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Historical Range and Variation (HRV)

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Synonyms

Natural Range of Variation (NRV)

Definition

Variation in ecosystem and landscape characteristics prior to European settlement in North America

Introduction

Many ecosystems and landscapes are experiencing rapid and potentially persistent changes as the result of complex and potentially novel interactions of anthropogenic climate changes; shifting fire regimes; exotic plant, insect, and pathogen invasions; and industrial, agricultural, and urban development (Moritz and Agudo 2013; Joyce et al. 2014; Bone et al. 2016; Kolb et al. 2016; Smith et al. 2016; Stephens et al. 2016; Schoennagel et al. 2017). In fire-prone, fire-adapted landscapes – those where fire is an integral part of ecosystem maintenance and functioning – anthropogenic actions can directly and indirectly influence fire regimes and fire effects via changes in vegetation distributions, fuel condition, and weather events that influence fire behavior (Loehman et al. 2014). Many of today's landscapes are fully departed from historical conditions, and it is difficult to determine if they should be managed as novel environments or as landscapes in transition or under recovery. A benchmark representation of those conditions that describe fully functional, healthy ecosystems or landscapes is key to understanding disturbance impacts and implementing sound ecosystem management (Cissel et al. 1994; Laughlin et al. 2004; Wiens et al. 2012). This benchmark can provide an ecological reference against which contemporary conditions can be evaluated to determine status, trend, and magnitude of departure. These departures can then be used to (1) prioritize areas for possible treatment, (2) design feasible treatments for restoration, (3) develop monitoring plans to evaluate treatment results, and (4) identify drivers of change associated with ecosystem transitions (Aplet et al. 2000; Andersen et al. 2009; Alagona et al. 2012; Dickinson 2014). Because ecosystems are inherently dynamic (White and Pickett 1985; Mori 2011), it is critical that reference conditions capture natural

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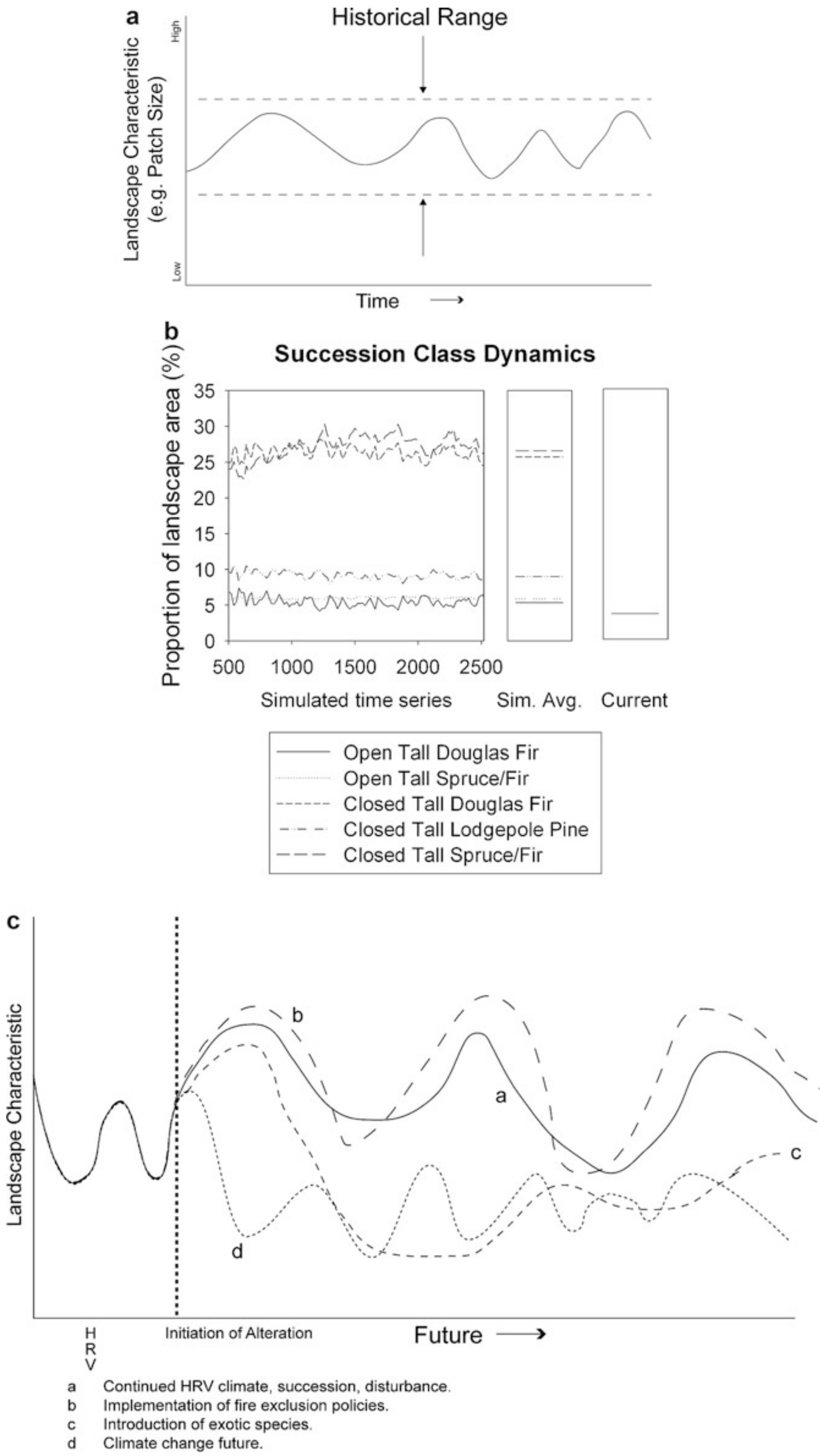


