Using Landscape Simulation Modeling to Develop an Operational Resilience Metric

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Abstract—Ecological resilience is a concept that is now being used to guide U.S. land management into the uncertain future. However, there are few operational means of assessing the resilience of a landscape or ecosystem. We present a new method for quantifying resilience that uses simulated historical range and variation (HRV) time series as the benchmark or reference to compare to contemporary conditions to assess resilience. However, managing for resilience based on historical conditions is somewhat tenuous in this era of climate change, therefore we integrate projected future conditions with HRV to inform the management of ecosystems and landscapes for resilience. We use simulation results from the FireBGCv2 landscape model applied to a large landscape in western Montana USA to illustrate the methods presented here.

Keywords: historical range and variation (HRV), future range of variability (FRV), landscape modeling, ecosystem management, climate change, land management, landscape ecology, historical ecology

INTRODUCTION

Managing for "ecological resilience" is mandated by U.S. policies to guide publicly-owned landscapes into a future made uncertain due to the anticipated complex and sometimes novel interactions of anthropogenic climate change; exotic plant, insect, and pathogen invasions; and industrial, agricultural, and urban development (Moritz and Agudo 2013; Schoennagel et al. 2017). The National Cohesive Wildland Fire Management Strategy, for example, specifies *creating resilient landscapes* as one of its three major goals (USDOI and USDA 2014) and the U.S Forest Service is mandated to restore natural resources to be "more resilient to climate change" (USFS 2012). However, there are few standard metrics available to easily evaluate or quantify resilience using existing theory (Angeler and Allen 2016; Falk 2016). To manage for ecological resilience, land managers must have a standardized and scientifically credible method of quantifying resilience that is based on tangible concepts that can be included in land planning analyses (Stephens et al. 2016; Colavito 2017).

We suggest that the first step towards moving from resilience theory to its application in land management is to create a simple operational method. In this paper we present a method to quantify resilience within a

In: Hood, Sharon; Drury, Stacy; Steelman, Toddi; Steffens, Ron, tech. eds. The fire continuum—preparing for the future of wildland fire: Proceedings of the Fire Continuum Conference. 21-24 May 2018, Missoula, MT. Proc. RMRS-P-78. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 358 p.

specific area, defined as a single ecosystem, a planning area, or an entire landscape. The primary assumption of this proposed method is that ecosystems are most resilient when they are within the broad of historical range and variation (HRV; Morgan et al. 1994) because HRV represents those conditions under which most of the biota has evolved. However, rapid climate change, land use actions, exotic species invasions, and a host of other human impacts into the future requires a broader assessment than HRV alone. Therefore, we have integrated a companion FRV (future range of variation) expression into this method to help inform future land management targets. Overlaps between HRV and FRVs may provide possible targets for specific management-oriented environmental variables. We show examples of how to deploy this method into operational use, even in cases where there is little apparent overlap between the HRV and FRV.

HRV-RESILIENCE METHOD

Creating HRV and FRV Time Series

To demonstrate our HRV-based resilience method, we use simulation modeling to derive time series representing historical and future ranges of variability. We recognize the limitations of a simulation approach to quantify HRV—mainly that all models simplify reality and are subject to bias from input parameters and model mechanics (Keane 2012; Loehman et al. 2016). But simulations can provide the necessary temporally deep, spatially-explicit, and rich historical data that can be difficult to obtain elsewhere (Humphries and Bourgeron 2001). Moreover, modeling provides a single, consistent platform for generating the required data to characterize HRV for multiple ecological attributes and for generating projections of FRV under future climates.

All examples presented in this paper were generated from the mechanistic landscape model FireBGCv2 (Keane et al. 2011b) as implemented for the 128,000 ha East Fork of the Bitterroot River (EFBR) watershed on the Bitterroot National Forest, Montana, USA. The lower elevations of the EFBR are dry, mixed-conifer ecosystems of ponderosa pine (*Pinus ponderosa* var. *ponderosa*) and Douglas-fir (*Pseudotsuga menziesii* var. *glauca*) generally with a primarily frequent, low-severity fire regime (Holsinger et al. 2014). Vegetation at montane elevations are mixed conifer forests (primarily lodgepole pine, Douglas-fir, and subalpine fir (*Abies lasiocarpa*)) with mixed severity fire regimes, while high elevations are whitebark pine (*Pinus albicaulis*), subalpine fir, and spruce (*Picea engelmannii*) forests with a long fire-free interval, high-severity fire regimes. The EFBR has been used in past FireBGCv2 simulation studies with its initialization, parameterization, calibration, and validation described in various papers for the EFBR and other landscapes (Clark et al. 2017; Holsinger et al. 2014; Loehman et al. 2011). We illustrate the HRV- and FRV-resilience procedures using simulations of historical conditions and three future scenarios that incorporate one future climate and three levels of wildfire suppression (0%, 50%, and 98% fires suppressed) under a climate scenario (CRM-C5 RCP 8.5) that represents continuation of current global emissions trends (Rupp et al. 2013). The EFBR landscape's current conditions circa 2010 were used as the initial conditions at the beginning of the simulation; these conditions were measured in the field in 2009-2010 (Holsinger et al. 2014). We output a suite of landscape response variables (table 1) at ten-year intervals for five replicates of 500-year long simulations (using only the last 400 years of output to eliminate the influence of initial conditions for a total of 200 observations).

