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Review

The use of historical range and variability (HRV) in landscape management

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ABSTRACT

This paper examines the past, present, and future use of the concept of historical range and variability (HRV) in land management. The history, central concepts, benefits, and limitations of HRV are presented along with a discussion on the value of HRV in a changing world with rapid climate warming, exotic species invasions, and increased land development. This paper is meant as a reference on the strengths and limitations of applying HRV in land management. Applications of the HRV concept have specific contexts, constraints, and conditions that are relevant to any application and are influential to the extent to which the concept is applied. These conditions notwithstanding, we suggest that the HRV concept offers an objective reference for many applications, and it still offers a comprehensive reference for the short-term and possible long-term management of our nation's landscapes until advances in technology and ecological research provide more suitable and viable approaches in theory and application.

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1. Introduction

The notion of managing ecosystems in a manner consistent with their native structure and processes was ushered into public land management during the 1990s as an alternative to the resource extraction emphasis that was historically employed by some government agencies (Christensen et al., 1996). This practice of ecosystem management demanded that the land be managed as a whole by considering all organisms, large and small, the pattern, abundance, and connectivity of their habitats, and the ecological processes that influence these organisms on the landscape (Bourgeron and Jensen, 1994; Crow and Gustafson, 1997). Terms like biodiversity, ecosystem integrity, and resiliency were used to describe the ultimate goal of ecosystem management – a healthy, sustainable ecosystem that could maintain its structure and organization through time (Whitford and deSoyza, 1999).

To effectively implement ecosystem management, managers required a reference or benchmark to represent the conditions that fully describe functional ecosystems (Cissel et al., 1994; Laughlin et al., 2004). Contemporary conditions could be evaluated against this reference to determine status and change, and also to design treatments that provide society with its sustainable and valuable resources while also returning declining ecosystems to a more natural or native condition (Hessburg et al., 1999b; Swetnam et al., 1999). It was also critical that these reference conditions had to represent the dynamic character of ecosystems as they vary over time and across landscapes (Swanson et al., 1994). Describing and quantifying ecological health is difficult because ecosystems are highly complex with immense biotic and disturbance variability and diverse processes interacting across multiple space and time scales from genes to species to landscapes, and from seconds to days and centuries. One of the central concerns with implementing ecosystem management was identifying appropriate reference conditions that could be used to describe ecosystem health, prioritize those areas in decline for possible treatment, and design feasible treatments for restoring their health (Aplet et al., 2000).

The relatively new concept of historical range and variability (HRV) was introduced in the 1990s to bring understanding of past spatial and temporal variability into ecosystem management (Cissel et al., 1994; Swanson et al., 1994). HRV provided land use planning and ecosystem management a critical spatial and temporal foundation to plan and implement possible treatments to improve ecosystem health and integrity (Landres et al., 1999). Why not let recent history be a yardstick to compare ecological status and change by assuming recent historical variation represents the broad envelope of conditions that supports landscape resilience and its self-organizing capacity (Harrod et al., 1999; Hessburg et al., 1999b; Swetnam et al., 1999). Managers initially used “target” conditions developed from historical evidence to craft treatment prescriptions and prioritize areas. However, these target conditions tended to be subjective and somewhat arbitrary because they represented only one possible condition from a wide range of conditions that could be created from historical vegetation development and disturbance processes (Keane et al., 2002b). This single objective, target-based approach was then supplanted by a more comprehensive theory of HRV that is based on the full variation and range of conditions occurring across multiple scales of time and space scales, along with a plethora of descriptive ecosystem elements, to protect and conserve wildland landscapes. While easily understood, the concept of HRV can be quite difficult to implement due to scale, data, and analysis limitations (Wong and Iverson, 2004).

This paper examines the past, present, and future use of HRV in land management. We first present the central concepts and history of HRV. We then detail the key benefits and limitations of the use of the HRV concept in land management. Last, we speculate on the value of HRV in a world with rapid climate warming, exotic species invasions, and expanding land development. While the HRV concept can be used to describe any set of ecosystem or landscape characteristics, this paper will focus on the use of HRV to describe *landscape composition* (e.g., vegetation types or structural stages) and *structure* (e.g., patch characteristics, landscape pattern) in land management activities. This paper is meant as a reference or guide for managers on the pitfalls and advantages of using HRV in supporting future planning activities. While HRV has problems, we feel it offers an objective and comprehensive reference for the short- and long-term management of public landscapes, at least until advances in technology and ecological understanding provide suitable alternatives.

1.1. Background

The idea of using historical conditions as reference for land management has been around for some time (Egan and Howell, 2001). In the last two decades, planners have been using target stand and landscape conditions that resemble historical analogs to guide landscape management, and research has provided various examples (Christensen et al., 1996; Fule et al., 1997; Harrod et al., 1999; Brown and Cook, 2006). However, the inclusion of temporal variability of ecosystem elements and processes into land management has only recently been proposed. In a special issue of Ecological Applications, Landres et al. (1999) presented some of the theoretical underpinnings behind HRV. Reviews and other background material on HRV and associated terminology can also be found in 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), Hessburg et al. (1999b), Egan and Howell (2001), Veblen (2003) and Perera et al. (2004). The major advancement of HRV over the historical target approach is that the full range of ecological characteristics per se is a critical criterion in the evaluation and management of ecosystems (Swanson et al., 1994). It is this variability that ensures continued health, self-organization, and resilience of ecosystems and landscapes across spatio-temporal scales (Holling, 1992). Understanding the causes and consequences of this variability is key to managing landscapes that sustain ecosystems and the services they offer to society.

The theory behind HRV is that the broad historical envelope of possible ecosystem conditions, such as burned area, vegetation cover type area, or patch size distribution, provides a representative time series of reference conditions to guide land management (Aplet and Keeton, 1999) (see Fig. 1a as an example). This theory assumes the following: (1) ecosystems are dynamic, not static, and their responses to changing processes are represented by past variability (Veblen, 2003); (2) ecosystems are complex and have a range of conditions within which they are self-sustaining, and beyond this range they transition to disequilibrium (Egan and Howell, 2001; Wu et al., 2006); (3) historical conditions can serve as a proxy for ecosystem health (Swetnam et al., 1999); (4) time and space domains of HRV are sufficient to quantify variation (Turner et al., 1993); and (5) the ecological characteristics being assessed for the ecosystem or landscapes match the management objective (Keane et al., 2002b). In this paper, we refer to HRV as the variation of historical ecosystem characteristics and processes over time and space scales that are appropriate for the management application.

