Chapter 24

Use of the Historic Range of Variability to Evaluate Ecosystem Sustainability

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abstract

Ecosystems are not static, having evolved with disturbances such as fire, windstorms, floods, disease, and animal activity. The natural variability imposed by such disturbances must be included when defining sustainability goals. One approach is to target the historic range of variability (HRV), determining if current management maintains the ecosystem within its HRV. Tree cores; stand age; stable isotopes; ancient packrat middens; museum collections; and sediment records of charcoal, pollen, testate amoebae, or animal hair can provide data for reconstructing the HRV.

An advantage of using the HRV as a standard against which to measure sustainability of existing conditions is that it can provide a measurable target related to ecosystem biodiversity and productivity. Disadvantages are twofold. Historic data for some key ecosystem variables may be sparse, and climate change has altered the future trajectory from that of the past, confounding the interpretation of the effect of management actions. Supplementary analyses can help overcome these challenges.

Recommended approaches are (1) using modern natural areas to estimate the HRV under a climate similar to existing conditions and (2) mechanistic, stochastic modeling to bracket environmental variability and incorporate climate change. Climate change can be added to models to predict if the future range of variability under different management scenarios is beyond the long-term historic range of variability, treating climate change as an anthropogenic effect also changing ecosystem sustainability. The three approaches—HRV analysis, modern reference area comparisons, and stochastic, mechanistic modeling—can help modernize management and restoration success standards that are often static and do not consider the future trajectory in ecosystem states and variability.

introduction

Ecosystem sustainability is a societal goal closely linked with sustainability of present human cultures and values. Natural resources within ecosystems provide materials and energy needed for housing, food, water, air, transportation, medicine, recreation, and many other goods and services. Global decline in the ability of ecosystems to provide such goods and services would alter modern human lifestyles. The goal of sustaining ecosystems around the world, especially in the face of the current high rate of population growth is an urgent one. However, to achieve such sustainability requires understanding two important concepts described in this chapter. The first is an accurate definition of ecosystem sustainability. The second is a method of estimating ecosystem sustainability to provide numerical targets for adaptively managing ecosystems in a sustainable way, a method referred to as the historic range of variability (HRV) approach (Landres et al. 1999).

There are many definitions of sustainability. One definition is the characteristic of a *process or state* that can be sustained at a certain level indefinitely (Holdren et al. 1995). Only the focus of this definition on "process" can be appropriately applied to ecosystems. Ecosystems are not static, but rather have dynamic functions and processes that create a myriad of constantly changing states through time. Disturbance regimes, a natural part of ecosystems, create such dynamism. Fire, windstorms, insect outbreaks, disease, floods, and animals functioning as ecological engineers, (e.g., beavers), are examples of common disturbances that change the structure and function of the ecosystem (Jensen and Bourgeron 2001, Molles 2005).

Species within ecosystems evolved under such disturbance regimes and would be expected to have adapted to it as long as the regime continues to be within its "natural" range of variability. We put "natural" in quotes because humans are often not included in the definition of natural. Yet, humans have been on the earth for a long time and for the majority of that period, most ecosystems have evolved and adapted to human disturbances just as they have to other animal engineers. But with technological advances in the past 150 years that have increased the magnitude of human disturbance globally, the resilience and adaptability of the ecosystems are being challenged, pushing some ecosystems beyond the range of variability under which their component species evolved (Meyer et al. 2005). Therefore, we use the term "historic" range of variability (HRV) rather than "natural" range of variability to include effects of indigenous and pre-modern human societies within the range of variability.

A second definition of sustainability applied to ecosystems is development that meets the needs of the present without compromising the ability of future generations to meet their own needs (Bruntland 1987). We interpret this to mean that resource use is at a level that maintains the "historic range of variability" in key variables that affect the structure and function of the ecosystem. With such assurances, the likelihood is great that the ecosystem will continue to provide services and goods for future generations. In particular, biodiversity is less likely to decline.