Historical Range and Variation (HRV), Fig. 1 (continued) variability over appropriate scales of time and space (Swanson et al. 1994).

Describing and quantifying ecological health, resilience, and integrity are difficult because ecosystems are highly complex, with diverse ecological processes that interact across multiple space and time scales, creating immense biotic and disturbance variability (Seidl et al. 2016). Variability is itself an important property of ecosystems because it promotes heterogeneity, biodiversity, and resilience (Aplet and Keeton 1999; Cohn et al. 2015; Desjardins et al. 2015).

Historical conditions have been used extensively and successfully as references, benchmarks, or targets by researchers and land managers over the last three decades to describe ecosystem or landscape health, but the variability of these conditions has only recently been introduced as an important evaluation criterion (Hessburg et al. 1999a; Keane et al. 2007; Dickinson 2014).

The concept of historical range and variability (HRV), also called natural range of variation and historical range of variability, was introduced in the 1990s to bring understanding of past spatial and temporal variability into ecosystem management (Cissel et al. 1994; Landres et al. 1999), via its assumptions that historical variation in ecosystem characteristics represents the broad envelope of conditions that describe landscape health, resilience, and its self-organizing capacity (Hessburg et al. 1999b; Seidl et al. 2016). For land use planning and ecosystem management, HRV provides a critical spatial and temporal foundation to plan and implement possible treatments to improve ecosystem health and integrity (Morgan et al. 1994; Swetnam et al. 1999; Seidl et al. 2016). Use of HRV supplanted single objective, target-based approaches for land management, in which managers used “target” conditions developed from historical evidence to craft treatment prescriptions and to prioritize managed areas (Harrod et al. 1999). Target conditions tended to be subjective and somewhat arbitrary because they represented only one of a wide range of conditions created by historical disturbances and vegetation dynamics (Keane et al. 2002b; Wiens et al. 2012), versus the full variation and range of past conditions across multiple scales of time and space scales that is embodied by the HRV concept (Swanson et al. 1994; Veblen 2003).

This text describes the concepts of HRV, methods for developing HRV datasets, and application of HRV for fire management. Also discussed are the limitations of HRV and its use under future climates that are no longer representative of historical conditions.