Any quantification of HRV requires an explicit specification of the spatial and temporal context. The spatial context is needed to ensure that the variation of the selected ecological attribute is described across the most appropriate area relative to the spatial dynamics of the ecosystem or landscape. The variability of the area occupied by a vegetation type over time, for example, generally decreases as the spatial context increases until it reaches an

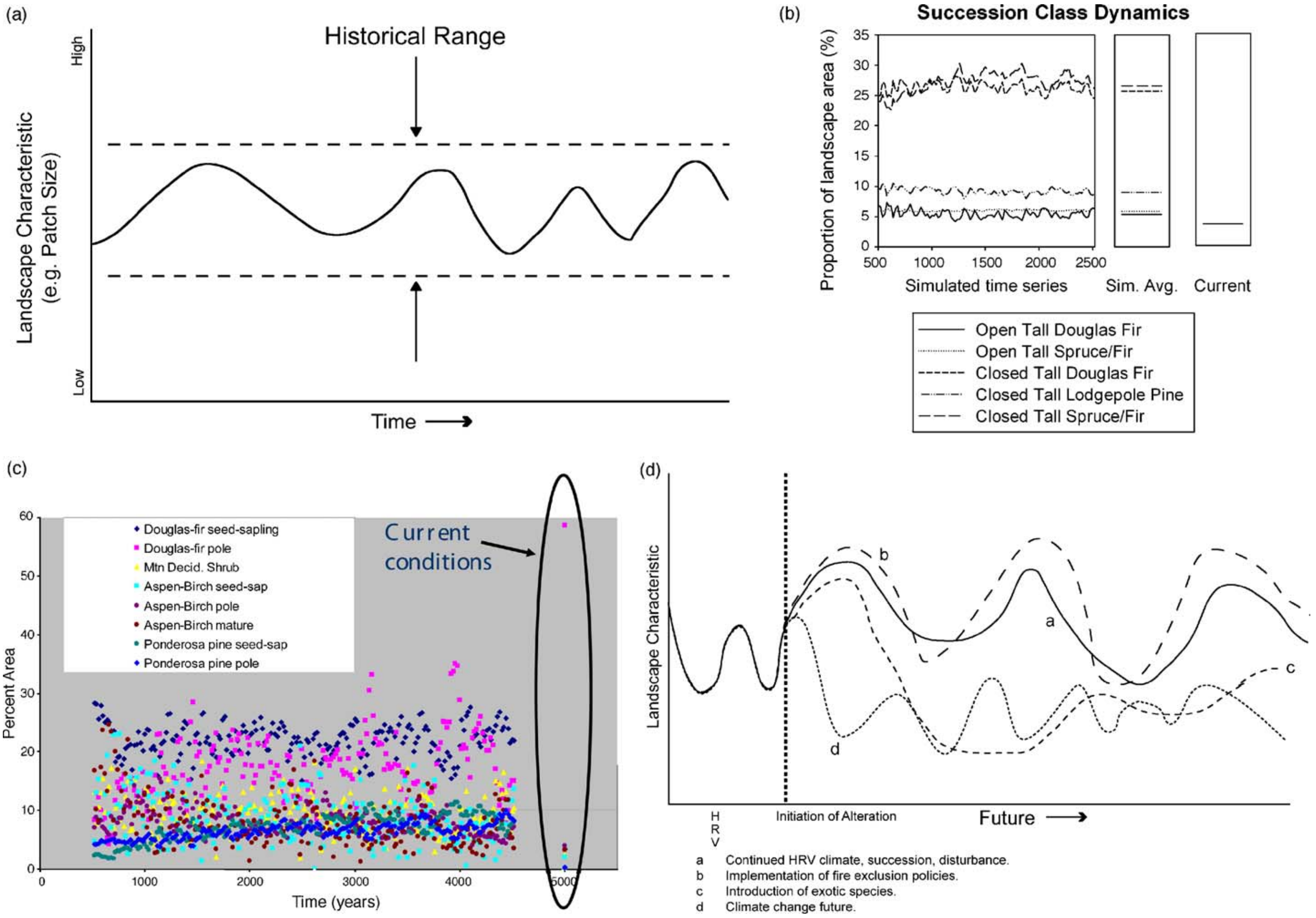

Fig. 1. Examples of time series for quantifying the historical range and variation of landscapes (HRV). (A) A simple example of how the range of a landscape characteristic can be used as an expression of HRV, (B) an illustration of the HRV for landscape composition for 10,000 ha in western Montana (Keane et al., 2008), (C) a more complex HRV time series for a 50,000 ha landscape in central Utah (Pratt et al., 2006), and (D) an illustration of how HRV can be altered by a management policy (b), introduction of exotics (c), or climate change (d).

asymptote, which can be used to approximate optimal landscape size (Fortin and Dale, 2005; Karau and Keane, 2007). The optimal size of evaluation area will depend on (1) the ecosystem attribute, (2) the dynamics of major disturbance regimes, and (3) the management activity being evaluated (Tang and Gustafson, 1997). Fine woody fuel loadings, for example, would vary across smaller areas than coarse woody debris loads (Tinker and Knight, 2001).

The time scale over which HRV is evaluated must also be specified to properly interpret the underlying biophysical processes that influenced historical ecosystem dynamics, especially climate (Millar and Woolfenden, 1999) (Fig. 1b). HRV of landscape composition might be entirely different if evaluated from 1000 to 1600 A.D. versus 1600 to 1900 A.D. because of the vast differences in climates between those periods (Mock and Bartlein, 1995). Temporal scale and resolution is usually dictated by the temporal depth of the historical evidence used to describe HRV but it can also be selected to match specific management objectives. These two scale properties are both a benefit and limitation of the HRV concept (see next sections).

Since it is impossible to quantify all ecosystem characteristics across time and space scales, HRV is most effective when confined to a set of variables that contain the following properties:

- *Measurable*. The selected variables should be quantifiable across the specified temporal and spatial extent. Insect infestations, for example, may be difficult to reconstruct over long time periods from historical evidence on the landscape.
- *Representative*. Selected variables should be representative of the patterns, processes, and characteristics that govern landscape dynamics (i.e., indicator variables). Vegetation type, for example, may be correlated to many other ecosystem characteristics, such as fire regime, to widen the scope of HRV analysis, or fire history can serve as a surrogate for vegetation successional status or disturbance frequency.
- *Appropriate*. Variables must be selected in the context of the management approach, objective, or application. The HRV of fine woody fuels, for example, may not be appropriate if the management activity or proposed action is to enhance wildlife habitat.

HRV may be used in many phases of land management. The departure of current conditions from historical variations have been used to prioritize and select areas for possible restoration treatments (Reynolds and Hessburg, 2005; Hessburg et al., 2007) or areas to conserve biological diversity (Aplet and Keeton, 1999). US fire management agencies have used Fire Regime Condition Class (FRCC), based on HRV of fire and vegetation dynamics, to rate and prioritize lands for fuel treatments (Hann and Bunnell, 2001; Schmidt et al., 2002; Hann, 2004) (www.frcc.gov). HRV is used in the LANDFIRE National Mapping Project to determine departure from historical conditions to calculate FRCC across the US at 30 m pixel resolution for fire management applications (www.landfire.gov). HRV can also be used to design treatments on the landscape. The HRV of patch size and contagion, for example, can be used to design the size of treatment area and the landscape composition can be used to select the appropriate management treatment to mimic patch characteristics (Keane et al., 2002a,b).