The HRV provides a standard to gauge current ecosystem sustainability. If key variables affecting the services of the ecosystem measured during modern times fall within the estimated range of variability for the variables during the historic period, then the ecosystem might be considered to be functioning at a sustainable level. Key variables include frequency and extent of disturbances (fire, wind, insect outbreaks, floods, fungal disease, etc.), structural variables (land cover type, successional stage, stem density, canopy cover, species diversity, keystone species), and process variables (nutrient cycling, water uptake, energy flows).

In this chapter we describe the HRV approach and the advantages of the method for evaluating sustainability of current ecosystems. We discuss important issues associated with the method including the spatial and temporal scale of analysis and sources of historic data. We then provide examples where we applied this method for United States Forest Service managers. Lastly, we evaluate the challenges of using this approach, particularly in the face of global warming, and offer potential solutions to such challenges.

HRV DEFINITION AND TEMPORAL SCALE

The historic period of interest for defining the HRV of an ecosystem is subjective, selected based on the objectives of the land manager. If the perspective and management goals desired are on an evolutionary time scale, the reference period could be up to 10,000 years or more in the past (Manley et al. 1995). Such a long time scale is important for assessing how climate changes the trajectory of ecosystems from one state to another (i.e., forest to grassland). More often, managers are interested in shorter time periods less influenced by climate change and glaciation, such as the 300–500 years prior to European arrival in the Americas. Such shorter reference periods are more comparable to current conditions, which is important for assessing effects of current management actions on ecosystem sustainability.

The "range of variability" during the historic reference period for a variable can be defined in different ways—as (1) the absolute range, calculated as the maximum minus the minimum value, (2) the range of means averaged over meaningfully-sized blocks of years, or (3) the standard deviation of values. A problem with using the absolute range of values over the entire reference period is that extreme conditions are included. For example, area burned per year can be consistently zero in modern times and still fall within the absolute range of variability, even though area burned historically was highly dynamic year to year (i.e., 0% falls within the historic range of 0 to 15% for area burned per year). The ecosystem has species adapted to >0% disturbance, such as lodgepole pine (*Pinus contorta*) serotinous cones that release seeds after fire, and thus complete fire suppression to 0% area burned does not produce a sustainable ecosystem.

The second method, using the range of means, avoids including extremes by coarsening the temporal resolution to large blocks of time that have similar climatic conditions within the blocked periods but less similar climatic conditions among periods. This method divides the entire historic reference period, as well as the modern periods used for comparison, into time blocks ideally sized to fit long-term pattern shifts from climate change or other forces that shape the ecosystem. Smoothing of raw climate data reconstructed from tree rings using cubic splines can aid the selection of the appropriate size of the time blocks.

Applying the range of means approach to the variable "area burned" (Figure 1b), values averaged over 50-year periods become the historic range for comparison to modern times rather than the absolute range, which can change the interpretation of whether the ecosystem is within or outside the HRV for the evaluated variable (compare Figure 1a to Figure 1b).

The third method, standard deviation of annual values, is useful because it informs one of the changes in variability, but used alone it does not quantify the relative magnitude of changes. As a single measure, the range of means method is most informative but both the range of means and standard deviation can be reported if the sample size is sufficient to calculate a reliable standard deviation or range of standard deviations (see Figure 1b).

