Pages 149-159. In L. Taylor, J. Zelnik, S. Cadwallader, and B. Hughes (compilers). Mixed Fire Regimes: Ecology and Management. Symposium Proceedings. November 17-19, 2004, Spokane, WA. AFE MIXC03.

FIRE RELATED RESTORATION ISSUES IN WOODLAND AND RANGELAND ECOSYSTEMS

Jeanne C. Chambers
USDA Forest Service
Rocky Mountain Research Station
Reno, Nevada USA

ABSTRACT

The goal of post-fire restoration is sustainable ecosystems that retain characteristic processes and provide important services like an adequate supply of high-quality water. In sagebrush ecosystems and pinyon-juniper woodlands, the biotic and abiotic characteristics of the ecosystem influence fire characteristics and determine the post-fire recovery potential. If either a biotic threshold (as defined by species composition and abundance) or an abiotic threshold (as defined by soils and other physical characteristics) has been crossed, then revegetation and perhaps other site stabilization measures are required. Factors that influence threshold crossings and that can be used to evaluate recovery potentials include climate and site attributes and the structural and functional diversity of native vegetation. Invasive plants, like the fire adapted annual, cheatgrass (*Bromus tectorum*), are rapidly spreading through these ecosystems causing threshold crossings and altering ecosystem recovery potentials. Restoration approaches should aim to maximize ecosystem resistance and resilience to invasive species and other perturbations following fire. In areas with invasive plants, pretreatments such as foliar or pre-emergent herbicides can be used to reduce population densities. Seeding mixtures need to be developed that include species with varying growth forms and phenologies which maximize resource use and fully occupy sites. Using locally adapted and fire tolerant species can increase establishment and promote resilience following future fires. Post-revegetation management is essential to the restoration process and should include grazing deferral, monitoring establishment and persistence of seeded species, and retreatment if necessary.

INTRODUCTION

Pinyon-juniper woodlands and sagebrush ecosystems in the Intermountain Region have undergone major changes in vegetation structure and composition since settlement by European Americans in 1860. These changes are resulting in dramatic shifts in fire frequency, size and severity. Throughout most of the region, the changes have taken one of two different forms: 1) an increase in woody species, primarily sagebrush or pinyon-juniper, that has resulted from decreases in fire occurrences and that has now led to increases in fuel loads and fire severity; and 2) an increase in exotic annuals, especially cheatgrass (*Bromus tectorum*), that is resulting in dramatic increases in fire occurrences and fire size (Miller and Tausch 2001). The consequences are an increased risk to human life and property, high fire management costs and, all too often, the conversion of the woodlands and shrublands to homogenous landscapes dominated by weeds.

The management challenges associated with maintaining or restoring the sustainability of these ecosystems are numerous. Considerable information has been developed for the restoration of woodlands and rangelands within the Region (see Monsen et al. 2004). However, several fire-related issues are yet to be resolved. Those discussed herein include: (1) using fire and fire surrogate treatments that will both decrease fuel loads and serve to maintain or improve existing native vegetation communities; (2) determining when weed removal or revegetation is necessary to maintain sustainable ecosystems following either fire or fire surrogate treatments or wildfires; and (3) developing revegetation methods for recreating communities that will resist weed invasions and persist under mixed fire regimes. An overview of management goals and restoration alternatives is presented, data and perspectives on defining recovery potentials are given, and integrated methods for removal of invasive species and revegetation are suggested. Many of the methods suggested are the focus of collaborative agency and university projects that are ongoing within the Region.

MANAGEMENT GOALS AND RESTORATION ALTERNATIVES

An overarching goal of woodland and rangeland management is maintaining or restoring sustainable ecosystems (e.g., Chambers and Miller 2004, D'Antonio and Chambers *in press*). Sustainable ecosystems, over the normal cycle of disturbance events, retain characteristic processes including hydrologic flux and storage (infiltration and retention), geomorphic processes (soil retention and surface stability), biogeochemical cycling and storage (nutrient cycling and retention), and biological activity and production (species composition and abundance) (modified from Chapin et al. 1996 and Christensen et al. 1996). Sustainable ecosystems are resistant to change following disturbance and they are resilient in that they recover within a reasonable period of time. Ecosystems that are sustainable provide valuable ecosystem services including an adequate supply of high quality water, habitat for a diverse array of organisms, and recreational opportunities.

