldest month (*mtcm*) at the seed source and the difference between *mtcm* at the seed source and planting site. Two steps were taken to construct the model for use in FVS (fig. 4, right). The first step was to replace space with time; seed source location and planting site location were replaced with birth year and the current year of the simulation. The second step was to transform the model to compute a proportionate change in growth (G_S) so that if there is no climate change the growth multiplier is 1.0 yielding the growth FVS would otherwise estimate for the trees.
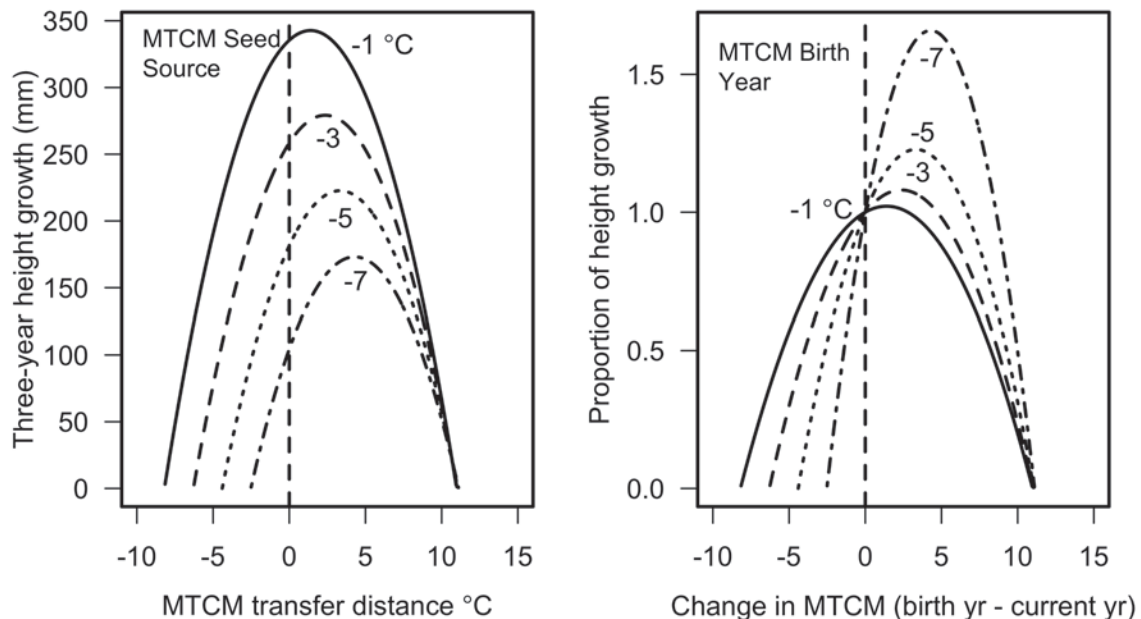

Figure 4. Left illustrates the climate transfer function for Douglas-fir from Leites and others (2012), and right illustrates the function used in Climate-FVS to compute proportion of height growth (MTCM is mean temperature of the coldest month).

The function in figure 4 indicates that increasing winter temperatures would initially benefit trees growing where winters are cold but otherwise would cause a reduction in growth. Reducing winter temperatures provides a growth decrease.

In Douglas-fir, clines relating genetic differences among seed sources to environmental gradients are relatively steep, with differences in growth potential occurring at relatively short intervals along climatic gradients. Seed sources tend to be genetically attuned to relatively specific environmental conditions and, under those conditions, are capable of expressing their growth potential (see Morgenstern 1996). Rehfeldt (1994) used the term specialist to refer to species like Douglas-fir in which clines are steep. In species with a generalist approach to adaptation (e.g., western white pine, PIMO3), clines tend to be flat; seed sources are capable of expressing their growth potential across a broad range of environments. Obviously, specialists and generalists require different sets of response functions to describe the relationship between growth and climate.

Similar, yet preliminary, response functions have been developed for western larch (LAOC) and ponderosa pine (PIPO; Leites 2009a,b), two species in which clines in genetic attributes are moderately steep. In western larch, growth is most sensitive to changes in winter temperature, while in the pine growth is most sensitive to changes in moisture index. In general, small changes in climate tend to cause either little effect or moderate increases in growth of existing populations, while large climate changes, positive or negative, always reduce growth.

Although models like these are not available for many species, some species in the western United States besides Douglas-fir have broad geographic distributions with steep clines, such as lodgepole pine (see Rehfeldt 1994). As a result, we use the values of G_S, which were calibrated for Douglas-fir, for lodgepole pine. For generalists like western white pine, Engelmann spruce (PIEN), and western hemlock (TSHE), for which clines tend to be flat, we use the values for western larch. In version 1, for all species for which geographic patterns of genetic variation are poorly documented or unknown, G_S is 1.0. In version 2, the average from the three species models is computed and it is applied to all other species. However, also in version 2, a cap of 3 times the base growth rate is imposed.

2.6.2. Growth modifier

With S, V_S, and G_S all defined, the growth modifier, P_S is chosen by the logic:

$$P_S = \min(S, V_S, G_S) \text{ if } \min(S, V_S, G_S) < 1.0, \text{ and}$$

$$P_S = \max(S, V_S, G_S) \text{ otherwise.}$$

The rationale is that if nothing is limiting growth, then the factor that results in the most growth is working in the ecosystem. Growth decreases if (1) the climate at the site becomes unsuitable to the species, (2) the site quality deteriorates, or (3) the seed source becomes maladapted to the climate.

2.7. Regeneration Establishment

Version 2 uses the same three rules used in version 1 to estimate the establishment of new trees added to under-stocked stands. The rules consider species viability scores (section 2.2) and stocking; they assume that seeds are available for regeneration or that the trees will be planted.

The first rule is that establishment will be initiated when stand density falls below a threshold set by default to 40 percent of full stocking. Full stocking corresponds to carrying capacity (section 2.4), and as a result, the density that constitutes full stocking will change as the climate changes. This default setting reflects choices made by many FVS users to simulate episodes of regeneration establishment that are usually dependent on disturbance. The second rule deals with the calculation of the number of trees to be established, which is initially set to a default of 500 trees/a (1235 trees/ha). From this maximum, the trees to be added are computed from the actual stocking and the viability scores of the species suited to the climate of the site. The proportion of the maximum number eligible for reforestation is determined by stocking levels (fig. 5a), that is, by a linear function between zero for the stocking threshold (as set by the first rule) and 1.0 when stocking is less than 25 percent of full stocking. According to figure 5a, which assumes a reproduction threshold of 50 percent of full stocking, a stand that is only 45 percent of full stocking would be allowed to receive only 20 percent of the maximum number of trees that could be established.
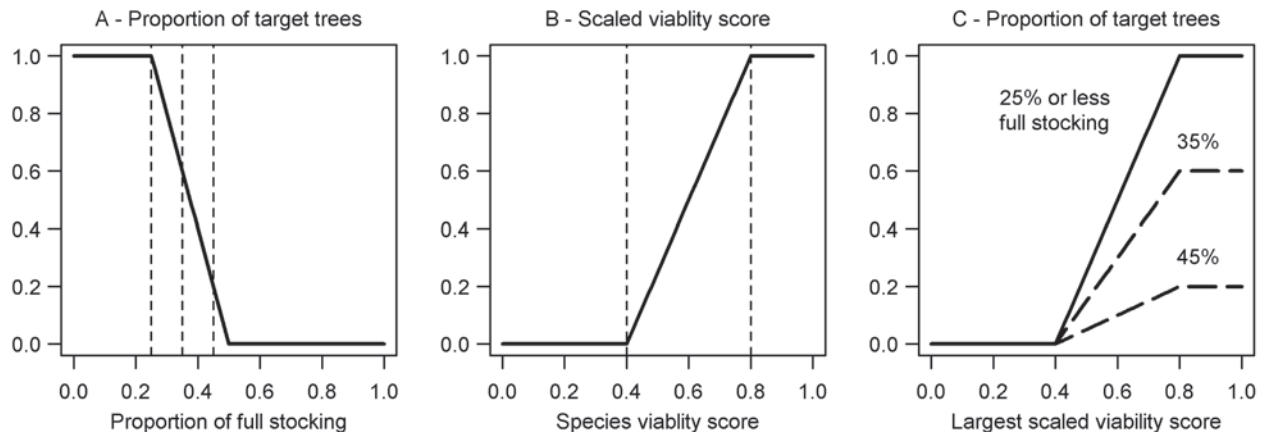

Figure 5. Regeneration–establishment rules for determining the maximum number of trees to be established in relation to full stocking (A), the scaling of species-specific viability scores (B), and the proportion of target trees to be established as a function of the proportion of full stocking and the largest scaled score (C). Vertical hashed lines in A correspond to the three values (25, 35, and 45 percent) of full stocking illustrated in (C).