SPATIAL SCALE

It is important that the spatial scale at which the HRV is estimated appropriately fits the objectives of the HRV analysis. Ecological scales are often categorized as being at the "stand" scale or "landscape" scale, where a stand is an individual patch of one contiguous vegetation type and the landscape is a mosaic of different vegetation types or successional stages over larger areas. If the spatial extent of analysis is too small, restricted to within a stand, key variables affecting the sustainability of the ecosystem may be missed. For example, sources of seed and pollen outside a stand affect the successional trajectory of the stand (Doyle et al. 1998). Animal, fire, and wind vectors move materials and energy between
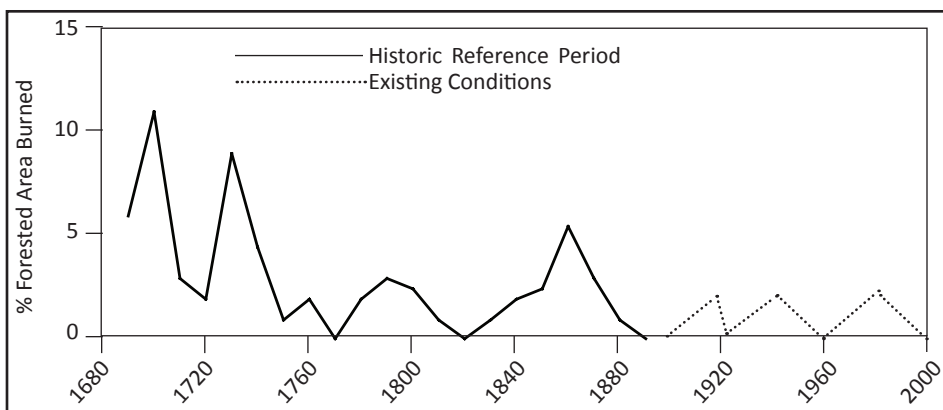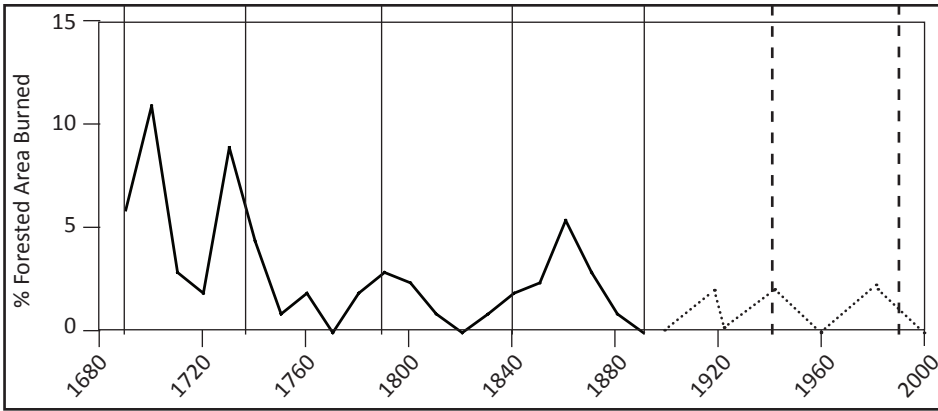

Figure 1a.

Figure 1b.

Figure 1. Two different methods used to estimate historic range of variability (HRV) of area burned that differ in interpretation of whether existing conditions are within the HRV. (a) The absolute range during the historic period extends from 0 to 11%. Existing conditions (post-European settlement) for area burned range from 0 to 2%, which falls within the 0 to 11% historic range. The absolute range misses the reduced variability during modern times. In contrast (b), the range of means ($\bar{x}$) produces an HRV of 1.5 to 6.2%. Existing conditions range from 0.8 to 1.0%, falling outside the HRV. The reduced variability is captured. Similarly the range of standard deviations (s) falls outside the historic range. The periods used to estimate the range of means are 50 years each, which approximates the scale of broad temperature shifts observed in the Bighorn National Forest (BNF; see reconstructed temperatures in Figure 18 in Meyer et al. 2005). This example is for existing conditions on the BNF but the historic, reconstructed data on area burned (Romme and Despain 1989) were from nearby Yellowstone National Park, used as a proxy for the BNF.

ecosystems (Reiners and Driese 2004). Fragmentation, connectivity, and proximity of different stands affect microclimate (Chen et al. 1992), diversity (Debinski and Holt 2001), and extinction rates (Hanski 1998). These variables are only captured if landscapes are evaluated.

In contrast, if the scale is too broad, key variables within the stand may be missed such as live and dead tree density within a stand, whose effects may not be characterized correctly when averaged over a mosaic of stands. Dead standing trees (snags) or old trees with broken tops or branches within each stand are structures required as nest substrate to sustain a greater variety of bird species and large-seeded plant species in a forest stand (Lohr et al. 2002, McClanahan and Wolfe 1993). Percent cover of the ground by large downed wood, referred to as coarse woody debris, must be measured at the stand scale, which provides long-term release of nutrients and organic matter to the soil (Tinker and Knight 2000) and important complex habitat for many mammals (Bull 2002). Ideally, evaluation of key ecosystem variables that shape the structure and function of ecosystems or affect species abundance and diversity should be measured at multiple spatial scales when evaluating if they are within the HRV. Moreover, the species that are components of the ecosystems respond to habitat characteristics at different spatial scales, which vary among species depending on their microhabitat needs, territory size, and dispersal patterns (Meyer and Thuiller 2006, Meyer 2007)