Reference conditions for HRV have been described for many ecosystems across the western United States and Canada. Veblen and Donnegan (2005) synthesized available knowledge on forest conditions and ecosystem disturbance for National Forest lands in Colorado, USA. The ecological and economic implications of forest policies designed to emulate historical fire regimes were investigated by Thompson et al. (2006) using a simulation approach. Historical vegetation and disturbance dynamics for southern Utah were summarized in the Hood and Miller (2007) report. Wong et al. (2003) compiled an extensive reference of historical disturbance regimes for the entire province of British Columbia, Canada. Dillon et al. (2005) and Meyer et al. (2005) detail the historical variations in upland vegetation for two national forests in Wyoming. These efforts are excellent qualitative references for understanding and interpreting historical conditions, however, they do not provide the quantitative detail needed to implement the described reference conditions directly into management applications (see Fig. 1b,c).

2. Quantifying HRV

A comprehensive quantification of HRV demands temporally deep, spatially explicit historical data, which is rarely available and often difficult to obtain (Humphries and Bourgeron, 2001; Barrett et al., 2006) (Fig. 1b,c, for example). Historical reconstructions of ecological processes and attributes can be made from many sources if they exist for the landscape (see Egan and Howell (2001) for a summary). Patterns of fire frequency and severity can be finely to broadly quantified across space and time scales using (1) fire scar dates measured from trees, snags, stumps, and downed logs, (2) charcoal deposits in soil, lake, and ocean sediments (broad), and (3) burn boundary maps from past and present sources (Swetnam et al., 1999; Heyerdahl et al., 2001; Humphries and Bourgeron, 2001). Historical vegetation conditions can be reconstructed or described from (1) pollen deposits in lake or ocean sediments, (2) plant macrofossil assemblages deposited in middens, sediments, soils, and other sites, (3) dendrochronological stand reconstructions, (4) land survey records (Habeck, 1994), and (5) repeat photography (Gruell et al., 1982; Arno et al., 1995; Humphries and Bourgeron, 2001; Friedman and Reich, 2005; Montes et al., 2005; Schulte and Mladenoff, 2005). Unfortunately, these sources can have significant limitations when used to describe landscape-level HRV in a spatial domain appropriate to land management. These data have either a confined or unknown spatial domain because they were collected on a very small portion of the landscape (i.e., plot or patch), or they pertain to a general area (middens, lake sediments) and lack spatial specificity with respect to patterns. Moreover, some ecosystems on a landscape have little evidence of past conditions with which to quantify HRV and any available data are usually limited in temporal extent. In general, those methods that describe HRV at fine time scales, such as tree fire scar dating, are constrained to multi-centenary time scales, while those methods that cover long time spans (millennia), such as pollen and charcoal analyses, have a resolution that may be too coarse for management of spatial patterns of structure and composition (Swetnam et al., 1999).

For landscape level HRV time series development, there are three main sources of spatial data to quantify historical conditions (Humphries and Bourgeron, 2001; Keane et al., 2006b). The best sources are spatial chronosequences or digital maps of landscape characteristic(s) over many time periods. These maps can be digitized with GIS software and spatial analysis programs can be used to compute HRV statistics (McGarigal and Marks, 1995). Unfortunately, temporally deep, spatially explicit time series of historical conditions are missing for many US landscapes because aerial photography and satellite imagery are rare or non-existent before 1930 A.D. and comprehensive maps of forest vegetation are scarce, inconsistent, and limited in coverage prior to 1900 (Keane et al., 2006b). Tinker et al. (2003) quantified HRV in landscape structure using digital maps of current and past landscapes in the Greater Yellowstone Area from aerial photos and stand age interpretation.

Another HRV data source is to substitute space for time and collect spatial data across similar landscapes, from one or more times, across a large geographic region (Hessburg et al., 1999a,b). Theory posits that if one samples spatial pattern of vegetation of similar biophysical environments with similar disturbance and climatic regimes, a representative cross section of temporal variation may be observed. In effect, differences in space are equivalent to differences in time, and inferences may be drawn regarding variation in spatial pattern that might occur at a single location over time. Particularly where process explanation is sought, care must be taken in application to select study locations having comparable underlying biophysical and climatic conditions. However, subtle differences in landform, relief, soils, and climate make each landscape unique and grouping landscapes may tend to overestimate range and variability of landscape characteristics (Keane et al., 2002a). Landscapes may be similar in terms of the processes that govern vegetation, such as climate, disturbance, and species succession, but topography, soils, land use, and wind direction also influence vegetation development and fire growth (Keane et al., 2002b).

A third method of quantifying HRV involves using computer models to simulate historical dynamics to produce a time series of simulated data to compute HRV statistics and metrics (Humphries and Bourgeron, 2001) (see Fig. 1b). This approach relies on the accurate simulation of succession and disturbance processes in space and time (Keane et al., 1999). Many spatially explicit ecosystem simulation models are available for quantifying HRV patch dynamics (for reviews and summaries see Gardner et al., 1999; Mladenoff and Baker, 1999; Humphries and Baron, 2001; Keane and Finney, 2003; Keane et al., 2004), but most are (1) computationally intensive, (2) difficult to parameterize and initialize, and (3) overly complex, thereby making them difficult to use, especially for large regions, long time periods, and inexperienced staffs. On the other hand, those landscape models designed specifically for management planning may oversimplify vegetation development and disturbance (Keane et al., 2004). Even the most complex landscape models rarely simulate spatial interactions between climate, disturbance dynamics, and vegetation development because of the lack of critical research in those areas and the immense amount of computer resources required for such an effort. Simulation models can include explicit simulations of climate and human activities to generate more relevant and realistic estimates of the range and variation of landscape dynamics under today's conditions. Simulation is the most common method of creating HRV time series.

Many studies have used simulation to quantify HRV for a wide variety of landscapes and ecosystems using a wide variety of models. Non-spatial models, such as VDDT (Beukema and Kurz, 1998, were used to estimate landscape composition in a wide variety of areas from the Pacific Northwest to the northern Rocky Mountains (Hann et al., 1997; Hemstrom et al., 2001, 2007; Merzenich and Frid, 2005; Merzenich et al., 2003). The LADS model was used for the Oregon Coast Range to determine the appropriate level of old growth forests (Wimberly et al., 2000), to quantify HRV in landscape structure (Nonaka and Spies, 2005), and to simulate the effect of forest polices (Thompson et al., 2006). McGarigal et al. (2003) quantified historical forest composition and structures of Colorado landscapes. Keane et al. (2002a) simulated historical landscape patch dynamics using the LANDSUM model for northern Rocky Mountain USA landscapes. As mentioned, the LANDFIRE program quantifies historical time series for landscapes across the US using the LANDSUM model (Keane et al., 2007).

Major issues must be addressed when using simulation to generate HRV time series in spatially explicit models (see Keane 2010[in press] for a review). The size and shape of the simulation area is important to the accurate representation of HRV (Keane et al., 2002b). Long, linear simulation landscape shapes, such as those created from watershed boundaries, may be inappropriate because simulated fires often reach landscape boundaries before achieving their full size (emigration problem) resulting in simulated fire size distributions that are different from historical fire size distributions (Keane et al., 2002a). More reasonable simulation landscapes are those that are large enough to contain the biggest fires (Swanson, 1981; Swanson et al., 1997) and they are defined by simple shapes with relatively low edge (circle- or square-like, Keane et al., 2002b). A related and more important problem is the absence of fires, or other disturbance processes, that immigrate or spread into the simulation area from outside the simulation boundary. An additional buffer area about 3–5 km wide surrounding the evaluation area is often needed to ensure offsite fires are allowed to burn onto the evaluation area. If the simulated landscape is too small, the simulated disturbances will be infrequent and smaller because of the mentioned immigration limitations, resulting in additional and undesirable variation in the HRV time series (Karau and Keane, 2007) (Fig. 2).