The number of trees to be established also depends on species viability scores. To use viability scores for this purpose, they are scaled between values of zero (all scores less than 0.4) and one (scores greater than 0.8), as depicted in figure 5b. If the viability score is less than 0.4, then no trees will be established, regardless of allowable proportion; but, if viability is greater than 0.8, all of the allowable trees will be established. These threshold values were selected in order to be consistent with the occurrence of species (figure 1 and the lower viability thresholds in table 2). To compute the proportion of trees that will be established, the allowable proportion (fig. 5a) is multiplied by the scaled viability score of the species with the highest score (fig. 5b) to arrive at the proportion to be established (fig. 5c). For example, if the target is 500 trees/a, the proportion of full stocking is 0.35, and the maximum of the scaled viability scores is 1.0, then the number of trees to be established is 300 trees/a. However, if the maximum scaled viability score is 0.6, the number to establish would be about 150 trees/a, and if the score is 0.4 or less no trees would be established.

In the third rule, the trees to be established are allocated among species. To accomplish this, all species with scaled viability scores less than 0.40 are ignored. From the species remaining, a maximum of four (by default) species are selected according to their viability scores. The number of trees to be established is apportioned among the species using the scaled scores as weights; the proportion allocated is determined by the ratio of the scaled score for a species and the sum of the weights. Figure 6 provides four examples of applying these rules. In figures 6A and 6B the viability scores are the same, but because the percentage of full stocking differs, the numbers of trees to be established differ greatly. In figure 6C and 6D, the percentage of full stocking is low and equal, but species viability scores differ greatly. As a result, most of the trees to be established are those best suited for the climate of the site.
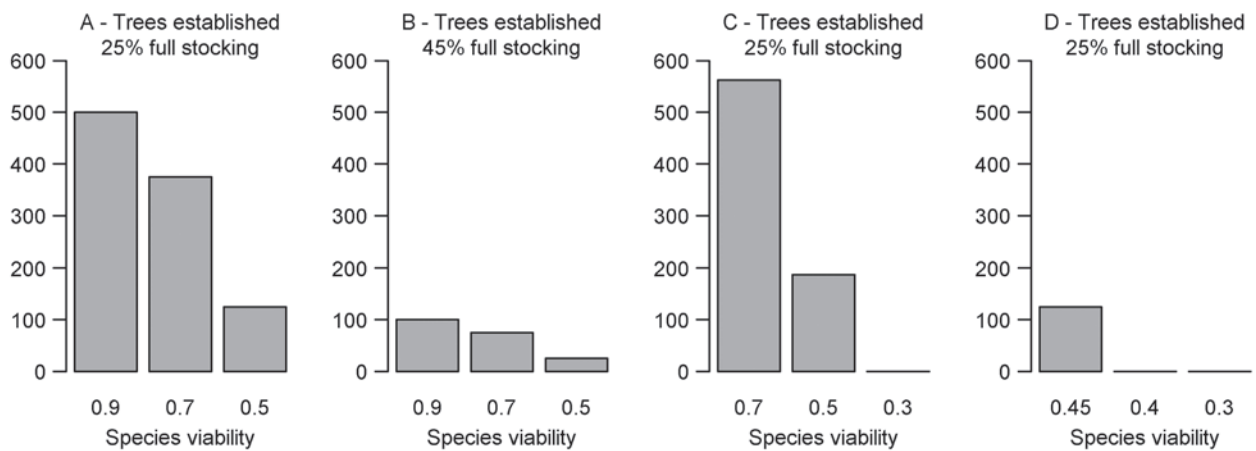

Figure 6. Four examples of applying the establishment rules, each illustrating responses for three species according to their viability score.

3. Users Guide

3.1 Keywords

Climate-FVS is controlled using standard FVS keywords, see Dixon (2013 revision) for an explanation. As with other FVS extensions, the Climate keywords must be preceded with the `Climate` keyword and finish with the `End` keyword, that signal the start and end of the Climate-FVS keywords. The FVS User Interface (Suppose) will automatically add these keywords to the simulation, therefore there is no need to add them if you are using Suppose. Only one of the keywords is required: `ClimData` is used to signal Climate-FVS to read a data file to get necessary climate and species viability information. It is also used to specify which of several general circulation models (GCM) and scenarios will be used in the simulation. The other keywords control the establishment, growth, and mortality features of Climate-FVS allowing the model to be tuned as needed. Note that the arguments to four Climate-FVS keywords can be specified using the `Parms` feature of FVS (Dixon 2013 revision, p 157) as an alternative to using the fixed fields normally used to enter data using keywords. Those that support this feature are `AutoEstb`, `GrowMult`, `MxDenMlt`, and `MortMult`.

ClimData Signal that the climate and species-viability data be read from an external file. Climate-FVS reads this file and stores information for the current stand and for a specific GCM/scenario combination. This keyword must follow the specification of the stand identification in the keyword file.

Supplemental data:

There are two supplemental data records that follow the `ClimData` keyword. The first is the short name (table 1) of the general circulation model (GCM) and scenario that is being run. Optional values for these entries depend on the contents of the climate-viability file (section 3.2). The second record contains the climate-viability file name. By convention this name is: `FVSClimAttrs.csv` but can be any other name and there is no default.

SetAttr Change the values for a single attribute from those in the climate attributes file to new values. This keyword must follow the `ClimData` keyword.

Field 1: A character string that matches one of the attributes in the climate attributes file. The string is case-sensitive and there is no default.

Field 2: The value associated with the first row (year) of the data; blank values are interpreted as zeros.

Field 3: The value associated with the second row of the data; blank values are interpreted as zeros.

Field 4: The value associated with the third row of the data; blank values are interpreted as zeros.

Field 5: The value associated with the fourth row of the data; blank values are interpreted as zeros.

AutoEstb Signal that Climate-FVS automatic establishment logic is turned on and that the base FVS automatic establishment features are turned off. If this keyword is not used, Climate-FVS establishment features are turned off. As stated above, this keyword supports using the `Parms` feature of FVS.

Field 1: The FVS cycle number or the calendar year when automatic establishment starts, or when the values in fields 2, 3, and 4 below are changed to new values. When this field is left blank the option takes effect immediately.

Field 2: The stocking threshold, expressed as a percentage of full stocking. If stand stocking is below this value, Climate-FVS *plants* new trees. *Default is 40 percent.*

Field 3: The number of trees per acre that are planted. The species planted are determined by Climate-FVS and depend on the viability data. *Default is 500 trees/a.*

Field 4: The number of species to establish. *Default is 4.*

Note: The logic within Climate-FVS in addition to the fields specified by the `AutoEstb` keyword, generate the number of seedlings by species. Climate-FVS automatically inserts one or more of the `Natural` keywords into the simulation and then the Establishment Model adds new trees to the projection.

GrowMult Specify a species-specific adjustment to the magnitude of the growth-rate multiplier computed by Climate-FVS. The details of the implementation are defined below. Three examples illustrate how to use this adjustment: (1) code a zero to turn off the Climate-FVS impacts on growth; (2) code 0.9 if you want 90 percent of the Climate-FVS impact to be used (for example, a computed growth decrease of 10 percent would become a 9 percent decrease, and a computed increase of 10 percent would become a 9 percent increase); or (3) code 1.5 if you want the Climate-FVS impact to be 150 percent of its original value (for example, a 10 percent growth decrease would become a 15 percent decrease, and a 10 percent increase would become a 15 percent increase). The growth rate adjustment is applied to the height growth for small trees and the diameter growth for large trees. Lastly, note that this keyword supports using the `Parms` feature of FVS.

Field 1:   The FVS cycle number or the calendar year when the multipliers are changed. When this field is left blank the multipliers are changed immediately.

Field 2:   Species code to which the multiplier is applied. *Default = All*.

Field 3:   The adjustment factor. *Default = 1.0*.

Details: Let x_i be a growth rate multiplier applied to tree i, c_i be the growth rate multiplier computed by Climate-FVS, and m be the value specified in field 3 of this keyword, then $x_i = 1 + ((c_i - 1) m)$. Note that x_i and c_i are always bounded to $>= 0$.

This logic is illustrated in figure 7. Note that a consequence of the logic is that for any value of m the growth adjustment actually applied to a given tree (x_i) will be less than one for any tree where c_i is less than 1.0 and it will be greater than 1.0 for trees where c_i is greater than one. The values of c_i can be less than one for some trees and greater than one for others within the same FVS cycle.
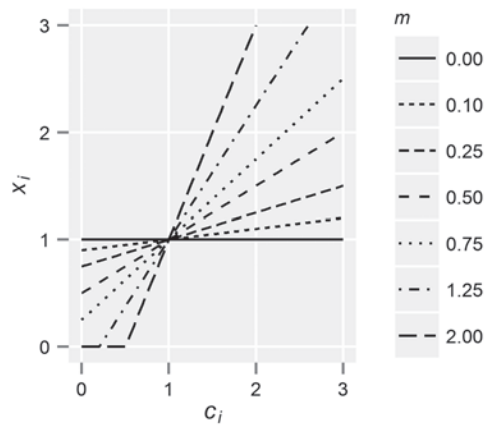

Figure 7. The logic used to scale the growth rate multiplier computed by Climate-FVS (c_i) that are applied to individual trees (x_i) given multiplier specified on the keyword (m).