Of equal importance is the change in the HRV with spatial scale. The HRV of most variables declines as spatial extent increases (Figure 3). For example, snag density is extremely variable through time when measured at the "stand" scale. After a stand-replacing hot fire, all trees within a forest stand die and become standing, dead "snags", but in 20 to 30 years, the snags fall to become "coarse woody debris" and are replaced by a stand of young trees (Lotan et al. 1985). Through historic time, snag density can range from 0 to 100%. However, at the landscape scale, it is unlikely snag density will ever be 0% or 100% across the entire landscape. The HRV will be a narrower range at the landscape scale (Figure 2). Therefore, the spatial scale of the HRV for a variable must be reported and comparable to the scale of the compared current conditions.

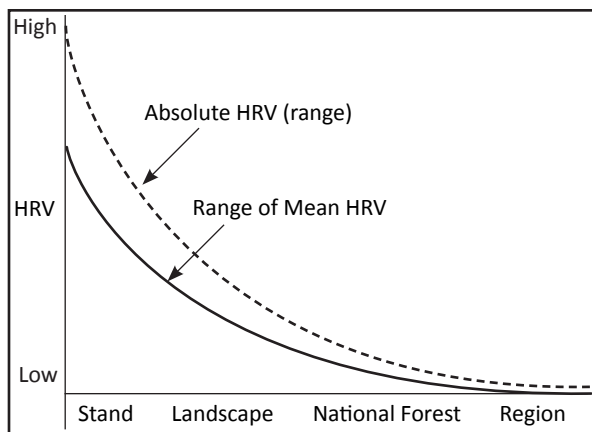## DATA SOURCES AVAILABLE TO ESTIMATE HISTORIC RANGE OF VARIABILITY

Figure 2. Decline in the historic range of variability (HRV) of a hypothetical variable as the spatial extent increases. The range of the mean HRV over smaller blocks of time for a variable is always less than the range between the maximum and minimum for the entire period.

Data available for characterizing the HRV of many ecosystem processes and structural variables for reference periods are found in many natural data sources containing historical "records" such as tree rings, the most commonly used source. For example, fire and insect outbreak frequency can be determined by dating tree ring scars (Veblen et al. 1994, Brown et al. 2000,). Area burned can be reconstructed using trees rings combined with current stand age distributions and knowledge of successional changes (Romme 1982, Despain and Romme 1989). Water use efficiency (Duquesnay et al. 1998) and nutrient uptake (Poulson et al. 1995) can be evaluated using stable isotopes in tree rings. For longer reference periods dating back

thousand of years, ancient packrat middens (Lyford et al. 2003) and sediment cores of pollen, macrofossils, and charcoal (Jackson and Whitehead 1991, Long et al. 1998) provide information on changes in vegetation composition and fire frequency, although at a lower temporal resolution than tree rings. Changes in testate amoeba composition in bogs reveal changes in water availability over thousands of years (Booth and Jackson 2003). For animals, long-term, extensive museum collections (Beissinger and Peery 2007) and animal hair in sediments (Liguang et al. 2004) provide indicators of variability in populations through time.

Once variability is determined for some ecosystem processes using natural records, variability in other key variables possibly could be inferred based on current understanding of ecosystem functions. For example, when frequency of surface fires is reduced in ponderosa pine (*Pinus ponderosa*) forests, stands typically become denser (Veblen and Lorenz 1991). If ponderosa pine tree rings show an increase in fire scar frequency during a historic period, one could conjecture that stand density was lower with more open forest canopy during that period compared to the present. As further evidence of past openness, the thick bark of ponderosa pine trees in the American West suggests this species evolved under frequent low-intensity surface fires. Such fires did not kill the large trees but prevented dense seedling establishment. In contrast, the thin bark of other species such as lodgepole pine (*Pinus contorta*), Englemann spruce (*Picea sitchensis*), and subalpine fir (*Abies lasiocarpa*) suggest these species evolved under less frequent stand-replacing crown fires, indicating dense stands between fires may have been common in the past. Such deductive thinking based on scientific principles can further improve our estimates of the historic disturbance regime and its effects on forest structure.