The HRV Concept

The concept that underpins HRV is that the characteristic behavior of an ecological system or its components (e.g., burned area, vegetation composition, population size), summarized over century to millennial time scales, provides an envelope of representative conditions (Aplet and Keeton 1999) (see Fig. 1 for examples). Landres et al. (1999) provided some of the initial theoretical underpinnings behind HRV, followed by a numerous reviews and applications of HRV (Kaufmann et al. 1994; Morgan et al. 1994; Swanson et al. 1994; Foster et al. 1996; Millar 1997; Aplet and Keeton 1999; Hessburg et al. 1999a; Egan and Howell 2001; Veblen 2003; Perera et al. 2004). A major assumption of HRV is that today’s biota evolved under historical conditions and, given this, HRV essentially represents the genetic potential of the flora and fauna to adapt to change (Moritz et al. 2013; Falk and Millar 2016). The HRV concept is based on the recognition that ecosystems are complex and dynamic and that the historical forces that shaped ecosys-

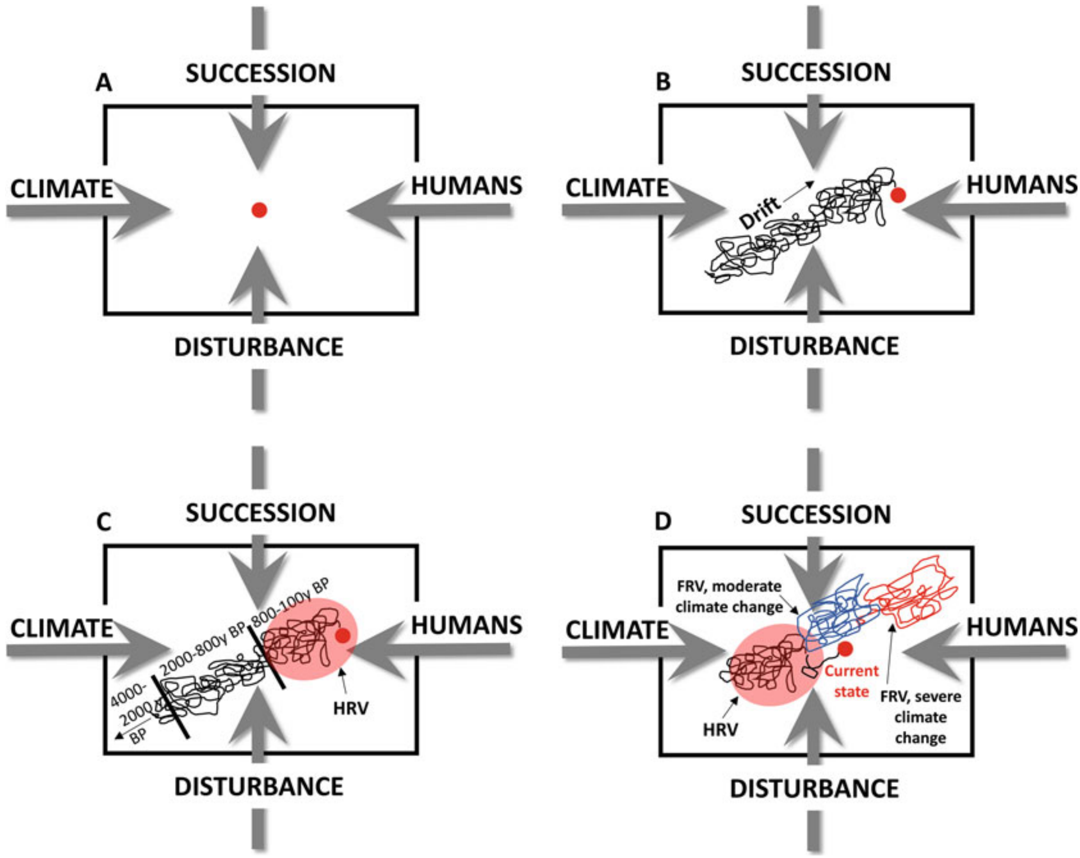
Historical Range and Variation (HRV), Fig. 1 Illustrations of the use of HRV from Keane et al. (2009): (**a**) the envelope of historical conditions represented between the two dotted lines, (**b**) simulated historical and current landscape conditions for different communities (simulated historical time series and the average and the current conditions) on a high-elevation landscape in Montana, USA, and (**c**) different trajectories of future landscape conditions under fire exclusion, exotics, and climate change tems or landscapes (e.g., climate and disturbance regimes, biotic interactions) created a range of conditions within which they are self-sustaining and, beyond this range, they may transition to disequilibrium (Egan and Howell 2001; Wu et al. 2006). As a result, historical conditions can serve as a proxy for ecosystem health (Swetnam et al. 1999) and a guide for land management (Wiens et al. 2012).