HRV simulation modeling is rarely used to replicate past disturbance events. Instead, landscape models are employed to simulate disturbance regimes and vegetation dynamics over long time periods under static climate envelopes indirectly represented by the input parameters. Usually, parameters used in simulations are quantified from extensive sampling of past disturbance events that occurred under past climates that influenced historical disturbance and vegetation response regimes (Keane et al., 2006b). Eventually the variation in simulated attributes will tend to stabilize over long simulation time (100–500 years), especially in deterministic landscape models (Baker, 1989). Some may feel it is inappropriate to simulate fire and landscape dynamics over millennial simulation spans while holding climate and fire regimes constant. This would be true if the objective of the landscape modeling were to replicate historical fire events. However, most HRV simulation efforts attempt to describe the envelope of variability in historical landscape dynamics, so it is more important that the entire range and variation of landscape conditions and processes be documented to create a more comprehensive

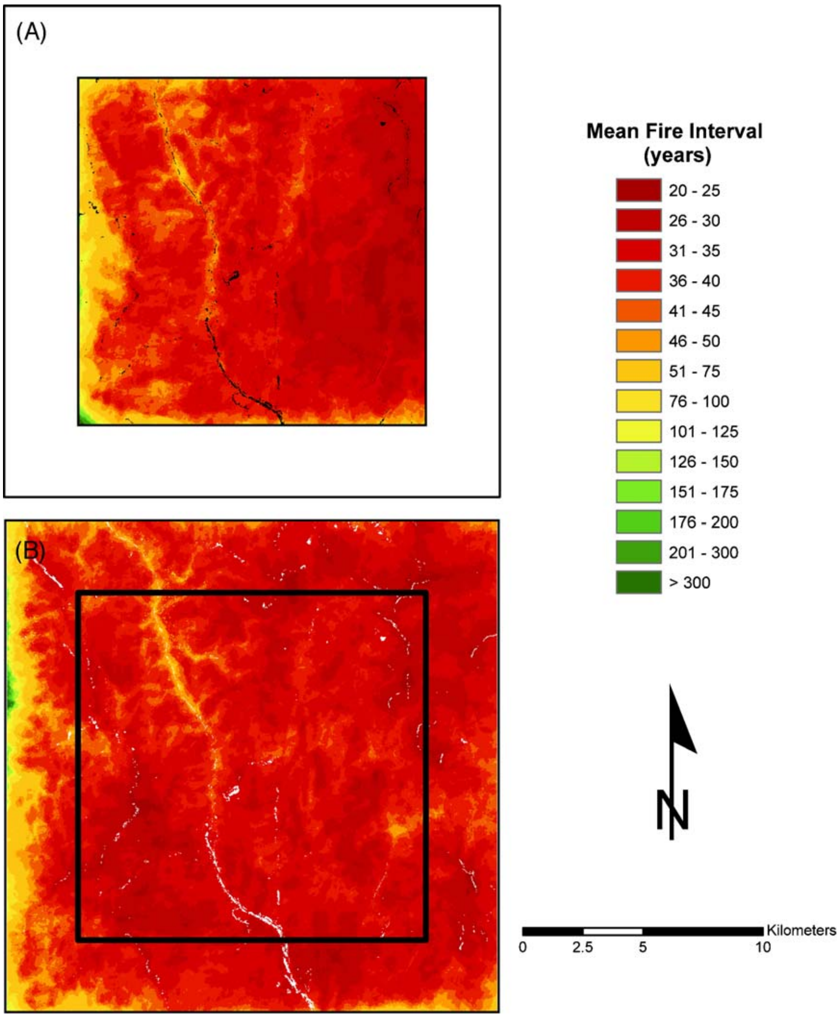

Fig. 2. To create more realistic simulations, disturbance processes should be allowed to spread onto the area of evaluation. This means that an additional buffer area needs to be added to the simulation area to ensure disturbance immigration. The following buffer sizes are used (A) none, (B) 5 km, (Pratt et al., 2006).

reference database. An alternative to simulating long time spans is to conduct simulation replicates using Monte Carlo techniques providing the effects of initial conditions are minimized.

The fire history study results that are used to parameterize landscape models only represent a relatively narrow window of time (300–400 years), yet it is generally assumed that this small temporal span is a good proxy for the creation of reference conditions used in HRV simulation. Since this window is small, it may seem that only 400 years of simulation are needed to quantify HRV. However, the sampled fire events that occurred during this time represent only one realization of a time series of the initiation and spread of disturbance (fire) events that shaped the unique landscapes observed today. If these events had happened on a different timetable or in different locations, an entirely new set of landscape conditions would have resulted. It follows then that the documentation of landscape conditions from only historical records would tend to underestimate the historical variability of past conditions. Simulation models can quantify the entire range of conditions by simulating the historical fire regime for thousands of years to capture the full range of possible landscape realizations.

3. Applying HRV

The operational use of HRV needs a metric or statistic to compare current landscapes to the historical time series (Fig. 1b,c). This seemingly simple step is actually quite complex for a number of reasons. First, there are few statistical analyses specifically designed to evaluate multiple observation historical time series and compare against a single observation of contemporary conditions. HRV series often contain spatial and temporal autocorrelation that may influence any parametric statistical measure of variability (see next section). It is also difficult to design a statistic that will meet the needs of managers and match the goal of the HRV analysis. Landscape compositional thresholds, for example, may be determined as one standard deviation from the mean for one application, but as the 10th and 90th percentile for another (Hann, 2004). Last, there are few statistical tests to determine statistical significance of any difference in a historical-contemporary comparison (Steele et al., 2006).

Some simulation approaches use the suite of indices that have been developed in vegetation ecology for rating the similarity between plant communities (Mueller-Dombois and Ellenberg, 1974; Gauch, 1982). Hann (2004), for example, used a variation of the Sorenson's Index to compute departure in vegetation conditions for an assessment of FRCC. Keane et al. (2008) also used Sorenson's Index to evaluate the departure of future landscapes from historical and current conditions under climate change. The Sorenson's Index (SI) is:

$$\mathrm{SI} = \left(\frac{\sum_{j=1}^{m}\sum_{i=1}^{n}\min(A_i, B_j)}{m\mathrm{Area}_{\mathrm{LRU}}} \right) \times 100$$

where the area of a landscape class i, common to both reference A and simulation output B from simulation output interval j, summed over all landscape classes n and simulation intervals m, divided by the total area of the landscape reporting unit ($\mathrm{Area}_{\mathrm{LRU}}$) and number of simulation intervals (m), and then converted to a percentage by multiplying by 100. The resulting value has a range of 0–100, where 100 is completely similar (identical, no departure) and 0 is completely dissimilar (maximum departure). The problem with these similarity indices is that they are (1) sensitive to number of classes used in the calculation, (2) insensitive to subtle differences across time intervals, and (3) difficult to implement in statistical analyses and tests for significance.