EXAMPLES OF THE HRV APPROACH

The HRV concept has assisted the United States (U.S.) Forest Service in planning their management activities, allowing them to set dynamic sustainability goals. In their planning documents, they determine if current management is maintaining the ecosystems on the national forest within the HRV. Under contract with the U.S. Forest Service, we prepared reports for three national forests that assessed the historic range of variability of the upland vegetation (, Dillon et al. 2005, Meyer et al. 2005, 2006). Variables that we evaluated included disturbance regimes (frequency, extent, and intensity) and stand structure at the scales of stands and landscapes for high- and low-elevation forests. For the
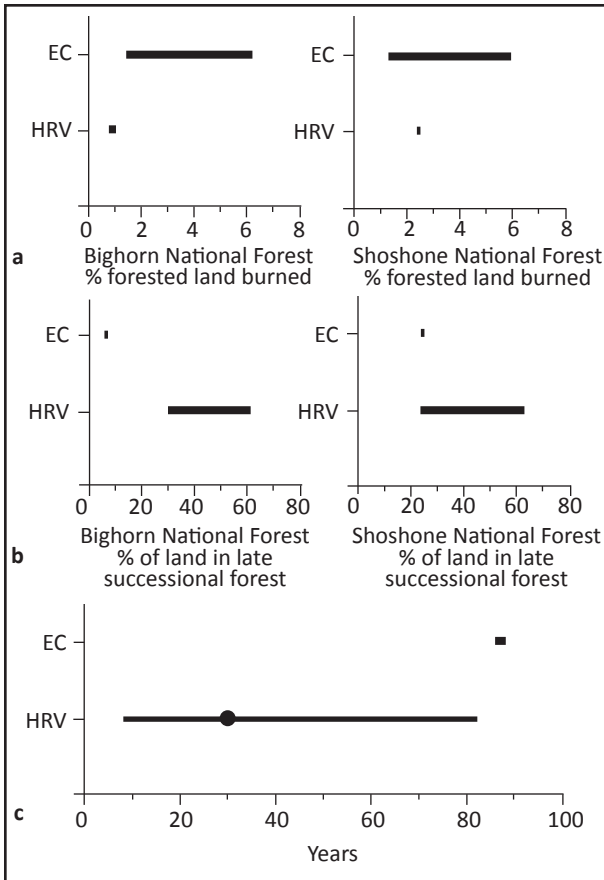
Figure 3. Existing conditions (EC) are estimated to be outside the HRV (1.5 to 6.2% using range of means) for high-elevation forests in the Bighorn National Forest but are inside the HRV for the Shoshone National Forest for (a) percent of area burned and (b) percent of area in late-successional stage forests (data from Meyer et al. 2005, 2006). Existing conditions are outside the HRV for (c) fire return intervals in the low-elevation forests of the Medicine Bow National Forest (data from Brown et al. 2000). The filled circle in the solid line is the median. All show range of means for historic periods except fire return intervals, where the absolute range was used as the HRV.

Forest Service analysis, we defined the historic period as before European-American arrival, up to 300 to 400 years ago.

Often historical data on the National Forest were limited and funds for field studies to obtain such data were unavailable. In such situations, proxies for the HRV were used. For example, we used the HRV of some variables reported for Yellowstone National Park in Wyoming as the proxy HRV for the Wyoming national forests. Caution is advised when applying the HRV from one area to another, as climatic or other conditions that affect the measured variables can differ substantially between the two areas. Fortunately, the slight climatic differences and fuel loading between the watersheds evaluated in Yellowstone National Park and the three national forests were not considered substantial enough to invalidate our comparisons of the fire regimes (see discussion in Meyer et al. 2005).