MortMult   Specify two species-specific mortality multipliers. The first multiplier applies to the mortality rate related to species viability scores as in version 1.0 of Climate-FVS and the second is related to the new mortality component related to the magnitude of climate change as covered in section 2.5. Climate-FVS multiplies climate-caused mortality rates by these multipliers. It then compares these rates to the background rates computed by FVS for each tree and applies the highest rate. Therefore, you can turn off the climate-caused mortality features for a species by setting the corresponding multipliers to zero. Note that this keyword supports using the `parms` feature of FVS.

Field 1: The FVS cycle number or the calendar year when the multipliers are changed. When this field is left blank the multipliers are changed immediately.

Field 2: Species code to which the multiplier is applied. *Default = All.*

Field 3: The multiplier applied to viability-related mortality, blank implies no change to existing values. *Default = 1.0.*

Field 4: The multiplier applied to mortality due to climate change magnitude (dClim rule). A blank implies no change to existing values. *Default = 1.0.*

MxDenMlt Specify an adjustment of the maximum density multiplier computed by Climate-FVS. The details of the implementation follow the pattern for `GrowMult`, including `Parms` feature support.

Field 1: The FVS cycle number or the calendar year when the multiplier is changed. When this field is left blank the multiplier is changed immediately.

Field 2: The adjustment factor, blank implies no change. *Default = 1.0.*

ClimRept Generates the Climate-FVS output report (as described in section 3.4).

3.2. Climate and Species Viability Data File

This section describes the general specifications for the climate and species viability data file. Following the specifications, a source for files that comply with these specifications is presented. Climate-FVS does not require users to use the source specified and it is possible for users to edit the data from the source prior to using that data in Climate-FVS. Indeed, a user can supply new information or edit the names of the scenarios, the climate data, the viability data, or any of these in combination so long as the requirements of the general specification are met. In addition, the `SetAttr` keyword can be used to modify values after they are read.

Version 2 of Climate-FVS uses additional data items when compared to version 1.0. Note that if you use a version 1.0 file with the version 2, features of the model that require the additional data will be turned off. For example, if the values that measure the magnitude of climate change corresponding to 300 m change in elevation are not present (the dClim rule), the mortality model (section 2.5) that relies on this information is not used. If you use a file generated for version 2 with a version 1 of Climate-FVS, the additional information in the file is ignored.

The climate and species viability data file contains sets of climate information for contemporary climate and for three points in future time, for a total of 4 data records per set (table 3). Sets are labeled by the stand identification to which they apply and the short name of the GCM and scenario they represent (table 1). There can be many sets in the file. Logic in Climate-FVS scans the file for the stand being simulated and for the GCM and scenario desired, storing the information needed for the simulation.

Table 3. Column names used in the Climate and Species Viability Data file; all temperature values are in centigrade and precipitation measures are in mm.

Column identification	Definition
Time stamp	The first column of the data is the stand identification (case sensitive); however, starting in version 2, this column name field is used to convey the date and time the Climate-FVS data was created when the web-based method described in section 3.3 is used.
Scenario	The scenario short name (see table 1)
Year	The year to which the data record corresponds
mat	Mean annual temperature
map	Mean annual precipitation
gsp	Growing season precipitation
mtcm	Mean temperature of the coldest month
mmin	Mean minimum temperature
mtwm	Mean temperature of the warmest month
mmax	Mean maximum temperature
sday	Julian date of first frost-free day in the spring
ffp	Number of frost-free days
dd5	Degree days above 5 degrees centigrade
gsdd5	dd5 accumulated within the frost-free period
d100	Julian date that dd5 reaches 100
dd0	Degree days below 0 degrees
smrpb	Summer precipitation balance: (jul+aug+sep)/(apr+may+jun)
smrsprpb	Summer/spring precipitation balance: (jul+aug)/(apr+may)
PlantCD1	Plant code for the first species (see table 2)
…	Additional plant codes (see table 2)
PlantCDn	Plant code for the nth species (see table 2)
pSite	The predicted site index, used to compute proportionate change, see Crookston and others 2010, p. 1204.
DEmtwm	Change in mtwm over a 300 m elevation gradient.
DEmtcm	Change in mtcm over a 300 m elevation gradient.
DEdd5	Change in dd5 over a 300 m elevation gradient.
DEsdi	Change in sdi over a 300 m elevation gradient.
DEdd0	Change in dd0 over a 300 m elevation gradient.
DEpdd5	Change in map times dd5 over a 300 m elevation gradient.

Each time period is labeled with a year. Values associated with the earliest year are used when simulated time proceeds the earliest year found in the file and values associated with the latest year are used when simulated time exceeds the latest year in the file. Within the time span covered by the input data, linear interpolation is used to get values for simulated years that do not coincide with one of the four years specified in the file.

The file format must be comma-separated values (csv). The first line is a header that identifies the contents of the columns. Climate-FVS assumes that the order of the first three columns are as shown in table 3, but the other columns may be in any order so long as the column identifications are exactly as shown in table 3 (they are case sensitive and exact matches are made).

Generally two kinds of information are present: climate data and species viability data. Short names for both are used to identify the contents of each column. The short names for the climate date are shown in table 3 and species abbreviations for the viability data are listed in table 2. Note that the list in table 3 is not exhaustive; columns for other species may be added and columns for species that are present at the site but whose presence should be ignored by the model can be removed from the file.

The species viability data are numeric scores between 0.0 and 1.0, where zero signifies that the species is not found in places with the corresponding climate and 1.0 signifies that the climate is consistent with places where the species is found.

3.3. Data Available From the Moscow Forestry Science Laboratory Web Site

A source of the climate and species viability data file can be found at http://forest.moscowfsl.wsu.edu/climate/customData/fvs_data.php. Instructions are present on the web site. In general, first prepare a file of location information for each stand, then send the file to the web site, receive the data back from the site, and make the file available to FVS to read. The location file specification is as follows: stand (or location) identification, longitude (decimal degrees), latitude (decimal degrees), and elevation in meters (see the web site for details). (The coordinate system of longitude and latitude is WGS84.)

Species viability scores are computed for the species listed in table 2. However only those species that have scores of more than 0.1 in any stand in your list, for any time period, and any climate scenario, are returned.

3.4. Output Reports

The effects of changing climate on growth, mortality, and regeneration are evident in the standard FVS output reports. Climate-FVS provides two outputs, one that displays the data read from the external climate and species viability data file (section 3.2), and another report designed to display how the model is working. The first of these outputs is generated when the **ClimData** keyword is used. Figure 8 is an illustration of that information, except that several lines and columns have been deleted from the figure so that it will easily fit in this document.

```
CODES:   *USED*  *USED*  *USED*  *USED*  *USED*  *USED*
YEAR       mat     map     gsp    mtcm    mmin    mtwm    mmax
1990       4.0   885.0   323.0    -6.1   -11.2    15.2    25.5
2030       5.9   916.0   345.0    -4.6    -9.2    17.3    28.1
2060       6.7   959.0   352.0    -3.0    -7.5    18.0    28.6
2090       7.2   933.0   339.0    -3.2    -7.8    19.9    30.8

...Several lines and columns were deleted in this figure.

CODES:            4=GF    9=AF                    20=MM
YEAR      ABCO    ABGR    ABLA   ABLAA    ABPR    ACGL   ACGR3
1990     0.021   0.945   0.686   0.030   0.014   0.951   0.012
2030     0.015   0.950   0.536   0.000   0.019   0.950   0.060
2060     0.039   0.935   0.110   0.044   0.106   0.574   0.051
2090     0.128   0.699   0.060   0.003   0.119   0.424   0.075

CODES:   *USED*  *USED*  *USED*  *USED*  *USED*  *USED*  *USED*
YEAR     pSite  DEmtwm  DEmtcm   DEdd5   DEsdi   DEdd0  DEpdd5
1990      61.3    1.70    1.10  283.00    0.02 -185.00  250.46
2030      63.9    1.70    1.10  283.00    0.02 -185.00  250.46
2060      71.6    1.70    1.10  283.00    0.02 -185.00  250.46
2090      82.2    1.70    1.10  283.00    0.02 -185.00  250.46

SPECIES WITHOUT ATTRIBUTES:
FVS INDEX= 19, ALPHA CODE=CO , PLANT CODE=POPUL
FVS INDEX= 22, ALPHA CODE=OH , PLANT CODE=2TD
FVS INDEX= 23, ALPHA CODE=OS , PLANT CODE=2TE
```

Figure 8. Output generated in the FVS keyword table when the **ClimData** keyword is used.