Steele et al. (2006) took a more statistical approach and developed a program called HRVSTAT that computes departure and a measure of significance using a regression-correlation strategy. Their program was used in the LANDFIRE prototype project to determine ecological departure (Pratt et al., 2006). Cushman and McGarigal (2007) used Principle Components Analysis to reduce multivariate variability across area by vegetation types to facilitate the measurement of departure from HRV for wildlife applications. Hessburg et al. (1999a, 1999b, 2000) used the FRAGSTATS program and an historical sample median 75 or 80% range of patch and landscape metrics (their estimate of HRV) to determine departure of contemporary conditions from the HRV. They coupled these estimates with transition analysis, which enabled them to identify transitions that were responsible for observed departures, and to detect statistically significant but "nonsense" changes resulting from rasterization of historical and contemporary vegetation coverages in the GIS.

4. Advantages of HRV

One advantage of the HRV approach is that it can be used for single or multiple characteristics that describes an ecosystem, stand, or landscape at any scale (Egan and Howell, 2001). The HRV of coarse woody debris loading, for example, can be computed 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 the specific land management objectives at their most appropriate scale. For instance, fuel managers might decide to evaluate, at a watershed level, the HRV of coarse woody fuels and severe fire behavior, along with the HRV of landscape contagion (Hessburg et al., 2007), to manage landscapes in favor of continued ecological integrity. Similarly, each HRV element can be prioritized or weighed based on their importance to the land management objective. This forms a critical linkage to adaptive land management where iterative HRV analyses can be used to balance tradeoffs in landscape integrity of ecosystems with other social issues and economic values.

Another advantage of HRV is that by including the variation of selected ecosystem attributes in the evaluation analysis, more flexible, robust, and realistic treatment regimes can be designed such that social and economic values are better balanced with ecological concerns. The idea that treatments can be scheduled to create specific target conditions into the future is flawed because of the uncertainty in unplanned disturbances such as wildfires, windstorms, or insect infestations. Instead, land areas could be periodically evaluated (e.g., every 10 years) using HRV concepts to determine if they are outside historical ranges, and, if so, appropriate treatments can be designed to return the evaluated area to a semblance of historical conditions. Planning pro-active treatments over long time periods, such as thinnings during harvest rotations, may be unreasonable where disturbance frequencies are short and their consequences more severe or variable (Agee, 1997).

Historical conditions need not be the only references for HRV analyses; other scenarios can be developed and implemented to generate time series for completely different sets of reference conditions, such as those that contain extensive domestic livestock grazing or future climatic change signals (see last section). The invasion of late serial native species or exotics may be so extensive that most of the landscape has semi-permanently departed from historical conditions and it is strictly impractical, both economically and ecologically, to return the landscape to prior conditions. Grazing can be included in the simulation as a dominant disturbance so that the associated reference condition can be derived. Exotic species may be incorporated into simulation models to show alternative pathways of development and their likelihood. In other applications, historical reference conditions may not be viable for heavily managed areas, such as recreation sites or wildland urban settings, so fire parameters, for example, can be modified to reflect an extensive fire suppression program. Multiple HRV time series can also be created for a wide variety of response variables, such as landscape composition, fuel loadings, and fire behavior. Multiple HRV time series will be very important for managing highly altered landscapes, such as those in the eastern US, China, and Europe.

Last, the most important benefit of HRV is the increased understanding about ecosystem dynamics and ecosystem responses to changing conditions. Understanding the causal mechanisms that drive ecosystem variability is essential in interpreting HRV analyses, and this understanding allows us to address inherent ecological complexity in land management. Exploring the causes underlying the HRV of fire dynamics, for example, will help design silvicultural treatments that can provide sustainable timber products while also reducing fire hazard and returning ecosystem health (Reinhardt et al., 2008).

5. Limitations of HRV

While HRV seems to have many advantages for use in land management, there are also issues, caveats, and cautions in its application. This section attempts to describe the major problems with the HRV approach in an order of importance to land management. A thorough knowledge of these HRV limitations is critical for comprehensive evaluation and interpretation of HRV analysis results and implementations.

5.1. Limited data

Field data in adequate abundance and appropriately scaled are seldom available to define HRV of characteristics at many scales. On-site historical evidence of past disturbance events or ecological conditions is often destroyed by recurrent disturbance or decomposition, and surviving evidence often lack adequate spatial and temporal distribution and resolution for adequate HRV representation. For example, charcoal samples from varved lake sediments provide an important source of historical data, but the spatial resolution of the data is insufficient for quantifying the annual variation in patterns of fire regimes because the source area for the deposited charcoal is difficult to define. Fire scars on trees provide excellent records for the temporal resolution of fires, but scarred trees are rarely distributed across large areas at the densities needed to adequately describe fire frequency and severity and the resultant landscape characteristics, especially in stand-replacement fire regimes (Baker and Ehle, 2001; Hessburg et al., 2007). Many other ecosystems lack the means for recording disturbance events (e.g., grass and shrub lands) and our knowledge of historical trends is necessarily very limited in these systems (Swetnam et al., 1999)

5.2. Autocorrelation

Most historical time series are autocorrelated in space and time (Ives et al., 2003; Hsieh et al., 2008). Any place on a landscape is ultimately dependent on the condition of the surrounding area as disturbance spreads or as water flows through the landscape (Turner, 1987). Related to this that the instantaneous status of any landscape is dependent on the landscape composition and structure the previous instant, day, year, and so on with declining influence over time (Reed et al., 1998). In addition, the extent of any vegetation type used to evaluate landscape HRV is related to the extent of all other vegetation types; any increase in one type must result in the corresponding decrease of one or more of the other vegetation types (Pratt et al., 2006). It is important to minimize autocorrelation in historical time series by selecting a reporting interval that is long enough to reduce the interdependencies of time, space, and succession status but short enough to provide a sufficient number of observations to compare in a valid statistical test. This reporting interval will vary by landscape depending on fire frequency and succession transition times. The LANDFIRE prototype effort used 50-year reporting intervals to minimize autocorrelation for their LANDSUM simulations (Pratt et al., 2006). A new set of statistical analysis tools, such as those used in economics, are critically needed to compute an index of departure that is useful to land management and satisfies the assumptions of the analysis technique.

5.3. Scale effects

HRV is highly scale-dependent and the range and associated variation drifts with pronounced and long-term shifts in the climatic regime, disturbance regimes, geomorphic and geologic processes and also the effects of some human land uses (Morgan et al., 1994) (see Fig. 1d). Using a limited temporal and spatial extent to evaluate landscapes across large regions can introduce bias into the computation of HRV measures because spatio-temporal variation in the climatic forcing, and vegetation/disturbance responses across a larger domain will typically be broader than would be observed in a smaller domain. For examples, the LANDFIRE prototype time span of 1600 to 1900 A.D. (Keane et al., 2007) may be inappropriate for those landscapes where fire return intervals are greater than 300 years, and the 1 km^2 area used to summarize HRV to compute FRCC for national fire management concerns (Schmidt et al., 2002) may be inappropriate for areas where the average fire size is greater than 1 km^2 (Karau and Keane, 2007).