The three national forests represented a gradient in timber harvest levels (see maps in Dillon et al, 2005, Meyer et al. 2005, 2006). The Medicine Bow National Forest is the most heavily harvested (>50% of forest), followed by the Bighorn National Forest (18% of forest). The Shoshone National Forest is the least harvested of the national forests (3% of forest). Yellowstone National Park, the HRV proxy, had no timber harvest. We first evaluated if forested area burned and percentage of land classified as early, middle, or late successional stage was within the HRV, variables that might be affected by timber harvest. Reconstructions of these variables by decade were available for Yellowstone National Park (Romme 1982, Romme and Despain 1989) and compared to variables we measured for the national forests using the spatial data on fire dates, age and successional stages in the U.S. Forest Service fire and timber Geographic Information System (GIS) databases. The range of means approach was employed over 50-year periods.

Using high-elevation forests in Yellowstone National Park as the proxy HRV for Wyoming high-elevation national forests composed of lodgepole pine, subalpine fir, and Engelmann spruce, the percent of area burned on the landscape was outside the HRV for the Bighorn National Forest, a forest with moderate levels of timber harvest. In contrast, percent of area burned was inside the HRV for the Shoshone National Forest, a forest with relatively low levels of timber harvest (Figure 3a). The same was true for percent of area in late successional forest, with the Bighorn National Forest being

outside and the Shoshone National Forest inside the HRV (>200 years old, Figure 3b). A reasonable explanation for the different results on the two forests is that timber harvest, which is at moderate levels on the Bighorn National Forest, is not only removing old-growth forest but is also reducing fuel loads and increasing fire breaks in the form of clearcuts.

We also compared the existing stand-level fire regime to the HRV for low-elevation ponderosa pine and Douglas-fir (*Pseudotsuga menziesii*) forests on one of the national forests (Medicine Bow). The HRV was determined from a study conducted on that national forest (Brown et al. 2000). The fire return interval for low-elevation forests at the stand-level was outside the HRV for the Medicine Bow National Forest, even when the absolute range of fire return intervals was used (Figure 3c). Unlike the high-elevation forests which experience low-frequency stand-replacing crown fires at typical return intervals of 200 to 400 years, most low-elevation forests in Wyoming appear to have evolved under high-frequency surface fires in the understory with return intervals averaging 20 to 30 years (Meyer et al. 2005). But the frequent surface fire regime has changed in modern times due to successful fire suppression. Firefighters are able to suppress surface fires in the low-elevation forests much more easily than the crown fires prevalent in the high-elevation forests. As a result, the sharp reduction in fire frequency from fire suppression in low-elevation forests appears to have changed the forest structure, whereas there is no evidence tree density has changed within stands from the reduction in fire spread in high-elevation forests. A comparison of historical photographs in most low-elevation forests in Wyoming to present conditions shows the present stands are denser with a greater number of small trees surviving. Ultimately, the denser stands are increasing fuels, and the branches of the smaller trees form ladders to the canopy, switching the fire regime from surface to stand-replacing crown fires (Meyer et al. 2005, 2006). Such dramatic changes fall outside the HRV and have justified prescribed surface fire programs on U.S. western lands to attempt to return low-elevation forests to within the HRV.

CHALLENGES OF THE HRV APPROACH AND SUPPLEMENTARY APPROACHES

A problem with the HRV approach is that climate is assumed to be similar between the historic period and existing conditions, which is not likely to be true (see Figure 18 in Meyer et al. 2005). If not true, differences may be due to climate change rather than land management practices. It is best to supplement the HRV approach by comparing a relatively natural reference area during a modern period to the area evaluated for sustainability during a modern period, ensuring comparisons are during periods with similar climatic conditions. The natural reference area would provide the range of variability standard for estimating if the ecosystem is sustainable. The results from such an approach can be compared to the HRV approach to see if the same conclusions are supported as to whether existing conditions are within or outside the natural range of variability.

For the example evaluating area burned in high-elevation forests, we compared a relatively natural reference area without fire suppression during modern times (Yellowstone National Park from 1972 to 1988) to each national forest during the same time period. An estimate of the range of means is not possible due to the short time period (16 years), but the absolute range was informative. The absolute range as well as the mean area burned per year during this period were greatest on the national park, which had no timber harvest (Figure 4). Both the absolute range and mean decreased as levels of timber harvest increased on the national forests. The Medicine Bow National Forest had the most timber harvest and the smallest area burned each year, whereas the Shoshone National Forest had relatively little timber harvest and correspondingly larger areas burned per year (Figure 4).