The HRV "envelope" can be visualized as the movement of a marble (ecosystem or landscape) in two-dimensional space (flat plane or table) (Fig. 2a) (Keane et al. 2018). The two dimensions of the table may represent two of the many variables that define a specific biophysical envelope or fundamental niche space, such as vegetation composition and structure (Keane et al. 2018). The marble (ecosystem) is constantly pressured by endogenous and exogenous forces, causing it to move (range) through various states on the table, each defining an expression of realized niche space. Four major forces – climate, disturbance, ecological succession, and human activity – are depicted as arrows in Fig. 2b, but other forces can be added to represent the major influences on specific ecosystems or to account for evolutionary processes. Although rare, cataclysmic events (e.g., meteor impacts, tsunamis, or volcanic eruptions) may act to push the marble (an ecosystem) off the table and onto another table representing an alternate state or biophysical setting. These exceptional events are not considered part of the HRV envelope. Ecosystems and landscapes are constantly in a state of flux, as indicated by the circuitous path of the marble over time (Fig. 2b), because the exogenous (climate, disturbance, humans) and endogenous (succession, evolution) forces exert continual pressure. For example, paleoecological records indicate major shifts in species composition, hydrology, and fire regimes in many regions of North America over the last 4,000 years of the Holocene (Gavin et al. 2007; Whitlock et al. 2011), contributing to considerable variation as represented by the long trajectory in Fig. 2c. However, during periods of more rapid environmental change, such as the Pleistocene-Holocene transition or anthropogenic climate changes that define the Anthropocene, the path of the system may respond to secular trends in the climate or disturbance signal (Fig. 2d) (Bond et al. 2005; Falk and Millar 2016).

An advantage of the HRV approach is that it can use any number of variables to describe historical variability of ecosystems and landscapes at many scales (Egan and Howell 2001; Wiens et al. 2012). The HRV of tree basal area, evapotranspiration, and coarse woody debris, for example, can be assessed at the stand, landscape, and regional spatial scale, and similarly, the HRV for landscape composition and patch structure can be computed for a watershed, National Forest, or an entire region. This multi-scaled, multi-characteristic approach allows HRV attributes to be matched to specific land management objectives at their most appropriate scales. For instance, fuel managers might decide to evaluate the HRV of coarse woody fuels and severe fire behavior at a unit level, and fire ecologists may want to evaluate HRV of patch size and contagion (spatial metrics that describe landscape patterns) at a broader, multi-watershed scale (Hessburg et al. 2007) to manage landscapes for continued ecological integrity and connectivity (Keane et al. 2018). Similarly, each HRV element can be prioritized or weighed based on its importance to land management objectives. This allows for a critical linkage to adaptive land management, where iterative HRV assessments can be used to balance trade-offs in landscape integrity of ecosystems with other social issues and economic values.

Spatial and Temporal Domains of HRV

Explicit specification of spatial and temporal domains over which the HRV envelope will be evaluated is critical. A defined spatial context ensures that variation in the selected attribute is described across the most appropriate area relative to the spatial drivers of ecosystem or landscape processes (Karau and Keane 2007). Multiple studies have shown that vegetation-environment relationships vary with the spatial