Quantifying Resilience Using Single and Multiple Response Variables

We use tree basal area (BA, m2 ha-1), often used to represent forest biomass and is commonly used in management, in the box-and-whisker diagrams that show median, 25th, and 75th percentile BA for each 10-year observation interval for the five, 400-year simulations (fig. 1). The comparative range of variation in BA among the four scenarios is immediately evident: the current BA ("Present"; the line on the graph in fig. 1) is well within the HRV interquartile range (IQR, 25th to 75th percentile); indicating it is not departed from the simulated, historical baseline ($p<0.001$). The FRV3 scenario has a significantly smaller IQR and higher median BA (pairwise t-test against FRV1 and FRV2 respectively, $p<0.001$ and $p<0.001$) than the other scenarios because the high (98%) level of fire suppression implemented

Table 1—Response variables output from the FireBGCv2 model and used in the multivariate analysis to determine a metric for resilience.

Variable	Code	Description	Units
Composition	FA-Spp, FS-Spp	Proportion of the landscape occupied by the fire-adapted species (FAD) and fire-sensitive species (FSS), respectively	%
Structure	Seed, Sap, Pole, Mat, Lrg, VLrg	The proportion of the landscape occupied by each of five structural stages	%
Basal Area	BA	Average basal area across all stands on the landscape	m^2 ha^{-1}
Coarse woody debris	CWD	Average loading of CWD (logs greater than 8 cm in diameter) across all stands in the landscape	kg m^{-2}
Fine woody debris	FWD	Average loading of FWD (woody fuel particles less than 8 cm diameter) across all stands in the landscape	kg m^{-2}
Outflow	OUTFLOW	Amount of surface water that flows out of a stand each year averaged across all stands	kg water m^{-2}
Net Primary Productivity	NPP	Average biomass production of the stand across the landscape	kg C m^{-2}
Area burned	BURN	Average annual area burned	ha

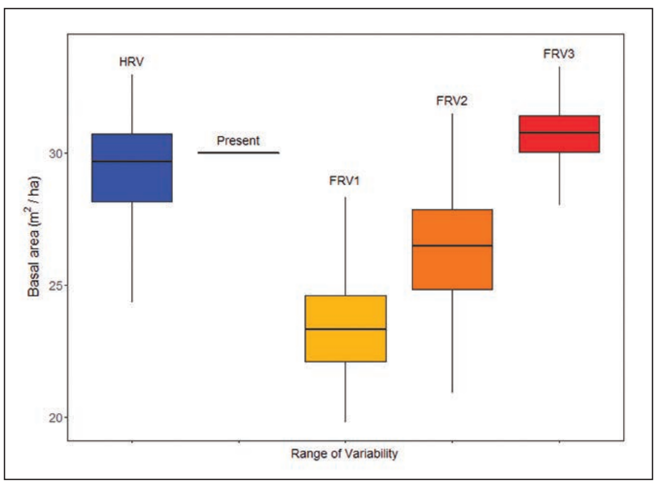

Figure 1—An illustration comparing historical (HRV) and future (FRV) ranges of variability in basal area (m^2 ha^{-1}) compared with current conditions (Present; the initial conditions at the start of the simulation) of the EFBR landscape. There appears to be a zone of overlap between HRV and FRV2 and FRV3, which may provide a possible reference for management. FRV1, FRV2, and FRV3 are future simulations with RCP4.5 climates with zero, 50 percent and 98 percent of the fire ignitions suppressed respectively. The box in this figure are the 25th and 75th interquartiles and the whiskers represent the range of the data.

in this scenario maintains high biomass on the landscape and minimizes fire-caused biomass loss. Its median BA falls within the IQR of the historical reference. The FRV2 scenario has a lower median BA, consistent with a lower implemented suppression level (50%), and a smaller zone of overlap with the historical reference, in which BA is departed for at least half of the simulation years ($p<0.001$). There is little overlap between HRV and FRV1: most observations are outside of the historical reference, where tree mortality from frequent fires and climate stress result in persistently lower BA than the historical reference With this this limited univariate example, it is interesting that greater fire suppression in the future (FRV3) may keep stands within HRV under new climates.