Climate metrics directly used by the model are marked with a tag *USED* while the others are reported for information only. In figure 8, for example, mat (mean annual temperature) is being used and mmax (mean maximum temperature in the warmest month) is not, although it may have been used in predicting species viability for some species.

Species viability scores from the file are also reported. Those that are used by Climate-FVS are marked with the FVS internal species numeric code and alpha code. For example, in the case illustrated in figure 8, grand fir (ABGR) is tagged as being identified by Climate-FVS as FVS species 4 with alpha code GF. White fir (ABCO) is not recognized by the regional variant of FVS used in this example.

At the end of the table, species that are recognized by FVS but have no viability data are listed. In this case, generic cottonwood (Plant code POPUL) as well as FVS species 22 and 23 (other hardwood and other softwood) have no viability data. If tree records are present in the FVS run coded with these species codes, the viability score is set to 1.0 for the entire time period.

The second output report, created by including the **ClimRept** keyword, is illustrated in figure 9. Table 4 provides detailed information on the column headings.

```
         CLIMATE-FVS VERSION 2.0 VIABILITY AND EFFECTS REPORT
    ----------------------------------------------------------------------
             SP VIA-                    VIAB. dCLIM GROWTH SITE MXDEN AUTOESTB
    YEAR SPEC BILITY  BA/A    TPA   MORT  MORT MULT   MULT MULT  TPA
    ---- ---- ------ ------ ------ ----- ----- ----- ----- ----- --------
    2005  WP  0.557   0.00    0.0 0.000 0.000 1.000 1.000 1.000      0.0
    2005  WL  0.796   0.00    0.0 0.000 0.000 1.000 1.000 1.000    109.1

    ...Lines deleted, there is one line for each species within a cycle

    2005  MM  0.951   0.00    0.0 0.000 0.000 1.000 1.000 1.000    110.1

    ...Lines deleted, there is a set of lines for each FVS cycle

    2095  WP  0.648   0.00    0.0 0.000 0.000 1.000 1.081 0.992     97.9
    2095  WL  0.459   0.08    3.5 0.137 0.180 0.932 1.081 0.992      0.0
    2095  DF  0.730  19.04   63.6 0.000 0.062 1.034 1.081 0.992    130.3
    2095  GF  0.711   0.05    0.0 0.000 0.900 1.081 1.081 0.992    122.8
    2095  RC  0.777   0.00    0.0 0.000 0.000 1.000 1.081 0.992    148.9
    2095  MM  0.418   0.00    0.0 0.273 0.000 1.000 1.081 0.992      0.0
    2095  PB  0.622   0.00    0.0 0.000 0.000 1.000 1.081 0.992      0.0
```

Figure 9. Climate-FVS output.

Table 4. Column heading descriptions for the Climate-FVS output illustrated in figure 2.

Title	Description
YEAR	The year corresponding to the first year of the FVS cycle in which the output is generated.
SPEC	The FVS species code.
SP VIA-BILITY	The species climate viability score which ranges from 0 to 1.
BA/A	The basal area per acre at the beginning of the FVS cycle
TPA	The trees per acre at the beginning of the FVS cycle
VIAB. MORT	The probability that a tree will die due to low viability scores (this is a 10-year rate, regardless of thelength of the cycle). This number will reflect values coded using field 1 of the **MortMult** keyword. Note that it does not display the base model mortality rate for the species and also that the value displayed will be applied during the model run only when it implies the highest mortality rate for trees of the given species. Also see the MXDEN MULT information below as it also affects mortality.
dCLIM MORT	The probability that a tree will die due to climate change corresponding to the amount of change expected with an elevation change of 300 m. The actual rate may be different for each tree because it is based on the year the tree was born. What is reported here is the basal-area-weighted average rate for trees of a given species. Values reported here reflect multipliers coded using field 2 of the **MortMult** keyword. Also see the MXDEN MULT information below as it also affects mortality.
GROWTH MULT	The proportion of FVS growth that trees of this species will get. This number reflects values coded using the Climate-FVS **GrowMult** keyword.
SITE MULT	The growth rate multiplier related to changes in site index. Note that the value reported is after the Climate-FVS **GrowMult** keyword is applied.
MXDEN MULT	A multiplier of base FVS maximum stand density. This number is a stand-level value and the same value is repeated for each species. Note that the value reported is after the Climate-FVS **MxDenMlt** keyword is applied. This option impacts FVS chiefly by changing the maximum density point which would trigger density-related mortality but it can also trigger harvest activities if they are dependent upon rules related to how close the stand is to its maximum carrying capacity.
AUTOESTB TPA	This is the number of trees of a given species that would be inserted in to the FVS simulation if (1) the **AutoEstb** feature were turned on, and (2) the density were low enough to trigger establishment.

USDA Forest Service Gen. Tech. Rep. RMRS-GTR-319. 2014

25

4. Applications

Crookston and others (2010) illustrated model behavior for three landscapes in the West that showed that climate change impacts on species- and size-composition as well as carbon loads compared to no climate change. The magnitudes vary depending on the climate change scenario and GCM model used as well as the initial inventory. In general, lessons learned for that paper remain valid even in light of changes in the GCMs and emission scenarios and model changes. While specific comparisons between the results in that paper and this one are not offered, the difference in the outputs between versions 1 and 2 of Climate-FVS can be traced to the introduction of the dClim rule (section 2.5).

This section provides examples of how to use the model to meet practical purposes, while simultaneously illustrating model behavior. Additional information on model behavior is presented in section 5. Three stands are used, one each from the three areas used by Crookston and others (2010). However, only the Ensemble_rcp60 scenario (table 1) is used in these examples.

4.1 West Cascades, Washington

We start with a predominately Douglas-fir stand growing on the Gifford Pinchot National Forest in southwestern Washington. The stand was inventoried in 2008, mean elevation is 3357 feet (1023 m), slope is low, and the Douglas-fir site index is 167. There are 230 small western hemlock trees/a (568 t/ha) over topped with about the same number of larger Douglas-fir and about 100 western redcedar trees/a (247 t/ha) and a few Pacific silver fir. The quadratic mean DBH is 6 in (15 cm), and there is 4036 ft^3/a (282 m^3/ha) total volume.

Climate change predicted for this site using the Ensemble_rcp60 scenario includes about a 5 percent increase of annual precipitation over the century. More significantly, mean annual temperature rises from -0.5 °C to 3.1, degree days above 5 °C increase from 694 to 1266, and the frost-free period increases from 54 days a year to 93.

Viability scores for several species are high for the entire century. Pacific silver fir (ABPR) is one that starts high and loses its viability over time at this location. For this stand, however, it is Douglas-fir that dominates now and into the future and it is this species that is highlighted here.

The left side of figure 10 shows predicted volume over time for this stand. Note that the standing volume starts to decline at about 2060. This mortality is caused by the dClim rule described in section 2.5. When M_{dC} becomes greater than one, climate has changed so much that the current stock is deemed to be not adapted to the site and starts to die. Trees of the other species die as well. However, because Douglas-fir remains viable, Climate-FVS simulates that Douglas-fir regeneration will become established. The model tags these new trees with the year they are established and subsequent climate change driving the dClim rule is based on the difference between the climate at a specific point in future time and the year the trees are established. The assumption, therefore, is that new trees are adapted stock. As you can see from studying figure 10, the stand begins to grow again and by the end of the simulation it is well on its way. A logical management option in this case is to harvest the stand prior to the ensuing mortality and thereby capture the mortality as yield and get the stand back into production sooner rather than later. The middle panel of figure 10 shows the yield trajectory for this option.

The third panel of figure 10 shows the yield for a no harvest run with the dClim-caused mortality factor turned off. Climate-FVS outputs are sensitive to this mortality component; this is a recurring theme of all the examples in sections 4 and 5.
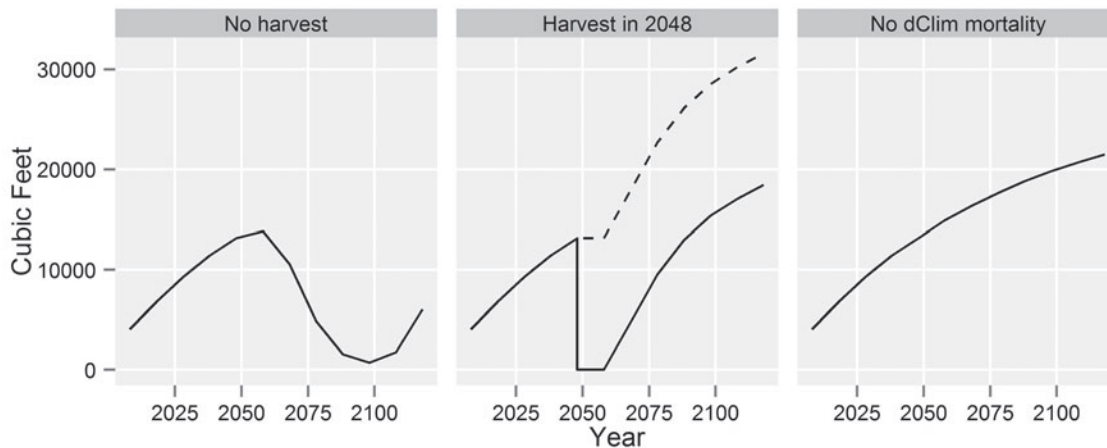

Figure 10. Cubic volume plotted over time for three run options using the example stand from western Cascade Mountains, Washington. The solid line is standing volume and the dotted line shows total production which is the standing volume plus prior removals (note that 10,000 ft^3/a is about 700 m^3/ha).