The Society for Ecological Restoration International (SERI) defines ecological restoration as the process of assisting the recovery of an ecosystem that has been degraded, damaged or destroyed. The type of management approach or restoration activity required to maintain sustainable ecosystems depends on the state of ecosystem degradation (see Whisenant 1999, D'Antonio and Chambers *in press*). In the initial stages of woodland or rangeland degradation, primary processes often are still functional and *preventative management* can be used to deter further degradation. For ecosystems affected by increases in woody species dominance or lack of stand regeneration, preventative management may involve reintroducing fire into the ecosystem or conducting fire surrogate treatments such as brush beating or tree removal. If the system has been invaded by nonnative species that influence the recovery of the system following wildfire, prescribed fire or fire surrogate treatments, a biotic threshold may be crossed. For this state, recovery of the ecosystem requires *removal* or control of the invasive species. If the native, perennial understory vegetation has been depleted due to overgrazing by livestock or competition from woody species, a different type of biotic threshold may be crossed and *revegetation* will be required. When invasive species occur in the system and the native understory vegetation has been depleted, both *removal* and *revegetation* are necessary. In the worst case scenario, an abiotic threshold may be crossed as a result of soil erosion or other abiotic factors. For this state, primary processes are nonfunctional or altered and returning to the original state may require modifying the physical environment, *revegetation* and, when necessary, *removal.* If the degradation is too severe and the recovery potential of the site has changed, it is necessary to develop restoration methodologies based on the new site potential.

Thresholds and Recovery Potentials

Determining the recovery potential and the management approach or restoration activity for a specific site requires understanding the factors that influence threshold crossings. Woodland and rangeland ecosystems are topographically variable, and elevation, temperature and precipitation regimes vary over short distances. Numerous ecological sites can exist within the area encompassed by a single project or wildfire, and the response to a management treatment or fire can vary spatially. The effects of elevation on potential ecosystem response to prescribed fire in pinyon-juniper woodlands are well-illustrated with preliminary data from a Demonstration Watershed based on a collaborative Joint Fire Sciences Program and Rocky Mountain Research Station project in central Nevada. Three different ecological types dominated by Wyoming sage (*Artemisia tridentata wyomingensis*), Vasey sage (*A. tridentata vaseyana*), and mountain brush, occur along the elevational gradient within the Demonstration Watershed. For intermediate tree covers (30 to 40%) herbaceous biomass doubled from 2103 m to 2225 m and doubled again from 2225 m to 2347 m (Fig. 1). Two years after a spring prescribed fire, herbaceous biomass was about twice that on burned than on control plots, and this difference was consistent across the elevational gradient.