In the univariate method, a simple percentile number can be used as a metric for resilience. In our example above, we would calculate the percentile in which the current (Present) landscape BA resides within the HRV distribution of BA and use that as a relative score to describe resilience (Present was in the 64th percentile or a score of 64 where 50 would be high resilience and below 25 and above 75 would be low resilience, for example). Central tendency statistics that define the variability of the historical envelope and standard probability tests (e.g. one-sample t-test, or one-sample Wilcoxon test for non-normal data) can be used to determine where in the HRV BA probability distribution is the current value for BA and if it is significantly different (departed) from the HRV value. The probability of the current condition in HRV distribution can also be used as a score (Steele et al. 2006), where anything above an alpha significance level of 0.05, for example, could be considered resilient. For current BA in the EFBR, the probability of the current landscape condition in the HRV distribution is 0.69 which is less than our designated alpha level ($p>0.05$) so this landscape could be considered resilient. Keane et al. (2011a) evaluated several similarity indices for use in HRV comparisons and found that the Sorenson's Index performed best for this task. The Sorenson's Index (number between 1 and 100) is computed for each instance in a time series and the average is compared against current conditions.

We used the PCA approach to assess the importance of multiple variables in the expression of HRV (fig. 2) the first two principal components, which together explained around 45 percent of the variance in the simulation variables, Comparison of the PCA results across all FRV climate-management scenarios provides insight into the potential impacts of changing climate and fire regimes on future landscape resilience (fig. 2). Unlike results from the single variable BA (Figure 1), all three fire management scenarios (0, 50, 98% suppression, respectively) under the RCP8.5 climate depart from HRV, especially FRV3. Moreover, the state of the contemporary landscape (green asterisk) is well outside of HRV and all three FRVs, indicating that it has low resilience when multiple variables are used, regardless of climate or fire management scenario, in contrast to the univariate case. This illustrates the value of using multiple variables when evaluating resilience. The zones of overlap among the three future fire management scenarios and HRV become smaller as suppression increases. Also notice that the zone of overlap for FRV1 and FRV2 (figs. 2B, 2D, 2F) includes all of the HRV "ellipse" so any treatment that moves the landscape towards HRV will also be viable in the future.

Creating a resilience metric from multivariate time series is more difficult. A statistical approach, such as MANOVA, might be used to determine if the current condition is significantly outside the PC1-PC2 centroid, and the magnitude of that distance relative to the acceptable distance could be the metric. In our example, we set the confidence ellipse of HRV at 0.68 or an ellipse containing 68% of the observations. We then computed the ellipse probability that encompassed the current EFBR landscape (Present) at 0.995. If we assume that a 95 percent confidence level ellipse represents a resilient landscape, this test would indicate that the present landscape is in a non-resilient condition. The multivariate PCA HRV-resilience approach can also employ box-and-whisker diagrams using the scores of PC1 from the HRV time series to compare to current conditions similar to our use of BA above. We can also average Sorenson's Index calculations for each variable against the current conditions across all points in the HRV time series to obtain a resilience metric that encompasses multiple variables.

Managing For Resilience

Enhancing resilience, especially in fire-excluded forests, will probably entail some degree of either ecosystem restoration or acceptance of change (Stephens et al. 2016). Other things being equal, restoration treatments should be designed to move the current landscape in the direction of HRV but with an eye towards anticipated future conditions (Falk 1990). For example, the current landscape BA in figure 1 is well within HRV but FRV1 and FRV2 scenarios have significantly less BA. Silvicultural thinnings combined with prescribed fire treatments could be used to reduce BA of fire-sensitive species to enhance the vigor and growth of fire-adapted species in stands in the EFBR landscape to make the restoration treatment more effective into the future. Alternatively or in combination, a higher proportion of natural ignitions could be allowed to burn without full suppression, reducing the effect of fire exclusion as illustrated in our simulation results (figs. 1, 2). Designing treatments using the multi-variate PCA results may be a bit more difficult, but based on the results in figure 2 and the