Historical Range and Variation (HRV), Fig. 2 Conceptual illustrations of historical range and variability (HRV) and future range and variability (FRV) (Keane et al. (2018)), using a marble to represent an ecosystem or landscape and a table to represent the range of biophysical conditions in a temporal domain. (**a**) The marble's position represents the state of a hypothetical ecosystem in two dimensions at any given time; the path varies over time depending on the spatial and temporal domain of evaluation and the environmental forces (arrows) acting on the marble. In this example the forces are climate, disturbance, humans, and succession. (**b**) Realignment of drivers for the last 4,000 years produces a trend driven by warming climate and increasing rates of disturbance. (**c**) HRV (colored circle) is defined using 800–100-year B.P. because of limited historical data and highest relevance to contemporary conditions. Cumulative human influence on ecosystem states and trajectories remains relatively small and nondirectional during this period. (**d**) Recent (last 100 year) conditions have pushed the ecosystem (current state) outside of the 800-year HRV envelope, as climate and disturbance regimes become more aligned and stronger, forcing the realignment of successional trajectories. Human influences become dominant during this period. Projections of the ecosystem under future climate by simulation models (blue lines) may or may not overlap with HRV, illustrated here for two possible future climate change scenarios

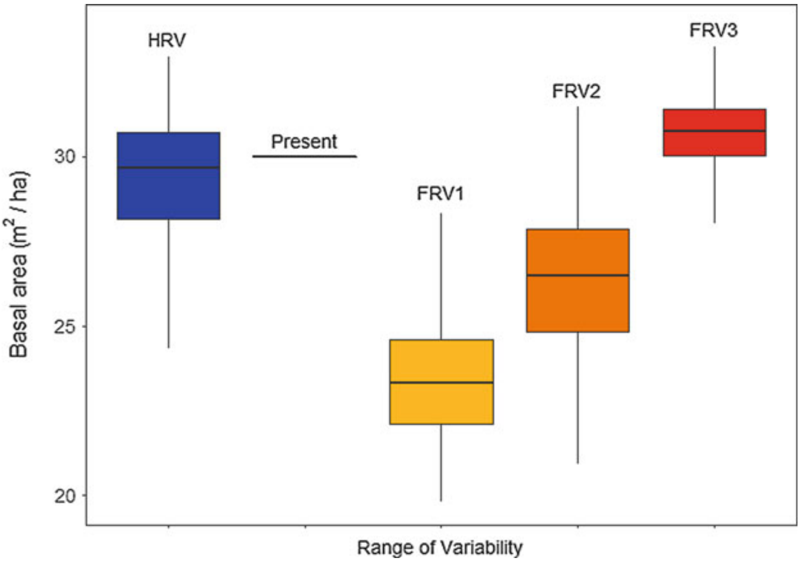
scale of observation (Wiens 1989; Palmer and White 1994; Polyakova et al. 2016), in part because the influences of edaphic, climatic, topographic, biotic, or disturbance-related variables are dependent on the dominant scale of a particular driver; the importance of climate relative to edaphic factors, for example, increases with increasing spatial extent and grain (Weins 1989); and fine woody fuel loadings vary at finer spatial scales than coarse woody debris loads (Tinker and Knight 2001). The optimal size of an HRV evaluation area will depend on (1) the ecosystem attribute evaluated, (2) the dynamics of native disturbance regimes, and (3) the relevant management issues (Tang and Gustafson 1997).

The time scale over which HRV is evaluated must also be specified to properly interpret the underlying biophysical processes that influenced historical ecosystem and landscape dynamics, especially climate (Millar and Woolfenden 1999). The HRV of vegetation species composition in a western North American landscape, for example, is likely entirely different if evaluated from 1000 to 1600 AD rather than from 1600 to 1900 A.D. because of the vast differences in climate and land use between those periods (Mock and Bartlein 1995; Swetnam et al. 2016). In general, our knowledge of ecosystem "paths" (Fig. 2c) is confined to the time domain of existing data for the landscape, as there are few detailed datasets of sufficient temporal depth, spatial extent, and appropriate resolution, to evaluate millennial-scale historical dynamics (Humphries and Bourgeron 2001; Barrett et al. 2006). Thus, temporal scale and resolution are usually dictated by the historical evidence used to define, describe, and compute HRV time series. However, some temporal parameters are selected to match specific management objectives and available data (Keane et al. 2009).