The two approaches, the HRV approach and the comparison to a modern-day natural reference area showed the same trend of area burned increasing as timber harvest decreases. The similar results support earlier conclusions that heavy to moderately harvested forests in Wyoming, such as those on the Bighorn and Medicine Bow National Forests, may be outside the historic range of variability in
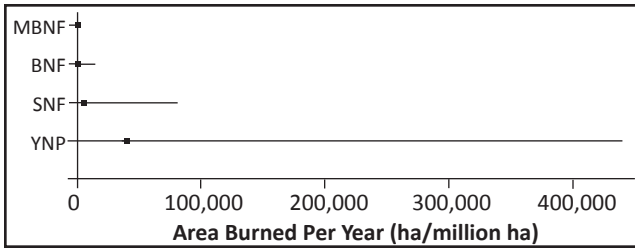
Figure 4. The absolute range and mean area burned decrease as timber harvest increases from lowest to highest levels for Yellowstone National Park (YNP, 0% harvest), Shoshone National Forest (SNF, 3% harvest), Bighorn National Forest (BNF, 18% harvest) ,and the Medicine Bow National Forest (MBNF, >50% harvest) during 1972-1988. Yellowstone had no fire suppression during this period and thus potentially represents the historic "natural" period for the national forests, but under a similar recent climatic regime (from Dillon et al. 2005 and Meyer et al. 2005, 2006).

regard to area disturbed by fire.

Many variables can not be quantified with tree rings or other natural record sources, particularly stand structure variables such as snag density, tree density, percent of forest floor covered by coarse woody debris, or functional variables such as nutrient uptake or recycling. The HRV of such variables is best quantified using mechanistic process models that incorporate stochasticity. For example, Tinker and Knight (2001) modeled how many years were required to completely cover a forest floor with coarse woody debris. The simulation model created was spatially explicit, stochastic (meaning values for some variables were randomly selected from an observed normal distribution), and run for 1,000 years to simulate effects of various clearcutting and fire regimes on coarse woody debris abundance. The stochasticity creates the range of variability expected through time. The model had routines that seeded and grew trees, converted some trees to snags over time, and applied a stochastic rate at which the snags fell over to become downed coarse woody debris. The trees fell over in directions randomly selected from the normal distribution of observed angles. Input parameters for the model came from coarse woody debris biomass measured and mapped in burned, clearcut, and intact lodgepole pine forests in the Medicine Bow National Forest and in Yellowstone National Park. The amount of coarse woody debris consumed or converted to charcoal by fire was estimated from a recently burned stand in Yellowstone National Park.

Output from the model showed that a stand with a 100-year fire return interval had coarse woody debris completely occupy the forest floor sooner than a typical stand on the Medicine Bow National Forest with a 100-year clearcut rotation. The harvested stands had slash (woody debris left on the ground) remaining at the "normal" levels observed in Medicine Bow National Forest clearcuts but scenarios with double and half the amount of slash normally remaining were also modeled. Only when slash levels were doubled did the coarse woody debris cover fall within the modeled HRV of a natural unharvested stand (Figure 5). The model highlighted that disturbances have opposite effects on downed woody debris. Fire burns fine woody debris and leaves coarse woody debris, whereas timber harvest removes coarse woody debris, leaving fine woody debris (slash).

The advantage of stochastic, mechanistic models is they can account for changing processes such as global warming. The coarse woody debris model can be run with realistic fire return intervals shortening over time if the climate is predicted to become warmer and drier in Wyoming. The model predicted that stands with 100-year fire return intervals generated more snags and thus greater coarse woody debris after 1,000 years (90% cover of forest floor) than stands with 200- or 300-year fire return intervals (78% and 75% cover, respectively). The difference indicates warming in Wyoming may increase production of coarse woody debris and correspondingly possibly restore some important functions that help sustain the ecosystem, assuming warming has a small to no effect on the parameters other than stand fire frequency in the model.