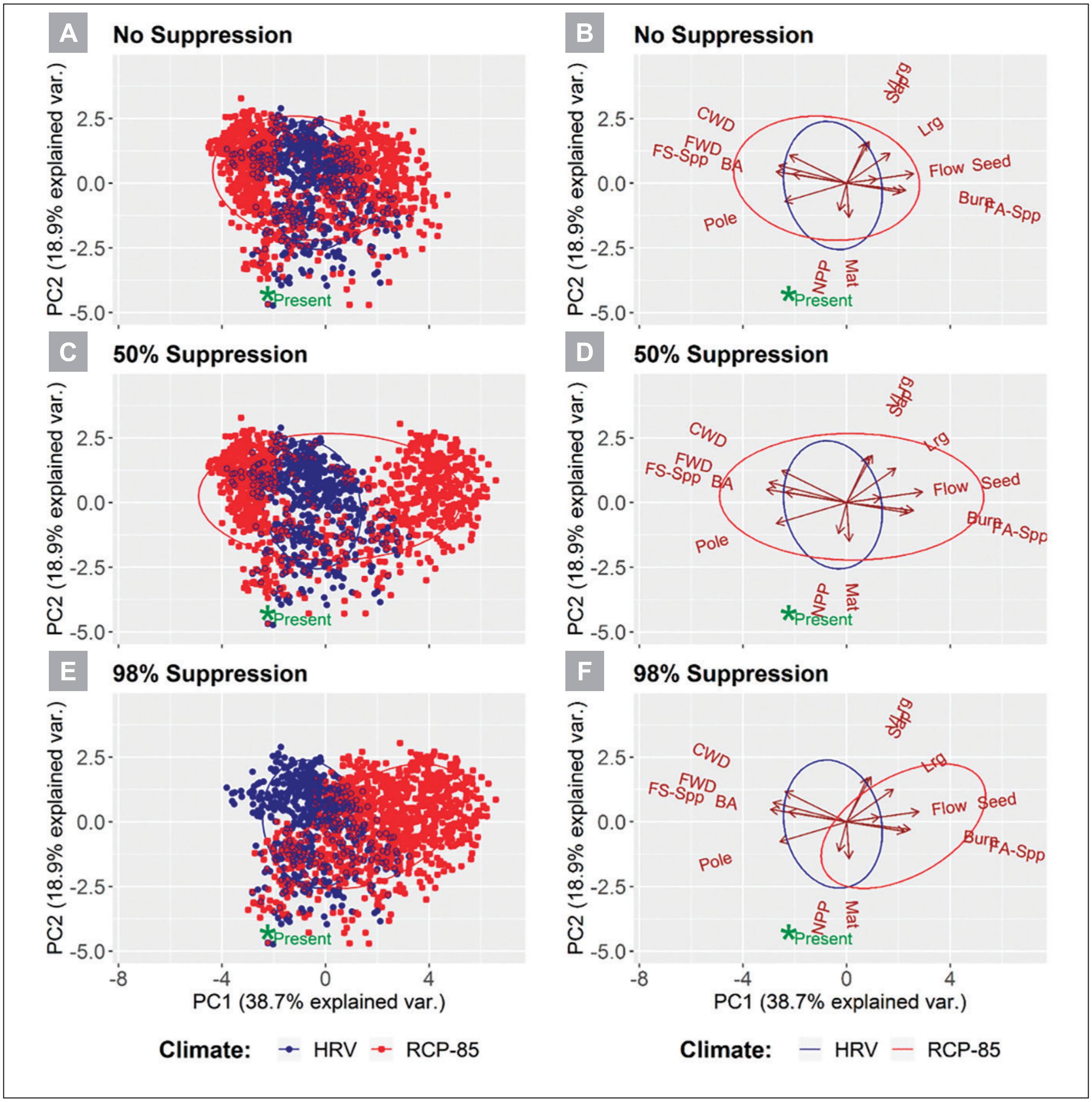

Figure 2—Results of the PCA analysis of the FireBGCv2 simulations for the EFBR landscape for the historical scenario (HRV; blue dots, reference) and for the future RCP8.5 climate (FRV1, FRV2, FRV3) under three fire suppression scenarios (no suppression, 50% ignitions suppressed, 98% ignitions suppressed) showing the simulation years (A,C,E) and the circles that contain 60 percent of the variation in the spread of the points (B,D,F). The green asterisk at the lower left of graphs A, C, E represents the condition of the landscape today. FRV1 is shown in A and B, FRV2 is C and D, and FRV3 is E and F. The variable names in B, D, and F are defined in table 1 and indicate the importance of the variables in the PC1 and PC2 scores.

variables in table 1, possible restoration goals may be to increase large (Lrg) and very large (VLrg) diameter structural stages on the landscape by thinning or prescribed burning in overly dense stands to ensure that smaller diameter pole stands eventually grow into the large structural stages.

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