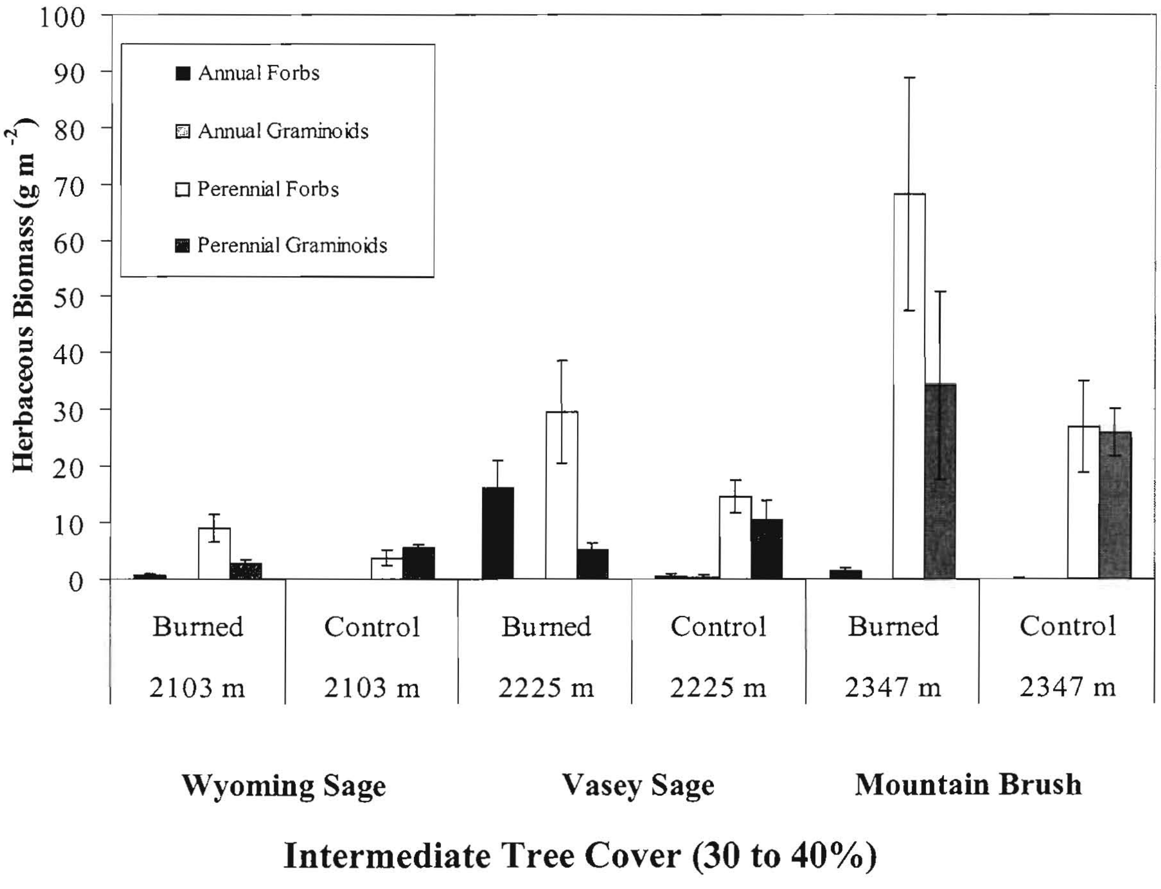

Figure 1. Biomass of herbaceous species (mean ± S.E.) in burned and control plots across the elevational gradient within the Demonstration Area in central Nevada. Tree cover was 30 to 40% (Dhaemers, Chambers, and Tausch unpublished data).

The characteristics of the vegetation community prior to treatment also have a significant influence on the recovery potential. For the Vasey sage ecological type at the 2225 m elevation within the Demonstration Watershed, herbaceous biomass declined progressively and significantly as tree cover increased from 12% to 38% to 74% (Fig. 2). Two years after the spring prescribed fire, plots with the lowest tree cover had the highest herbaceous biomass while plots with intermediate tree cover had intermediate herbaceous biomass. In contrast to plots with low and intermediate tree cover which were dominated by perennial grasses and especially forbs, plots with the highest tree cover had the lowest herbaceous biomass following the fire and were dominated by annual species. Other studies in lower elevation sagebrush communities have shown exotic species and/or cheatgrass cover to be inversely correlated with native species cover both in areas that had recently burned (West and York 2002) and areas that had not recently burned (Anderson and Inouye 2000).