4.2 Northern Idaho

4.2.1. Setting and no harvest run

The second example is from the Clearwater National Forest, Idaho. That stand was inventoried in 2005, it is on a west-facing 20 percent slope, the elevation is 5800 ft (1768 m), and the current habitat is recorded as grand fir/beargrass (code 510, *Abies grandis/Xerophyllum tenax*). At the time of the inventory, the stand is predominately Douglas-fir, with some grand fir, subalpine fir, Engelmann spruce, and mountain hemlock (TSME). The quadratic mean diameter is 17 in (43 cm), there is 187 ft^2/a (43 m^2/ha) basal area, 5675 ft^3/a (397 m^3/ha) total volume, and the species have similar size distributions rather than one growing in the understory of the others.

The climate data from the Ensemble_rcp60 scenario indicates about a 5 percent increase of annual precipitation, mean annual temperature rises from 2.7 °C to 5.9, degree days above 5 °C increase from 911 to 1555, and the frost free period increases from 38 days a year to 95.

Figure 11 illustrates which species are considered viable now and in the future. An interesting fact is that the initial viability score is very low for mountain hemlock (TSME) yet it is present in the inventory. This is an error of omission; the viability models used to generate viability predict that the climate is not suitable for this species when in fact it is recorded as present. Model rules described in section 2.5 automatically adjust for this fact and indeed the viability-related mortality rates for mountain hemlock are low at the beginning of the simulation but increase over time because the viability decreases. Viability-related mortality remains low for the remaining four species that are present at the initial inventory. However, mortality rates increase for all species due to the dClim rule.
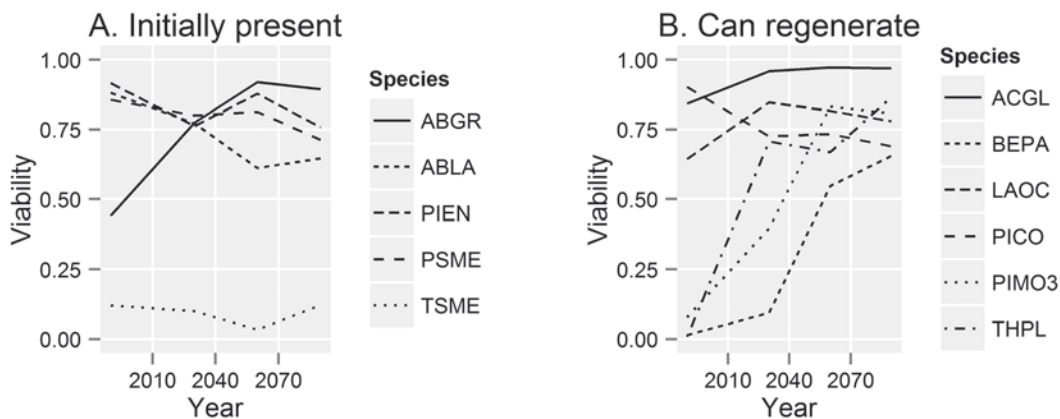

Figure 11. Species viability scores for (A), those species that are present in the initial inventory and (B) those that are not present but have greater than 0.5 viability scores at the end of the 21st century (Northern Idaho example).

The bar charts in figures 12 and 13 show the species composition in trees and volume for a no management simulation at 2045 and 2085. The figures show that Douglas-fir remains an important component of the species composition throughout the century, yet, as shown in figure 13, the volume plummets in the no-harvest simulation. This model behavior is due to (1) the mortality model killing Douglas-fir as discussed above, followed by (2) the regeneration model adding Douglas-fir trees. Recall from section 2.7 that species of high viability are added into the model and that furthermore, the trees are considered adapted to the location's climate at the time of establishment. Additional species also become viable and are indeed introduced as the existing trees die.
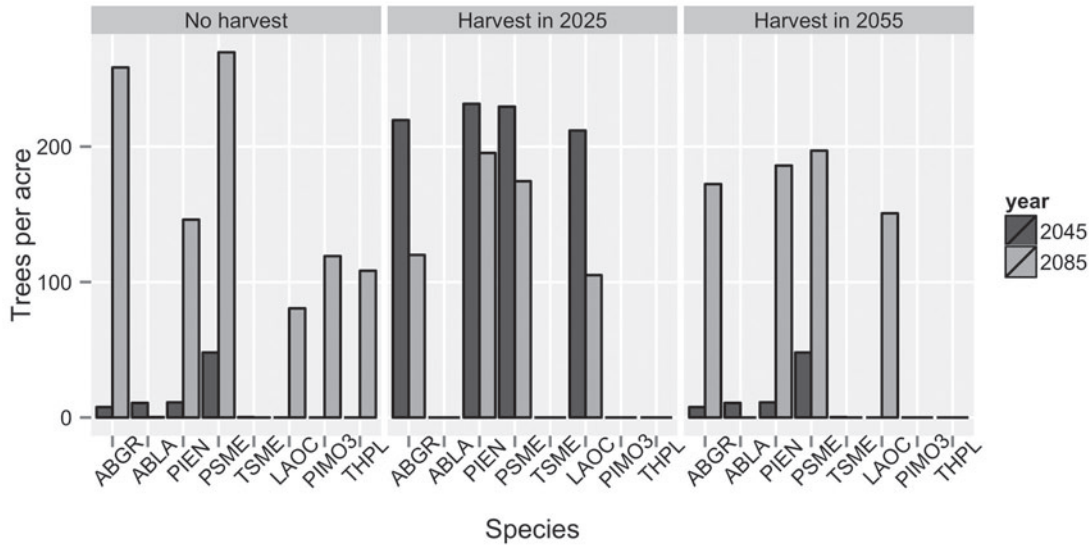

Figure 12. Trees per acre by species plotted for three simulations and two points in time (species codes are in table 2; Northern Idaho example). Note that 200 trees/a is 494 trees/ha.
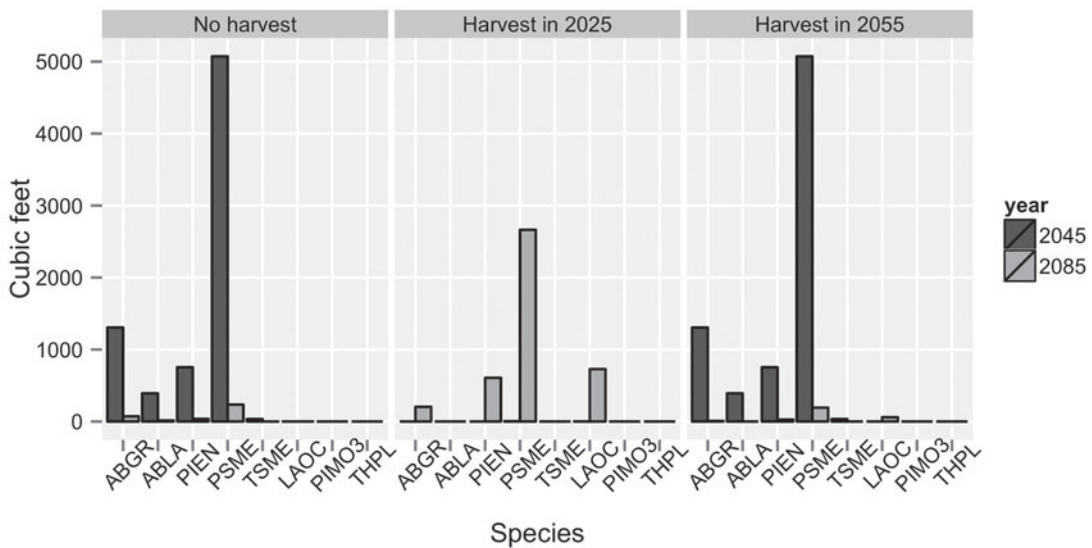

Figure 13. Volume per acre by species plotted for three simulations and two points in time for the Northern Idaho example. Note that 5000 ft^3/a is 350 m^3/ha.

4.2.2. Management alternatives

The no harvest simulation indicates that the future is bleak for this stand, with standing volume rapidly declining after 2055 (fig. 14, left) as well as the forest productivity. Can something be done to improve this prognosis? Two timing alternatives for harvesting are considered. The first is to harvest in 2025 and the second delays the harvest until 2055, about the time mortality ensues.