Spatial HRV approaches can be inappropriate when applied on small areas such as stands or landforms. Karau and Keane (2007) found that simulated HRV chronosequences summarized from landscapes smaller than 100 km^2 increased the variability in landscape composition by over 100% due to the spatial dynamism of simulated disturbance processes (Fig. 3). Thus, quantification of HRV is likely inappropriate when applied to small areas such as stands or individual landforms. For example, consider a contemporary 10-ha stand with a Douglas-fir cover type that was historically dominated by a ponderosa pine cover type; it may be appear to be outside the HRV when considered in isolation, but it will certainly be within the HRV if it is considered in the context of a 10,000 to 100,000 ha landscape dominated by ponderosa pine (the historical dominant species). On the other hand, when evaluation landscapes become too large ($>$5000 km^2), it becomes difficult to detect significant changes caused by small-scale ecosystem restoration or fuel treatments (Keane et al., 2006b). The optimum size of a HRV landscape reporting area is difficult to estimate because of subtle differences in topography, climate, and vegetation across large regions. Thus, it may be preferable to compute HRV across spatial scales ranging from 10^4 to 10^5 ha, depending upon the question (Karau and Keane, 2007). The resolution of the landscape is also important with higher resolutions resulting in higher variability (Fig. 3). An alternative might be to use non-spatial modeling for those areas that are small or have coarse resolution (Hemstrom et al., 2007; Merzenich and Frid, 2005).

There are several spatial domains that are important in the development and analysis of HRV time series using spatial modeling. First is the "evaluation" area defined as the context

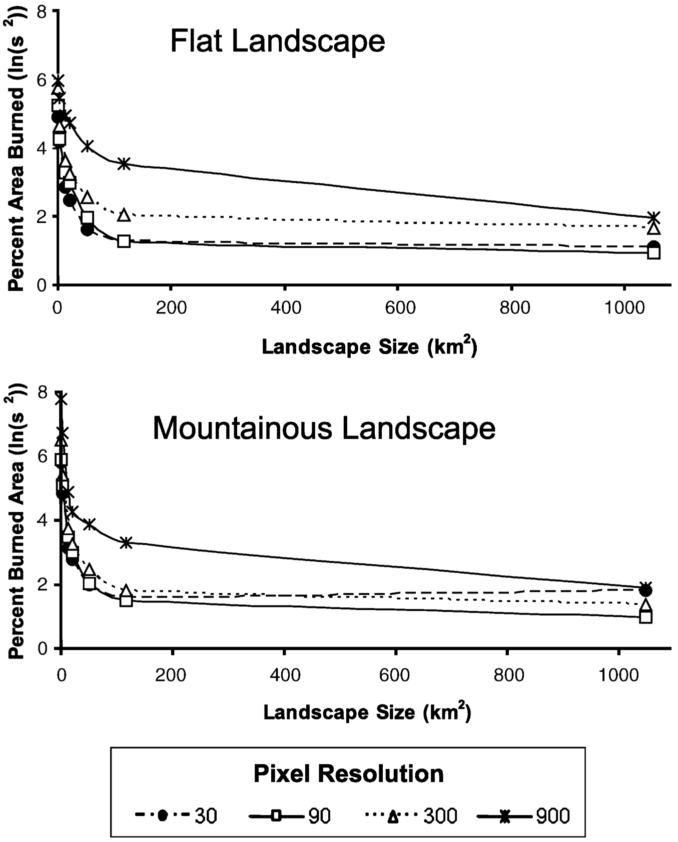

Fig. 3. The influence of the size of the HRV reporting area on the variation of percent burned area within two large simulation landscape (A) mountainous and (B) flat (from Karau and Keane, 2007). Each line represents a different resolution for the simulation landscape. Larger areas are required to allow disturbance regimes to become fully realized and the variation of that disturbance regime to be minimized.

area being assessed using HRV approaches (Fig. 4). If a modeling approach is used to create HRV time series, this area is the "simulation landscape" minus the buffer area (see next section; see Figs. 2 and 4). This evaluation area should be large enough to ensure that variation in ecosystem processes stemming from the inherent variability in the local (subregional) climatic and disturbance regimes, geology, and geomorphic processes is adequately represented. The evaluation area can then be divided into "reporting areas", which are the land units in which management activities may be implemented. Watersheds, landforms, square grids, or some other land stratification are often used as reporting areas. Schmidt et al. (2002) used 1 km^2 square pixels to summarize HRV while the LANDFIRE prototype project used a square reporting area of 0.81 km^2 (Pratt et al., 2006). These reporting areas must be large enough to ensure that spatial variation is minimized (Fig. 3) but small enough to be useful to management (Fig. 2).

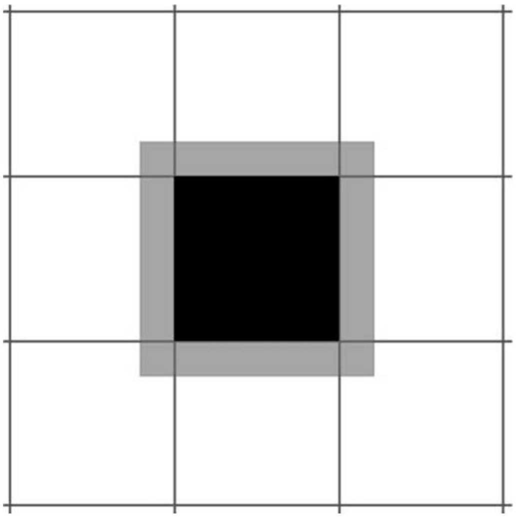

Fig. 4. Important landscape extents that must be explicitly defined in developing HRV time series. The entire area is called the simulation landscape and it is composed of a buffer (grey) and the evaluation area (black). If modeling is not used, then the evaluation is often called the reference landscape. Within the evaluation landscape are the reporting areas for summarizing HRV time series.

5.4. Assessment techniques

There are a limited number of statistical techniques currently available to apply HRV as an assessment or monitoring tool in land management. The departure methods described above usually apply common metrics from landscape and community ecology to estimate departure from HRV, but some of the methods have limitations when used in HRV applications. For example, the Sorenson's index is sensitive to the number of classes within a feature used to describe the ecosystem, community, or landscape (Fig. 5b) (Keane et al., 2008). Furthermore, some indices are insensitive to changes in landscape composition when the same categories appear in all time sequences, especially when the landscape areas of a vegetation feature are equal. Many statistics of departure fail to detect subtle changes in current conditions resulting from management action when compared to the HRV time series (Pratt et al., 2006). Again, the spatial and temporal autocorrelation of the HRV data also pose a challenge when using these indices and standard parametric statistical techniques (Steele et al., 2006).