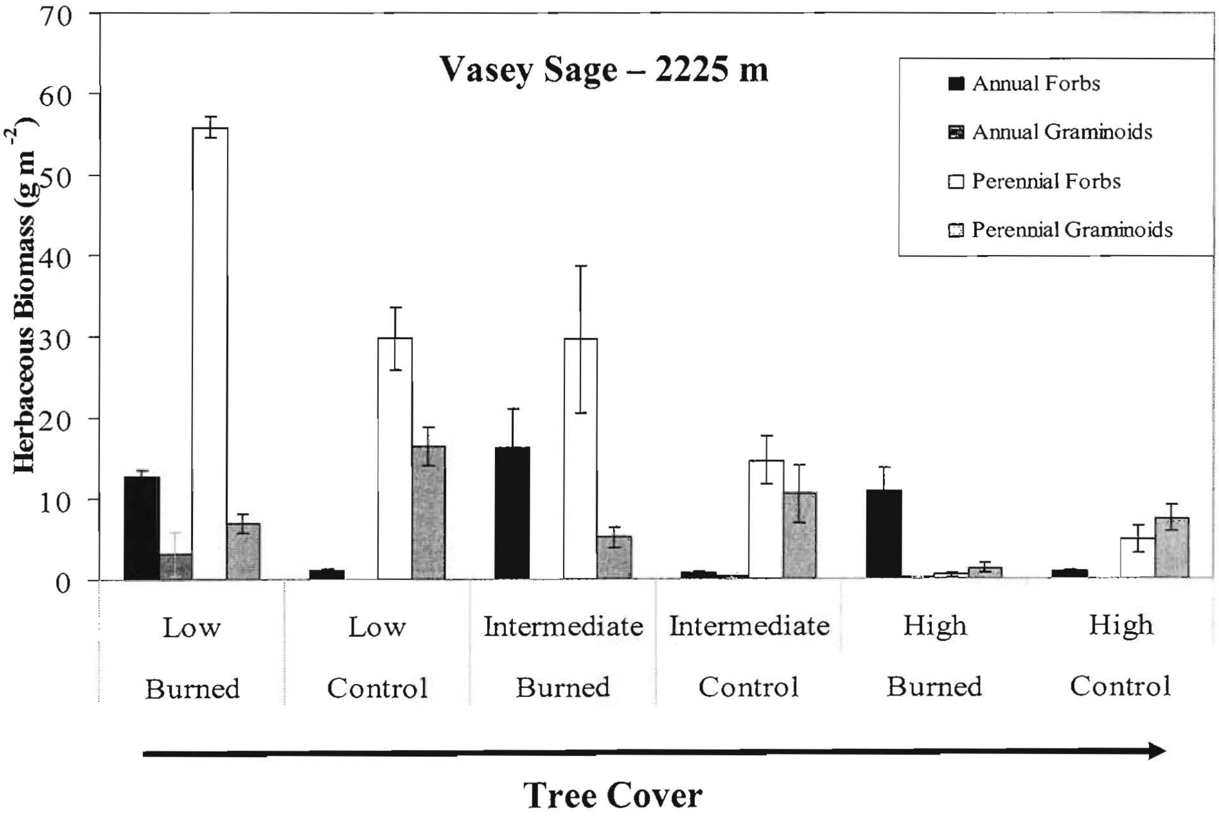

Figure 2. Biomass of herbaceous species (mean ± S.E.) in burned and control plots across for plots dominated by low (12%), intermediate (38%) and high (74%) tree cover at the mid elevation (2225 m plots) within the Demonstration Area in central Nevada (Dhaemers, Chambers and Tausch, unpublished data).

Resource availability is another major factor influencing recovery potentials and threshold crossings in these ecosystems following fire or fire surrogate treatments. Davis et al. (2000) have suggested that fluctuating resources, such as the increase in available nitrogen that usually occurs following fire, can result in windows of opportunity for invasive species to establish. On the Demonstration Watershed, available NH_4^+ showed an immediate increase in near surface soils as a result of the spring burn, while available NO_3^- decreased slightly due to volatilization. Available NH_4^+ remained elevated in under tree and especially under shrub microsites for two falls following the burn (Fig. 3). Available NO_3^- increased over time and with depth on all microsites, probably due to decomposition of roots, mineralization of NH_4^+, and the high mobility of the NO_3^- anion. Over the entire study area, available NO_3^- had increased in surface soils (0-8 cm) from 19 kg/ha (17 lbs/acre) the fall prior to the burn to 100 kg/ha (90 lbs/acre) 18 months after the burn (Rau et al. submitted). While some of this increase may be attributable to climatic variability, most resulted from the burn. Fertilization studies in many regions of the USA have shown that undesirable invasive species can increase with fertilization (e.g. Huenneke et al. 1990, Vinton and Burke 1995, Woo and Zedler 2002) and can potentially persist for long time periods after fertilization.