An HRV time series consists of the values of one or more variables at various time steps across an analysis area for the desired temporal domain (see examples in Fig. 1). Empirical historical reconstructions of ecosystem or landscape characteristics can be derived from sources such as pollen deposits in lake or ocean sediments; plant macrofossil assemblages deposited in middens, sediments, soils, and other sites; dendrochronological stand reconstructions; land survey records; or repeat photography (Gruell et al. 1982; Arno et al. 1995; Friedman et al. 2001; Humphries and Bourgeron 2001; Montes et al. 2005; Schulte and Mladenoff 2005) (see Egan and Howell (2001) for a summary). In general, data that can describe HRV at fine time scales, such as tree rings and fire scars, are constrained to multi-centenary time domains, whereas data that describe millennial-scale landscape phenomena, such as pollen and charcoal time series, have temporal resolutions that may be too coarse to inform land management needs (Swetnam et al. 1999). Other sources of spatial data to quantify historical landscape conditions include spatial *chronosequences* or digital maps of landscape characteristic(s) over time – these are rare or nonexistent before about 1930; *space-for-time* substitutions, which assume that samples from a broad geographic region provide representative range and variability (Hessburg et al. 1999a, b); and use of *simulation models* that can generate simulated time series data to compute HRV statistics and metrics (Keane 2012). The simulation approach relies on the accurate simulation of climate, succession, and disturbance processes in space and time (Keane et al. 2002a). Many spatially explicit ecosystem simulation models are available for quantifying HRV ecosystem or landscape dynamics (Gardner et al. 1999; Mladenoff and Baker 1999; Humphries and Baron 2001; Keane et al. 2004), but most are limited in their direct application for land management because they are computationally intensive, difficult to parameterize and initialize, and overly complex.

HRV for Land Management Applications

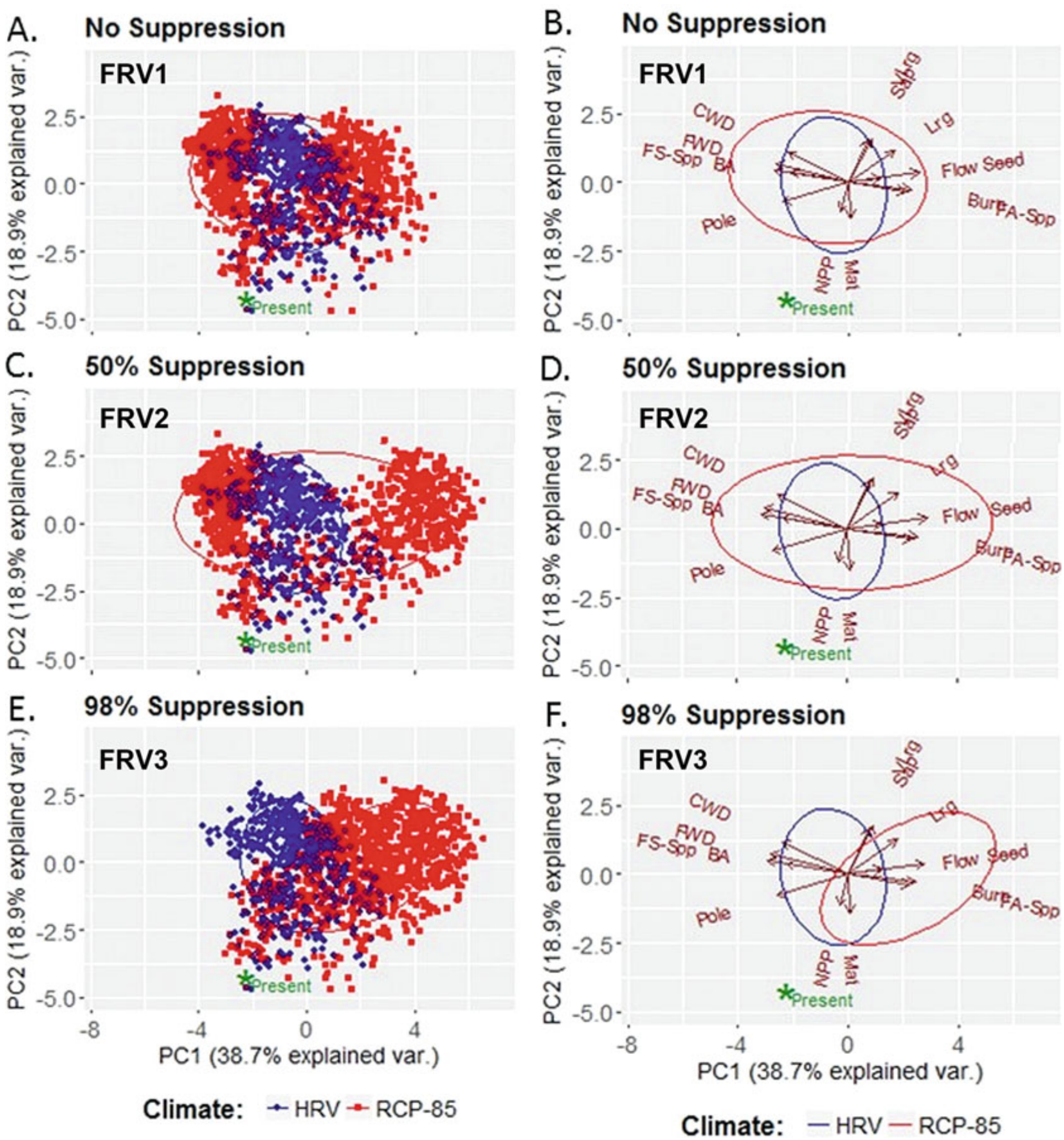
The primary management application for HRV is the comparison of current conditions with the reference HRV time series. The difference (departure) of HRV from current conditions can then be used as a tool or metric for prioritizing landscapes for restoration (Keane et al. 2007), designing treatments to restore ecosystem health (Shive et al. 2014), or quantifying ecological resilience (Keane et al. 2018). This use of HRV is illustrated using univariate and multivariate ecological responses derived from a spatial ecosystem model (Keane et al. 2011) simulated for a dry mixed-conifer watershed in the Northern Rocky Mountains, USA (Keane et al. 2018). A simple box-and-whisker plot with one response variable (Fig. 3) representing average tree basal area (BA, $m^2\ ha^{-1}$), an important forest management metric that represents forest productivity and biomass, compares conditions under current (present), historical (HRV), and three *future* ranges of variability (FRV) scenarios (FRV1, FRV2, FRV3) of increasing levels of fire suppression (0%, 50%, and 98% of natural ignitions suppressed, respectively) in a future climate (named RCP8.5, a climate scenario)