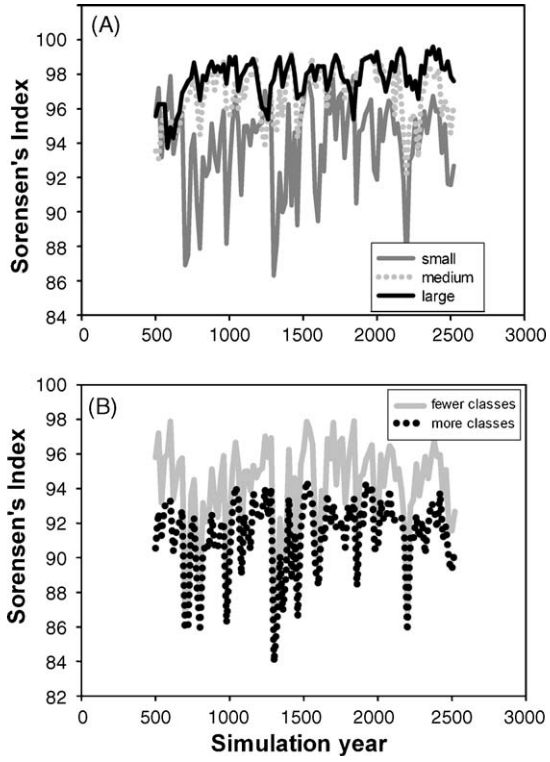

Fig. 5. The effect of the number of classes on calculation of Sorenson's Index where *fewer classes* denotes a simulation where only 20 classes (i.e., potential vegetation and succession class combinations) were used, and *more classes* represents a simulation using about 50 classes (Keane et al., 2008).

As suggested by Steele et al. (2006), simulated observations are less desirable than sample observations because simulated data depend on the assumptions of the simulation model that generated the data. Hessburg et al. (1999b), using sample-based observations, grouped 343 forested subwatersheds (~8000 ha in size) on the eastern slope of the Cascade Mountains in Washington State into ecological subregions by similarity of area in biogeoclimatic attributes. They then built spatially continuous "historical" (1938–1956) and "current" (1985–1993) vegetation maps for 48 randomly selected subwatersheds from aerial photo interpretations. From remotely sensed attributes, they classified cover types, structural classes, and potential vegetation types and attributed them to individual patches. A reference variation of landscape pattern was estimated by subwatersheds and five forested ecological subregions using spatial pattern analysis results (FRAGSTATS, McGarigal and Marks, 1995) from 48 historical vegetation maps. Finally, they compared the current pattern of an example subwatershed with the variation estimates of its corresponding subregion to illustrate how reference conditions can be used to evaluate the importance of spatial pattern change. By evaluating pattern changes in light of variation estimates, they were able to identify both current and historical conditions that fell outside the reference variation. The approach provided a tool for comparing characteristics of present-day managed landscapes with reference conditions to reveal significant pattern departures, as well as to identify specific landscape pattern characteristics that might be modified through management

5.5. *Complexity*

The complexity of the simulation models or historical maps can also influence the comparison of historical dynamics to current conditions and ultimately affect the computation of departure. In general, highly complex mechanistic models tend to have higher variation than simplistic models. For example, Keane et al. (2008) found that state and transition pathway landscape models that contained a large number of states (e.g., succession communities or structural stages) had more elements to compare with current conditions and, as a result, the simulated variation of landscape elements was much larger (Fig. 5b). Departure from a five succession class pathway, for example, would be greater than departure from a 40 class pathway because the large number of near zero values for the majority of succession class pairs tends to lower departure estimates (Pratt et al., 2006). Departure estimation is best when succession pathway complexity or age class ranges are somewhat equal across all simulation landscapes and reporting areas.

The design of landscape models can also affect HRV time series. Absence of critical disturbance processes into the simulation design can result in limited HRV time series. For example, the lack of mountain pine beetle simulation in a model used to simulate the HRV of lodgepole pine landscapes may create historical time series that underestimate ranges and variation of lodgepole pine successional stages. Moreover, the detail at which disturbance processes are simulated can also influence HRV simulated time series. Simplistic cell automata models, for example, may generate fire perimeters that are different from perimeters simulated by complex vector spread algorithms (Gardner et al., 1997; Keane et al., 2004).

5.6. *Conceptual dilemmas*

Historical variation may not always represent the range of conditions needed to maintain healthy, resilient ecosystems. Given the age spans of the organisms used to quantify HRV (e.g., trees are most often used to classify cover types and structural stages), it is difficult to obtain comprehensive historical data over stable climates and biophysical conditions. For example, it would be difficult to obtain the range of historical conditions of bristlecone pine or redwood dominated landscapes because these long-lived species can survive across many disparate climates and historical biophysical conditions. Therefore, the range and variation of most ecological characteristics tend to become more variable as climates represented in the historical time series become more diverse and the response times of ecosystems increase, resulting in an increase of variation of historical attributes. The problem then is to use an HRV time span that is supported by historical field data while also being representative of current and near future climate regimes.

Another dilemma is the interaction of Native American burning with the lightning-caused fires to define historical fire regimes on historically fire dominated landscapes (Barrett and Arno, 1982; Kay, 1995). Should human-caused fires be included in HRV when they are effectively absent in the current day fire regimes (Gruell, 1985; Keane et al., 2006a)? Comparing current fire regimes with historical fire regimes may be inappropriate because historical Native American influences were dominant across many areas of the US, such as in ponderosa pine ecosystems of the northern Rocky Mountains, and there will probably never be a time when humans will burn the vast amount of land that was burned by aboriginal ignitions (Arno, 1985; Gruell, 1985; Frost, 1998; Keane et al., 2006a). On the other hand, we can't discount the evolutionarily impact of thousands of years of burning by Native Americans and how such land use shaped genetic, community, and landscape ecology of today's ecosystems (Russell, 1983; Bonnicksen et al., 1999). To tease Native American burning from a purely lightning driven fire regime using historical data is difficult and problematic (Kay, 2007; Slocum et al., 2007; Bean and Sanderson, 2008), so we believe the best approach might be to consider humans as part of the historical ecosystem.

Another challenge in HRV quantification is where to bound the so called "suppression era" in HRV estimation on western US landscapes. Depending upon the geographic location, lower bounds range from the late 18th century (1770–1890, beginning with early fur trapping and trading – ending with the declining years of mining and domestic livestock grazing, Hessburg and Agee, 2003, and references therein) to the early 20th century (with the advent of the "10 AM rule" beginning in the early 1930s, but increasing in effectiveness much later). Under the 10 AM Rule, fires were targeted to be put out by 10-o-clock in the morning and kept smaller than 10 acres (4 ha). Inclusion of certain contemporary fire regime information (e.g., fire frequency and severity parameters) in the derivation of HRV estimates would decrease fire frequency and increase severity in many forested ecosystems that would result in dramatically different HRV time series (decrease variation). This era not only includes variably distributed effects of settlement and management, but also climatic variation differing from that of prior centuries (Kitzberger et al., 2007). A related dilemma is that this period is probably the most representative of possible future conditions considering expected management directions and climate trajectories. Most HRV simulations parameterize models using data from prior to the era of effective fire suppression (Keane and Finney, 2003). Added to these is another related problem: whether to include exotics in HRV analyses, given that their eradication seems unlikely in the near future. Whitebark pine landscapes, for example, may take centuries to recover from exotic blister rust infestations, even with intensive management actions (Tomback et al., 2001).

6. Future of HRV

6.1. *Climate change and HRV*

Some feel that HRV may no longer be a viable concept for managing lands in the future because of expected climate warming and increasing human activities across the landscape (Millar et al., 2007). Today's climates might change so rapidly and dramatically that future climates will no longer be similar to those climates that create past conditions, and the continued spread of exotic plants, diseases, and other organisms by human transport will permanently alter ecosystems (see Fig. 1d). Climate warming is expected to trigger major changes in disturbance processes, plant and animal species dynamics, and hydrological responses (Botkin et al., 2007; Schneider et al., 2007) to create new plant communities and alter landscapes that may be quite different from historical analogs (Neilson et al., 2005; Notaro et al., 2007).