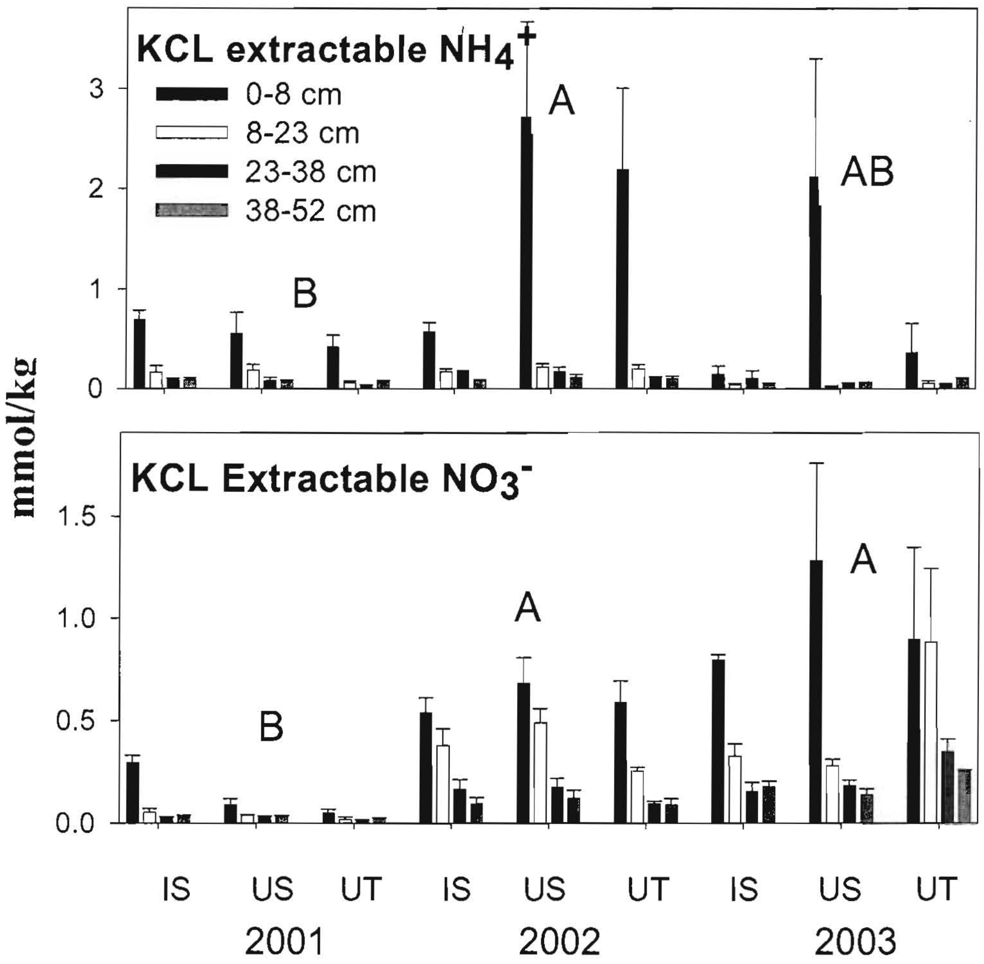

Figure 3. KCL Extractable NH_4^+ and NO_3^- (mean ±S.E.) on the mid elevation plot in the central Nevada Demonstration Watershed prior to a spring burn in October 2001, and following the burn in October 2002 and 2003. IS = interspace, US = under shrub, and UT = under tree microsites. Letter designations indicate significant differences among years (modified from Rau et al. *in press*).

Multiple factors affect species invasibility (Levine and D'Antonio 1999), and fire plays a particularly prominent role in the expansion of cheatgrass in the western U.S. largely because it can result in increased water and nutrient availability (D'Antonio and Vitousek 1992). The interacting effects of elevation, fire, and understory depletion on cheatgrass establishment, growth and reproduction were examined within the Demonstration Watershed in central Nevada. Results indicate that at higher elevations within the watershed (2380 m [7800 ft] and above), temperatures are probably too cold for cheatgrass growth and reproduction (Fig. 3). As anticipated, burning results in significant increases in both cheatgrass biomass and seed production, especially in highly fertile under shrub microsites. Herbaceous species removal alone results in relatively smaller increases in cheatgrass biomass and seed production, but the greatest increases result from the combination of herbaceous species removal and burning.