If maximum total production is the goal, then delaying harvest until climate-change induced mortality ensues is the best option. Harvesting in 2025 re-moved viable growing stock and replaced it with a new stand that was viable at the time of establishment. However, climate change continued, and the trees that were established soon after the 2025 harvest remained viable for about 50 years (ca. 2085), when they started to endure accelerated mortality. Indeed, the model output indicates that climate is projected to change so fast that trees will not live long enough to complete a rotation. Although delaying the harvest until 2055 indicated higher total production, it is likely that the same thing will happen to the stand established in the wake of that harvest. If the trees do not become merchantable ahead of the climate change, the indicated production will not be realized. Perhaps a fourth alternative could be contemplated: planting a species and genetic stock that can be expected to reach merchantable size in much shorter rotations.
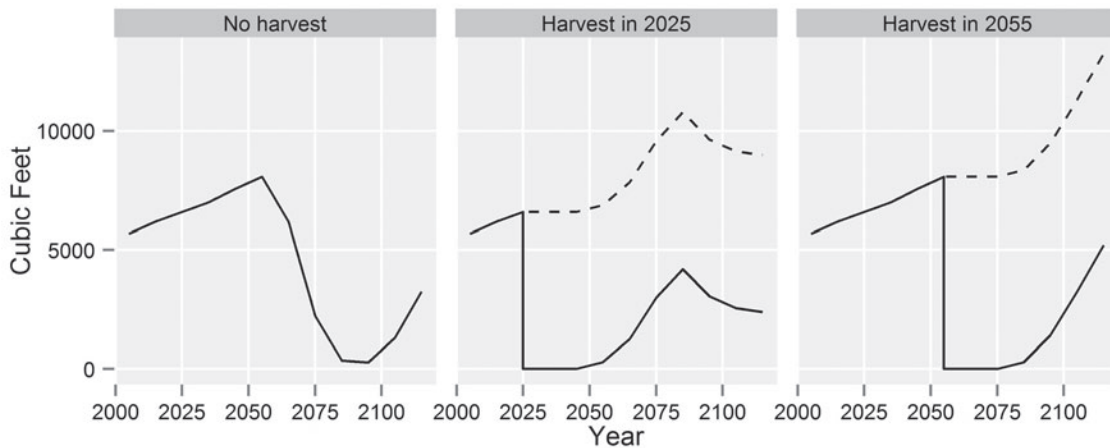
Figure 14. Standing volume and total production (dotted lines) for three simulations from the Clearwater, Idaho example.

USDA Forest Service Gen. Tech. Rep. RMRS-GTR-319. 2014

30

4.3 Western Colorado

4.3.1. Setting and no harvest run

The last example comes from the Gunnison National Forest of western Colorado. It is situated at 10,500 ft., slopes slightly to the west, and has an Engelmann spruce site index of 62 ft (19 m). Like the other examples, climate change predicted for this site using the Ensemble_rcp60 scenario includes about a 5 percent increase of annual precipitation over the century. Mean annual temperature rises from -0.5 °C to 3.1, degree days above 5 °C increase from 694 to 1266, and the frost free period increase from 54 days a year to 93. This stand was part of the Black Mesa example in Crookston and others (2010), but it is actually located north of that area.

Current stocking is about 600 subalpine fir and 350 Engelmann spruce trees/a (1483 and 865 trees/ha, respectively). The stand is dominated by large spruce that make up almost 90 percent of the 6770 ft^3/a (474 m^3/ha) at the inventory year of 2001. Species viability is generally high initially (fig. 15) for existing species but falls off quickly for spruce followed by subalpine fir. Aspen (POTR5) is viable for the life of the simulation but is not present in the initial inventory. Remarkably, Gamble oak (QUGA) becomes viable in the second half of the century. Not shown is corkbark fir (ABLAA), which briefly becomes viable but otherwise plays no important role in this stand's trajectory.
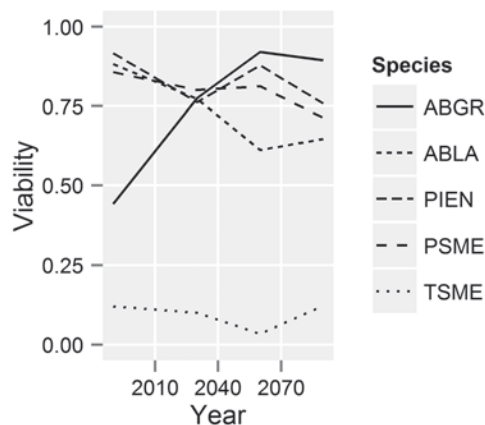
Figure 15. Viability plotted over time for the western Colorado example.

The first panel of figure 16 plots trees/a by species over time under a no manage-
ment alternative. The plot shows that the two predominant species start to die
quickly at about midcentury and that the model adds aspen, and small numbers
of corkbark fir and Gamble oak trees.

4.3.2. Management alternatives

The challenge for this stand is to keep it stocked with trees. Two approaches
were tried, one was to harvest once in 2051 and the other was to harvest twice
leaving a residual of about half of the basal area at each entry (figs. 16-17).
The reasoning behind the first alternative was to salvage dead and harvest
live trees at a time coincident with the accelerated mortality. This is fol-
lowed by regenerating aspen and Gamble oak. The objective of the second
alternative was to open the existing stand and to establish aspen prior to
the projected loss, beginning in the 2030s, of the currently growing trees.
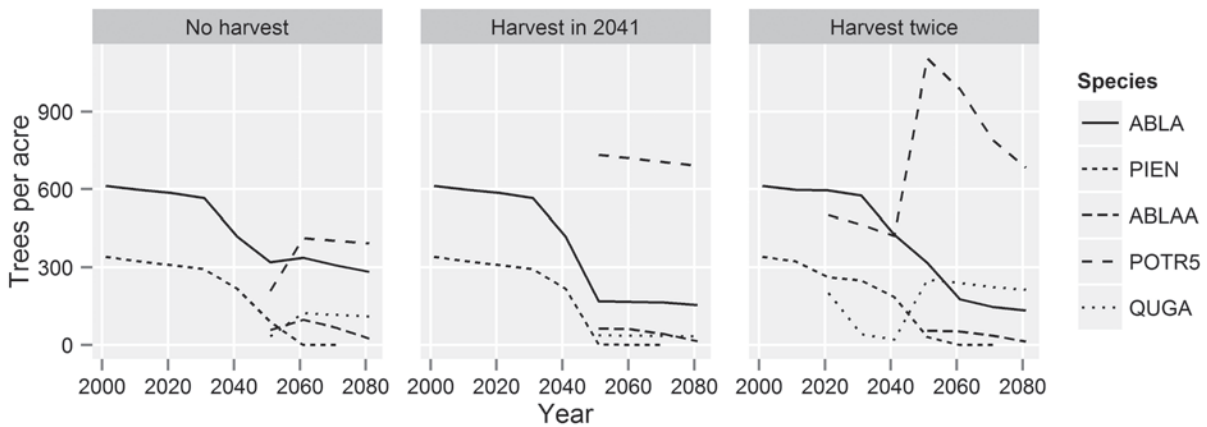

Figure 16. Trees/a plotted over time for the western Colorado example run under three management alternatives.
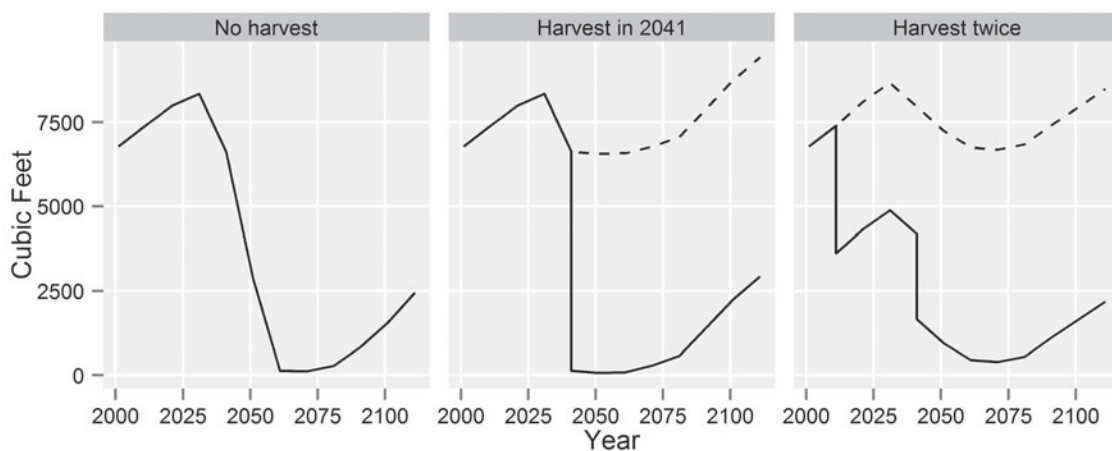Note that 900 trees/a is 2223 trees/ha.