Historical Range and Variation (HRV), Fig. 3 Comparison of historical range and variability (HRV), future range and variability (FRV), and current ("present" line) basal area (BA, $m^2\ ha^{-1}$) for a dry mixed-conifer watershed in the Northern Rocky Mountains, USA (Keane et al. 2018). FRV1, FRV2, and FRV3 are increasing levels of fire suppression (0%, 50%, and 98% of natural ignitions suppressed, respectively) in a future climate (RCP 8.5) (Keane et al. 2018). Current and FRV3 BA is not significantly different from HRV (within the HRV 25th to 75th percentile interquartile range), but FRV2 and FRV1 have progressively lower median BA, consistent with increased fire-caused biomass loss. (Taken from Keane et al. (2018))

(Keane et al. 2018). The current landscape BA is well within the HRV interquartile range (IQR; 25th to 75th percentile) indicating that forest productivity has not significantly departed from the simulated HRV ($p < 0.001$); thus the landscape can be considered "resilient" or "intact" using this simplistic univariate evaluation. The median BA for the FRV3 scenario falls within the HRV interquartile range (i.e., not significantly departed); however, FRV2 and FRV1 scenarios – those with lower levels of fire suppression – produce progressively lower median BA, consistent with increased fire-caused biomass loss. The zone of overlap in the IQR between each FRV scenario and the HRV scenario indicates the percentage of model simulation years where simulated BA resides within HRV. There is almost no zone of overlap between HRV and FRV1 because tree mortality from increased fire activity and climate stress results in persistently lower BA – thus, a landscape radically departed from the historical reference.