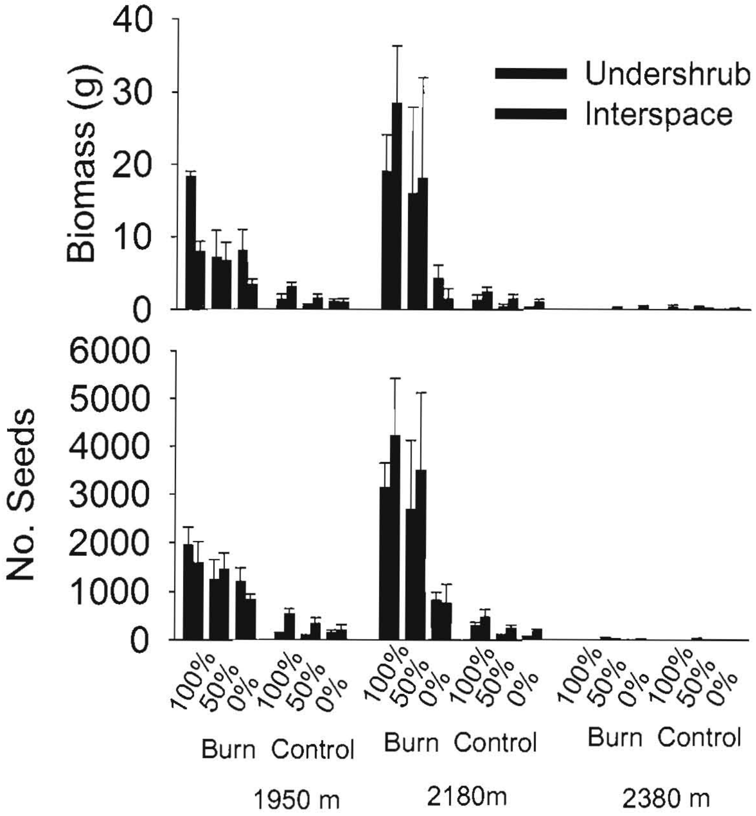

Figure 4. Biomass and number of seeds (mean ± S.E.) of cheatgrass on undershrub and interspace plots that were either burned or not burned and that had 0, 50, or 100% of the herbaceous understory removed with the foliar herbicide, glyphosate. Plots were seeded with 100 cheatgrass seeds. Sites were located at low (1950 m), intermediate (2180 m) or high elevations (2380 m) within the central Nevada Demonstration Watershed (from Chambers and others, unpublished data).

The data from the Demonstration Watershed and other studies indicate that ecosystem resistance and resilience is generally greater following fire or fire surrogate treatments for ecosystems with diverse and abundant native herbaceous vegetation, although exceptions likely exist (see D'Antonio and Thomsen 2005). They also indicate that it should be possible to define a range of values for specific ecosystem characteristics that can be used as indicators of "sustainable" ecosystems, i.e., ecosystems that will recover following fire or fire surrogate treatments. Because of the variation within woodland and rangeland ecosystems, the variables selected and the range in values used need to be specific to individual ecological types (for the Natural Resources Conservation Service website on ecological site information, see http://esis.sc.egov.usda.gov). The variables necessary to define recovery thresholds for sustainable woodlands and rangelands are being evaluated for the central Nevada Demonstration Watershed and via a new collaborative Joint Fire Sciences Program Project "A Regional Experiment to Evaluate Effects of Fire and Fire Surrogate Treatments in the Sagebrush Biome." Data from the Demonstration Watershed indicate that at a minimum, measures of the vegetation community should be examined - the biomass or cover of shrubs and pinyon/juniper trees, native herbaceous grasses or forbs, and harmful invasive species. In addition, measures of soils characteristics should be included – soil depth and texture, water infiltration and retention, and nutrient availability.

Preventative Management

There is increasing recognition that the underlying objective of both preventative management and ecological restoration should be to restructure or recreate communities to maximize resistance and resilience. Preventative management is a viable option for ecosystems that have not crossed biotic or abiotic thresholds and that have high recovery potentials. For woodlands and rangelands exhibiting increases in woody species preventative management often aims to promote sustainable ecosystems by reintroducing disturbance in the form of fire or fire surrogate treatments. Primary management objectives include reducing fuel loads to minimize the risk of high severity fires, and decreasing woody species competition with native understory vegetation. In sagebrush dominated ecosystems an additional objective often is to rejuvenate decadent shrub stands. Because viable habitat for a growing number of animal species obligate to sagebrush ecosystems, like sage grouse (*Centrocerus urophasianus*), is rapidly being depleted due to the ongoing changes in these ecosystems, project selection frequently is motivated by the need for habitat improvement (Hemstrom et.al. 2002). The specific treatments selected depend upon both the management objectives and site characteristics and are detailed elsewhere (e.g., Monsen et al. 2004). Treatments may include prescribed fire, hand or mechanical felling or removal of trees, brush beating or mowing of sagebrush, herbicide applications, or a combination of the above.