Figure 17. Standing volume and total production (dotted lines) plotted over time for three simulations of
the western Colorado example. Note that 7500 ft³/a is 525 m³/ha.

The reasoning was that this would ensure that some minimal stocking would exist throughout the century. Figure 16 clearly shows that the trees became established but figure 17 shows that the resulting actions did not notably improve the yield. Indeed, the minimum standing volume in the two entry approach was hardly more than letting the stand die on its own and regenerate after the mortality has occurred. The reason for this result is partly due to the dClim rule that played an important role in the results in the previous two examples. In this case, the aspen planted in early 2020 was not adapted for the entire period, resulting in the decline late in the century.

5. Sensitivity

Figure 18 displays total volume plotted over time for each of the three examples run for nine cases. The purpose is to explore the sensitivity of the model to its key subcomponents. The cases were created using the keyword commands (section 3.1) to alternately turn off subcomponents and double their effectiveness. There are three panels each corresponding to the examples discussed in section 4; the solid black lines repeat the "No harvest" options in those examples. That run is identified as Case M = 1 G = 1 D = 1 in the legend because the values for the keywords used are all 1.0 that signals that the corresponding Climate-FVS subcomponents should not be increased, as would be done by setting a multiplier to a value greater than one, or decreased as would be done using values less than one. The values were set using the `MortMult` keyword for M, the `GrowMult` keyword for G, and `MxDenMlt` keyword for D. Note that `MortMult` allows users to independently adjust the viability score based and the dClim mortality components but in this case the same value of M was used for both components.
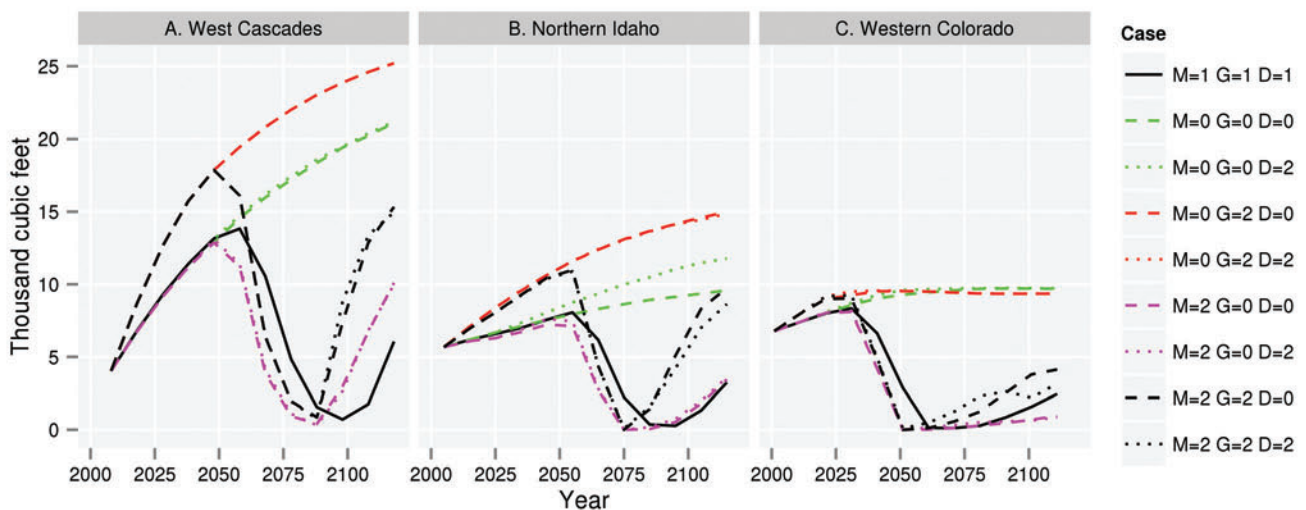

Figure 18. Yield forecasts that illustrate the sensitivity of the model to modifying the mortality components (M), the growth rates (G) and the density effect (D) to the values indicated in the legend.

A lot can be said about these outputs. Carefully studying the figure may provide the best understanding of Climate-FVS.

Clearly the mortality component is the biggest driver. Turning it off (M = 0) provides drastically different results than leaving it as is (M = 1) or doubling its effectiveness (M = 2). The trees die a bit faster with M = 2 as compared with M = 1 and slightly sooner.

Turning off versus doubling Climate-FVS's modification of growth rates does have an effect on the model outputs. Turning it off slowed the growth compared to both the base case and the cases where it was doubled in the West Cascades and northern Idaho examples. At these two locations, Climate-FVS increased growth due to climate change. In the western Colorado example, the growth rate modifications had little influence on the outputs.

In the western Colorado example, the total volume hit an apparent maximum of just below 10,000 ft^2/a. The dashed blue line essentially corresponds to a no-climate-change run and in that run, the stand simply stops growing. Note that each of these examples uses different regional variants of FVS. The West Cascades variant is used in the first example, the Inland Empire variant in the Idaho example, and the Central Rockies variant is used in the Colorado example. Different model formulations used among the regional variants influence the model results.

Changing a site's carrying capacity by modifying the maximum density (see section 2.4) has comparatively little effect. Only in the Northern Idaho example was the effectiveness of this model component evident. In that case, increasing the density effects had two opposite impacts on yield. When the mortality component was turned off (M = 0), doubling the density effect (D = 2) shows an increase in volume compared with it being off, but when the mortality component doubled (M = 2), the density effect showed a decrease in volume. In the other two examples, setting D = 0 verses D = 2 were practically identical.

6. Summary

How long will the trees survive? That is the key question that must be answered for any prediction of forest stand dynamics. Growth and yield models have always confronted this issue; if the mortality predictions are accurate, the projections can generally be used for many practical purposes.

How this question is addressed in Climate-FVS has an enormous consequence to the predictions. Most significantly, however, is that the answer to this question has an enormous consequence on the future for actual forests as opposed to simulation outputs.

Ecological geneticists have studied adaption for years and it is research results from that body of knowledge that lead to the mortality assumptions in Climate-FVS (Morgenstern 1996). Yet, an unsettled feeling sets in when the outputs are studied. Surely, existing trees will survive and if they are alive, they are growing—perhaps slowly.

Climate-FVS default settings are set up to represent science and analysis results covered in this document. Model options are included that allow users to change the model. This practice is explicitly encouraged for two reasons. First, it is important to understand the impact of model assumptions on the outputs as was done briefly in section 4.1 and in section 5. The second reason is that model users often possess ancillary information that should be considered in making projections. Taking that information into account can often be done using the commands presented in section 3.

There are many criticisms of Climate-FVS. Perhaps the most significant is directed towards using the species climate viability scores to drive mortality. These scores reflect the realized climate niche of species that is, by definition, smaller than their potential. Surely, it is argued, these species will have opportunities to exist in some conditions that are now unknown. A key idea is that the realized niche is a product of climate and competition and if the competition is removed, species will occupy a larger portion of their potential ranges. However, these expansions will not be observed until the composition changes, allowing the expansions to take place. Users that have information regarding such expansions are encouraged to override the model's values, replacing their better knowledge for the model's weaker evidence.

Another criticism is that Climate-FVS does not represent the underlying key processes driving growth. One of those has to do with the effect increasing carbon dioxide concentrations will have on water use efficiency. Indeed, this effect could result in trees being more tolerant of drought and thereby able to maintain viability beyond the conditions implied by this model. Again, the implications of this effect can be simulated using Climate-FVS by editing the viability scores to imply greater viability or by modifying growth rates. As was done in Version 1.0, representing the effects of increased carbon dioxide concentrations has been put off. Note that the sensitivity (section 5) results indicate that moderate changes in growth rates are not very important. Any factor that greatly influences mortality rates, on the other hand, is of urgent importance to include.

Generally, within the inland western United States the frost free period in forested stands is expect to more than double, and average temperatures increase between 3 and 4 °C, all while precipitation remains about the same. These are actually large changes. To get an idea of how large they are, consider two locations within your own range of experience. Pick two forested zones, one that has a mean average temperature that is 3 °C warmer than the other, with a growing season that is twice as long. Now, ask yourself just how different are the two ecosystems you have selected? When studying the outputs from Climate-FVS the magnitude of implied changes can be judged in that context.

The introduction states that providing insights into the future is an intended model use. In the West Cascades example (section 4.1), the model outputs suggest that a conversion of growing Douglas-fir growing stock from one seed source to another will be needed to keep this stand functioning as a wood producer. In the Colorado example, a high-volume conifer stand like the one that currently exists is not likely to exist in the future. Some managers may already know about these predictions and others may not. Running FVS without considering climate change will not provide relevant insights into the future as it would predict that no growing stock conversions need to be contemplated.

Acknowledgments

References

Bechtold, W.A.; Patterson, P.L., eds. 2005. The enhanced Forest Inventory and Analysis program – national sampling design and estimation procedure. Gen. Tech. Rep. SRS-80. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 85 p.