In a broader context, anthropogenic climate change from carbon dioxide increase in the atmosphere may switch the state of an ecosystem beyond its HRV over the past 1,000 years—such as from a forest to a grassland, grassland to desert, or wetland to upland. State changes can be added to stochastic process models to predict the future range of variability of a suite of key ecosystem variables under
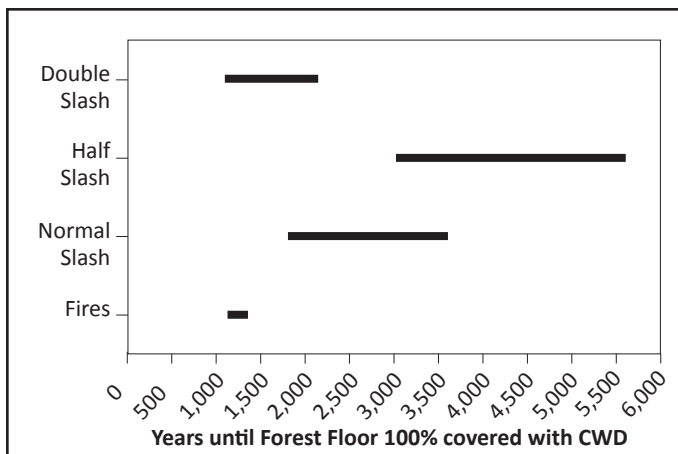
Figure 5. Output from a stochastic forest model shows the possible range of years until the forest floor is 100% covered with coarse woody debris (CWD). Stands modeled include Medicine Bow National Forest stands with fire disturbance intervals of 100 years (represents HRV) and 100-year clearcut rotations for comparison The stands with timber harvest represent those with observed normal levels of slash, half normal levels, and double normal levels. Under existing normal slash conditions, timber harvest reduces cover by CWD debris on the forest floor and may impair the key functions provided by abundant CWD such as wildlife habitat, nutrient recycling, and organic matter production for soils (adapted from Tinker and Knight 2001).

natural and future management scenarios, evaluated with and without climate change. Such an approach can help separate effects of land management activities from effects of anthropogenic climate change on sustainability, and can be used to evaluate the two effects in concert. Changes in state at a rate beyond the HRV likely will stress the ecosystem, reducing its biodiversity because species adapted to the old state will disappear. It takes times for migration of species adapted to the new state to arrive in the altered ecosystem. If a change in state is unavoidable, the challenge is to maintain sustainable and economically viable operations (timber harvest, mining, agriculture, etc.) in a system whose trajectory might take it through multiple socio-economic-ecologic states as the climate changes, while at the same time trying to maintain key variables of the ecosystem within their HRV for each state. A challenge of using stochastic models to help achieve such a goal is creating realism and accuracy in the model predictions. The combination of all three approaches—HRV approach, comparison to modern natural areas, and stochastic mechanistic models that incorporate climate change and evaluate potential state changes—can help one estimate if current and future management scenarios are sustaining an ecosystem with the range of variability under which the ecosystem evolved.

Range of variability analyses will help modernize success standards that currently do not incorporate variability in restoration or remediation goals. If models and HRV analyses show managed conditions fall outside the natural range of conditions, then managers can evaluate methods available to return the system to within the natural range. For example, the U.S. Forest Service uses prescribed fire, tree thinning, and harvest patch size to attempt to more closely mimic natural disturbance processes.

CONCLUSION

Comparison of the historic range of variability of key ecosystem variables to existing conditions can assist development of sustainability standards for managed ecosystems. However, this method assumes the historic climatic conditions are similar to modern times. We recommend that the HRV analysis and conclusions be supplemented with two other approaches. The first is to compare variability in natural reference areas in modern times to variability of managed ecosystems in modern times. This supplementary analysis can help ensure climate change does not alter the interpretation of whether management activities are pushing the ecosystem beyond the HRV. The second supplementary approach is to develop mechanistic, stochastic models that incorporate climate change and known processes based on field measurements to provide comparable estimates of past and current historic range of variability. Such models are useful for variables that can not be reconstructed from historical sediment and tree ring records and for evaluating future major changes in the state of an ecosystem that might result from global warming.

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