Multivariate HRV approaches incorporate multiple ecological response variables and account for interactions among drivers and responses (e.g., climate, fire, and vegetation feedbacks). Principal components analysis (PCA), a statistical technique that simplifies the complexity of datasets but retains essential patterns (Lever et al. 2017), was applied to a suite of 14 management-oriented variables from the same spatial ecosystem model (Keane et al. 2018). Two principal components (PC1, PC2) explained about 60% of the variance in the simulation variables (4). In contrast to the univariate analysis, the current condition (labeled as "present") of the multivariate landscape (green asterisk) lies well outside the point cloud for HRV and can be considered departed from historical reference conditions. The three fire climate scenarios (FRV1, 4a and b; FRV2, 4c and d; FRV3, Fig. 4e and f) are also departed from HRV, as evidenced by the separation of HRV and FRV points and ellipses. The FRV3 scenario is particularly distinct from HRV



Historical Range and Variation (HRV), Fig. 4 Principal components analysis of multivariate model results for a dry mixed-conifer watershed in the Northern Rocky Mountains, USA (Keane et al. 2018), where HRV is represented by blue dots, current conditions are shown as a green asterisk, and FRV1 (**a**), FRV2 (**b**), and FRV3 (**c**) (0%, 50%, and 98% of natural ignitions suppressed, respectively, in RCP 8.5 future climate) are red dots. **b**, **c**, and **d** are simplifications of the scatterplots with circles that contain 68% of the variation in the spread of the points for the three FRV scenarios. (Taken from Keane et al. (2018))

because a combination of warming climate and fire suppression has shifted multiple ecosystem and fire metrics away from historical conditions. As shown in these illustrations, a multivariate approach to HRV assessment can capture essential ecological patterns and processes not evident with univariate analysis.

Challenges and Limitations of HRV

The use of HRV as a benchmark to guide future management has been challenged because climate and other environmental conditions are changing so rapidly that the future may be significantly different than analogues in the ecologically relevant past (Millar and Woolfenden 1999; Millar et al. 2007; Shive et al. 2014). As climate projections indicate, future environments may become so distinct from the past that, at some point, managing to maintain strict HRV may be impractical if not irrelevant (Shive et al. 2014). While HRV may reflect the range of conditions under which the current flora and fauna have evolved, future, no-analog climate regimes may create environments unsuitable for the evolved biota making it difficult to manage future landscapes within historical envelopes (Falk and Millar 2016). However, understanding the causes and consequences of historical variability is key to managing landscapes in the future to sustain ecosystems and the services they offer to society. There are few alternative measures of ecosystem resilience and status that match the scale, scope, flexibility, and robustness of HRV analysis (Wiens et al. 2012; Keane et al. 2018). On balance, many feel that HRV remains a valuable tool to bracket potential ecosystem responses and frame resilient management goals (Alagona et al. 2012; Seidl et al. 2016; Keane et al. 2018), at least in the near term. Future climates and their potential impacts warrant considerations; one solution is to compare HRV with possible future ranges of variability (FRV) (Moritz et al. 2013; Hansen et al. 2014) and assess the degree of departure between projected future conditions and HRV to exploit zones of overlap, as described in Figs. 3 and 4.

The concept of HRV can be quite difficult to implement due to scale, data, and analysis limitations (Wong and Iverson 2004). Inappropriate temporal and spatial scales to evaluate landscapes may introduce bias and increased uncertainty into the computation of HRV statistics because the scales of climate, vegetation, and disturbance interactions are inherently different across landscapes (Morgan et al. 1994). Karau and Keane (2007) found that simulated HRV chronosequences of landscapes smaller than 100 km^2 had increased variability in landscape composition due to the truncated spatial dynamics of simulated disturbance processes as they encountered the landscape boundary. On the other hand, when evaluation landscapes are large (>500 km^2), it is often difficult to detect significant changes caused by ecosystem restoration or management actions implemented on small areas (Keane et al. 2006). Karau and Keane (2007) suggest that the region of analysis should be large ($\geq$120 km^2) if the priority is detection of changes in vegetation and smaller ($\leq$50 km^2) if fire regime attributes are an important consideration; in addition, assessment regions can be smaller for mountainous or topographically complex areas, but must be larger when in flat areas and when fires can become large.

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Cross-References

▸ Wildland Fuel Dynamics, Fire Ecology

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