Breiman, L. 2001. Random forests. Machine Learning. 45:5–32.

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. Online: http://www.treesearch.fs.fed.us/pubs/28474.

Crookston, N.L.; Rehfeldt, G.E.; Dixon, G.E.; Weiskittel, A.R. 2010. Addressing climate change in the forest vegetation simulator to assess impacts on landscape forest dynamics. Forest Ecology and Management. 260:1198-1211. Online: http://treesearch.fs.fed.us/pubs/35984.

Daly, C.; Halbleib, M.; Smith, J.I.; Gibson, W.; Doggett, M.K.; Taylor, G.H.; Curtis, J.; Pasteris, P. 2008. Physiographically sensitive mapping of climatological temperature and precipitation across the conterminous United States. International Journal Climatology. doi:10.1002/joc.1688.

Daniels, A.E.; Morrison, J.F.; Joyce, L.A.; Crookston, N.L.; Chen, S.C.; McNulty, S.G. 2012. Climate projections FAQ. Gen. Tech. Rep. RMRS-GTR-277WWW. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 32 p.

Dixon, G.E., comp. 2002 (2013 Rev). 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. 244 p. Online: http://www.fs.fed.us/fmsc/ftp/fvs/docs/gtr/EssentialFVS.pdf.

Hansen, J. 2010. Storms of my grandchildren: The truth about the coming climate catastrophe and our last chance to save humanity. New York: Bloomsbury. 336 p.

Hutchinson, M.F. 2004. ANUSPLIN version 4.3 User's guide. Canberra: Australian National University, Centre for Resource and Environmental Studies. 54 p.

Intergovernmental Panel on Climate Change (IPCC). 2000. Summary for policymakers: emissions scenarios. Special report of IPCC working group III. ISBN: 92-9169-113-5. 21 p.

Intergovernmental Panel on Climate Change (IPCC). 2013. Summary for policymakers. In: Stocker, T.F.; Qin, D.; Plattner, G. -K; Tignor, M.; Allen, S. K.; Boschung, J.; Nauels, A.; Xia, Y.; Bex, V.; Midgley, P. M., eds. Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. Online: http://www.climatechange2013.org/images/uploads/WGI_AR5_SPM_brochure.pdf.

Leites, Laura. 2009a. Preliminary analysis of western larch field tests data. Unpublished report on file at: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Forestry Sciences Laboratory, Moscow, ID.

Leites, Laura. 2009b. Final analysis of western larch field tests data. Unpublished report on file at: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Forestry Sciences Laboratory, Moscow, ID.

Leites, L.P.; Robinson A.P.; Rehfeldt, G.E.; Marshall, J.D.; Crookston, N.L. 2009. Height growth response to changes in climate differ among populations of interior Douglas-fir: A novel analysis of provenance test data. In: Leites Barrios, L.P., ed. Differences of Douglas-fir (*Pseudotsuga menziessi* (Mirb.) Franco) populations in height growth, water use efficiency, and carbon partitioning responses to changes in climate and water availability. Ph.D. Dissertation. Moscow, ID: University of Idaho, College of Natural Resources: 5–26.

Leites, L.P.; Robinson, A.P.; Rehfeldt, G.E.; Marshall, J.D.; Crookston, N.L. 2012. Height-growth response to climatic changes differs among populations of Douglas-fir: A novel analysis of historic data. Ecological Applications. 22(1): 154-165. Online: http://treesearch.fs.fed.us/pubs/40383.

Liaw, A.; Wiener, M. 2002. Classification and regression by randomForest. R News. 2:18–22.

Monserud, R.A. 1984. Height growth and site index curves for inland Douglas-fir based on stem analysis data and forest habitat type. Forest Science. 30:943–965.

Monserud, R.A.; Rehfeldt, G.E. 1990. Genetic and environmental components of variation of site index in Douglas-fir. Forest Science. 36:1–9.

Monserud, R.A.; Huang, S.; Yang, Y. 2006. Predicting lodgepole pine site index from climatic parameters in Alberta. Forestry Chronicle. 82(4):562–571.

Monserud, R.A.; Yang, Y.; Huang, S.; Tchebakova, N. 2008. Potential change in lodgepole pine site index and distribution under climatic change in Alberta. Canadian Journal of Forest Research. 38:343–352.

Morgenstern, E.K. 1996. Geographic variation in forest trees: Genetic basis and application of knowledge in silviculture. Vancouver: UBC Press. 209 p.

Radtke, Phil. 2014. [Phone conversation between author and Radtke]. January 7. Associate Professor. Blacksburg, VA: Virginia Polytechnic Institute and State University, Department of Forest Resources and Environmental Conservation.

Rebain, S., Reinhardt, E., Crookston, N.L., Tech. eds. 2009. The fire and fuels extension to the forest vegetation simulator: Addendum to RMRS-GTR-116. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Forest Management Service Center. 243 p. Online: http://www.fs.fed.us/fmsc/ftp/fvs/docs/gtr/FFEaddendum.pdf.

USDA Forest Service Gen. Tech. Rep. RMRS-GTR-319. 2014

37

Rehfeldt, G.E. 1989. Ecological adaptations in Douglas-fir (*Pseudotsuga menziesii* var. *glauca*): A synthesis. Forest Ecology and Management. 28:203–215.

Rehfeldt, G.E. 1994. Evolutionary genetics, the biological species, and the ecology of the interior cedar-hemlock forests. In: Proceedings of the conference: Interior Cedar-Hemlock-White Pine Forests: Ecology and Management; Spokane, WA; 1993 March 2–4. Pullman, WA: Washington State University, Department of Natural Resource Sciences.

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 Sciences. 167: 1123–1150.

Rehfeldt, G.E.; Ferguson, D.E.; Crookston, N.L. 2009. Aspen, climate, and sudden decline in western USA. Forest Ecology and Management. 258: 2353–2364.

Rehfeldt, G.E.; Wykoff, W.R.; Ying, C.C. 2001. Physiologic plasticity, evolution, and impacts of a changing climate in *Piuns contorta*. Climatic Change. 50(3): 355–376.

Rehfeldt, G.E.; Ying, C.D.; Spittlehouse, D.L.; Hamilton, D.A. 1999. Genetic responses to climate in *Pinus contorta*: Niche breadth, climate change, and reforestation. Ecological Monographs. 69: 375–407.

Reineke, L.H. 1933. Perfecting a stand-density index for even-aged forests. Journal of Agricultural Research. 46: 627–638.

Stocker, T.F., D. Qin, G.-K. Plattner, L.V. Alexander, S.K. Allen, N.L. Bindoff, F.-M. Bréon, J.A. Church, U. Cubasch, S. Emori, P. Forster, P. Friedlingstein, N. Gillett, J.M. Gregory, D.L. Hartmann, E. Jansen, B. Kirtman, R. Knutti, K. Krishna Kumar, P. Lemke, J. Marotzke, V. Masson-Delmotte, G.A. Meehl, I.I. Mokhov, S. Piao, V. Ramaswamy, D. Randall, M. Rhein, M. Rojas, C. Sabine, D. Shindell, L.D. Talley, D.G. Vaughan and S.-P. Xie, 2013: Technical Summary. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. On line at: http://www.climatechange2013.org/images/report/WG1AR5_TS_FINAL.pdf

van Mantgem, Phillip J.; Stephenson, Nathan L.; Byrne, John C.; Daniels, Lori D.; Franklin, Jerry F.; Fule, Peter Z.; Harmon, Mark E.; Larson, Andrew J.; Smith, Jeremy M.; Taylor, Alan H.; Veblen, Thomas T. 2009. Widespread increase of tree mortality rates in the western United States. Science. 323: 521-524.

vanVuuren, D.P.; and 14 others. 2011. The representative concentration pathways: An overview. Climatic Change. 109:5–31.

USDA Forest Service Gen. Tech. Rep. RMRS-GTR-319. 2014

38

Rocky Mountain Research Station

The Rocky Mountain Research Station develops scientific information and technology to improve management, protection, and use of the forests and rangelands. Research is designed to meet the needs of the National Forest managers, Federal and State agencies, public and private organizations, academic institutions, industry, and individuals. Studies accelerate solutions to problems involving ecosystems, range, forests, water, recreation, fire, resource inventory, land reclamation, community sustainability, forest engineering technology, multiple use economics, wildlife and fish habitat, and forest insects and diseases. Studies are conducted cooperatively, and applications may be found worldwide. For more information, please visit the RMRS web site at: www.fs.fed.us/rmrs.

Station Headquarters
Rocky Mountain Research Station
240 W Prospect Road
Fort Collins, CO 80526
(970) 498-1100

Research Locations

Flagstaff, Arizona	Reno, Nevada
Fort Collins, Colorado	Albuquerque, New Mexico
Boise, Idaho	Rapid City, South Dakota
Moscow, Idaho	Logan, Utah
Bozeman, Montana	Ogden, Utah
Missoula, Montana	Provo, Utah