At first glance, it may seem obvious that using historical references may no longer be reasonable in this rapidly changing world. However, a critical evaluation of possible alternatives may indicate that HRV, with all its faults and limitations, might be the most viable approach for the near-term because it has the least amount of uncertainty. While there is little debate that atmospheric CO_2 is increasing at an alarming rate, there appears to be a great deal of uncertainty about the effect that this rapid CO_2 increase will have on the world's climate (IPCC, 2007; Stainforth et al., 2005; Roe and Baker, 2007). This uncertainty will certainly increase as the climate predictions are made (1) at finer resolutions, (2) for different geographical areas, and (3) for longer time periods. The range of possible predictions of future climate from General Circulation Models (anywhere from a 1.6 to 8 °C increase in global average annual temperature) is much greater than the variability of climate over the past two or three centuries (Stainforth et al., 2005). And it is the high variability of climate extremes, not the gradual change of average climate, that will drive most ecosystem response to the climate-mitigated disturbance and plant dynamics, and these rare, extreme events are difficult to predict (Easterling et al., 2000).

This uncertainty will also increase as we try to predict how the earth's ecosystems will respond to this simulated climate change (Araujo et al., 2005). Mechanistic ecological simulation of climate, vegetation, and disturbance dynamics across landscapes is still in its infancy (Sklar and Costanza, 1991; Walker, 1994; Keane and Finney, 2003). Many models are missing detailed representations and interactions of disturbance, hydrology, land use, and biological processes that will catalyze most climate interactions (Notaro et al., 2007). As an example, the major mountain pine beetle epidemic currently occurring in western North America has been attributed to climate change (Logan and Powell, 2001), yet this epidemic was not predicted by major Dynamic Global Vegetation Models because insect and disease processes are not explicitly simulated in most of these models due to a lack of knowledge of epidemic mechanisms and inappropriate scales (Neilson et al., 2005). If this one critical disturbance is not represented in ecological models, then there must also be a host of unanticipated disturbances and ecological relationships that are also missing, which could result in still higher levels of uncertainty in describing future conditions. It also follows that any prediction of future ecosystems, climates, and landscapes become more uncertain the further into the future one looks. This becomes increasingly important when we factor in society's responses to climate change through technological advances, behavioral adaptations, and population growth (Schneider et al., 2007). Last, little is known about the interactions of climate with critical plant and animal life cycle processes, especially reproduction and mortality (Keane et al., 2001; Gworek et al., 2007; Ibanez et al., 2007; Lambrecht et al., 2007), yet these process could be the most important in determining species response to climate change (Price et al., 2001; Walther et al., 2002).

Given the uncertainties in predicting climatic responses to increasing CO_2 and the ecological effects of this response described above, we feel that HRV time series derived from the past may have significantly lower uncertainty than any simulated predictions for the future. Recall that large variations in climates of the past several centuries are already reflected in the parameters used to simulate HRV time series. In that light, we suggest it may be prudent to wait until simulation technology has improved to include credible pattern and process interactions with regional climate dynamics and there has been significant model validation before we throw out the concept and application of HRV. Improving ecosystems models may take decades before realistic landscape simulations can be used to account for climate change in species and landscape response. In the meantime, it is doubtful that the use of HRV to guide management efforts will result in inappropriate activities considering the large genetic variation in most species (Rehfeldt et al., 1999; Davis et al., 2005) and the robustness inherent in regional landscapes that display the broad range of conditions inherent in HRV projections

6.2. *Management implications*

To use HRV in an operational context, it must be assumed that the record of historical conditions more or less reflects the range of possible conditions for future landscapes; an assumption that we now know is overly simplistic because of documented climate change, exotic introductions, and human land use. While managers need to recognize the importance of using historical landscape dynamics as HRV reference conditions to ensure there is minimal loss of important landscape elements, managers also need to evaluate if current management will be within acceptable and feasible bounds for potential future landscape conditions. Looking both to the past and to the future will be essential for the future of land management. The most obvious action is to augment an HRV time series with an additional reference time series, we call FRV (Future Range and Variation), which represents predicted characteristics of future landscapes and ecosystems. These FRV time series can be generated from complex climate sensitive landscape models that mechanistically simulate disturbance and vegetation developmental processes in a spatial domain (Bachelet et al., 2001; Keane et al., 2004).

Again, historical and future variation scenarios need not be the only two scenarios used to compute departure and summarize HRV for simulation landscapes. Other scenarios should also be developed and simulated to represent other potential futures. For example, a set of six FRV scenarios may be designed to encompass three possible GCM climate predictions with and without exotics. Keane et al. (2008) developed a simulation design for two climate change scenarios with three levels of wildland fire occurrence. Current landscape conditions can be compared with all FRV scenarios using qualitative evaluation or quantitative statistical analysis to determine which landscapes to treat, how to design the most appropriate treatment, and where to implement these treatments using decision support software (Hessburg et al., 2007). The priority and weight given to each FRV scenario can be assigned according to management objective.

Future management efforts must also account for the high uncertainty in future climate and species migrations using ecological theory and principles. Millar et al. (2007) advocate an integrated ecological approach for managing future landscapes using a set of adaptation options that include enhancing resistance to climate change, promoting resilience to change, and enabling ecosystems to respond to change. Land managers must learn to anticipate responses to future climates and manage landscape and ecosystems to maximize resilience and stability so that future activities do not create conditions that facilitate the local or regional extinction of important species or processes. It is unfortunate that the anticipated shifts in climate from greenhouse gas emissions occur at the same time as exotic disease, animal, and plant species invasions and decades of fire suppression. Temperton et al. (2004) believes that there is no ideal reference for any ecosystem or landscape, but historical context must be considered to determine reasonable reference states. They advocate that assembly rules (ecological restrictions on the observed patterns of species dynamics) could be used to construct plausible restoration or management goals, especially under rapid climate change.

In closing, we feel it is important to mention that future land management and society will also require a brand new land ethic to provide context in which to make land management decisions. If expected biotic responses to climate change come true, tomorrow's landscapes will be so altered by human actions that current management philosophies and policies of managing for healthy ecosystems, wilderness conditions, or historical analogs will no longer be feasible because these objectives will be impossible to achieve in the future. Will the elimination of exotic plants and diseases, for example, still be an important management objective if we know that other novel plant communities may inhabit tomorrow's landscapes. A new management approach may be needed to balance ecology principles with society's demand for resource to create landscapes that are sustainable, ecological viable, and acceptable to society. Using assembly rules to restore landscapes may offer a possible direction (Temperton et al., 2004). Conserving historical landscape features while also providing for future species migrations and changes in disturbance regimes may be another strategy. In the end, this may require a totally different land ethic than we used to guide management in the past (e.g., fire suppression). Such an ethic will most likely require that we more explicitly identify the goals we intend to fulfill, and how and where these goals can be integrated across the landscape.

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