Removal and Revegetation

Removal and/or revegetation is necessary following either wildfire and fire or fire surrogate treatments for ecosystems that have crossed a biotic threshold due to invasion by exotic species or depletion of the native herbaceous vegetation. Removal alone may be appropriate when the perennial native understory is not too depleted. For example, rejuvenation of decadent sagebrush communities invaded by cheatgrass may involve brush beating to decrease shrub dominance and release the understory vegetation, and application of a pre-emergent herbicide to decrease germination of the annual grass. When both removal and revegetation are required, an integrated management approach is often used in which pre-treatments designed to remove the invasive species are implemented followed by revegetation designed to achieve the desired plant community (see Sheley and Krueger-Mangold 2003).

The objective of pretreating areas with high weed abundance is to eliminate or minimize seed production of annual species and both tillering and seed production of biennials and perennials. The most commonly used approaches for removal involve application of herbicides (see Vallentine 2004). For annual grasses like cheatgrass, preemergent herbicides (e.g., Imazapic) can be applied prior to fall seeding to decrease germination. Limitations are that legal restrictions currently exist in certain States, and that the effects on native species are poorly known. Foliar herbicides can be applied during the active growing season to cause plant mortality and prevent seed production, but these herbicides are nonselective, except within life forms, and also influence native species.

Because invasive species are often highly responsive to the level of resource availability, one promising approach to removal is using methods that decrease resource availability. Cheatgrass and other invasive species are especially responsive to nitrogen, and adding a carbon source (sucrose, sawdust) to the soil can promote microbial immobilization of inorganic nitrogen. Several studies have shown that carbon amendments can decrease the growth and reproduction of cheatgrass or other invasive species (e.g., Alpert and Maron 2000, Paschke et al. 2000). However, decreased nitrogen levels may affect native species (Monaco et al. 2003). Also, while nitrogen manipulations with a carbon source are useful for increasing our understanding of ecosystem processes, it is unlikely that management scale applications of sucrose or sawdust will be economically feasible.

It may be possible to increase community resistance, especially that of weed infested areas, by careful selection of the revegetation species (Sheley and Krueger-Mangold 2003, D'Antonio and Chambers *in press*). Seeded species can be selected and species mixtures can be structured so that the established community maximizes use of soil resources (nutrients and water). This can be accomplished by selecting native cultivars with a high probability of establishment and strong competitive abilities. It also can be done by devising diverse species mixtures that will fully occupy the site once established. Using this latter approach, species with varying phenologies are selected so that growth of some species occurs whenever environmental conditions are suitable. Species with varying life forms and rooting depths are included to facilitate resource extraction throughout the soil profile. Because rangelands and woodlands in the Intermountain Region are fire-dependent, species mixtures also should include fire tolerant species to promote resilience following future fires. For systems dominated by persistent invaders, like cheatgrass, it may be possible to first seed with competitive native cultivars and later interseed with a more diverse species mixture. Several of the integrated approaches described here are being evaluated by a regional USDA, Initiative for Future Agriculture and Food Systems (IFAFS) project on "Integrated Restoration Strategies Toward Weed Control on Western Rangelands."

Both applied and basic research is needed to identify individual species and species mixtures that can effectively compete with cheatgrass and other invaders. The short-lived perennial grass, bottlebrush squirreltail (*Elymus elymoides*), and annual cheatgrass serve as an example of a native perennial and invasive annual with similar life histories. Bottlebrush squirreltail and other native grasses are increasingly used in seeding mixtures following fire or fire management treatments, but limited information exists on the competitive attributes of many of these species or the seeding mixtures. The ability of various native grasses and cultivars to compete with cheatgrass is currently being examined at eight research sites across the Region by the IFAFS Project, but additional information is needed on the competitive ability of different seed mixtures. Other limitations to ecological restoration are the lack of native seed sources within the region and the difficulty frequently experienced in establishing native species. This limitation is being addressed partly by Great Basin Native Plant Selection and Increase Project, a collaborative effort of the Great Basin Restoration Initiative, USFS Rocky Mountain Research Station, Shrub Sciences Laboratory and other regional agencies and universities. The objective of this Project is to increase seed supplies of native plant species, particularly forbs, for the Great Basin. Its components include plant selection (source identified seed sources, methods of propagation), seed and seedling technology (genetic variability, pollination requirements, seed predation, seed germination, seedling establishment), and seed production (federal and state nurseries, NRCS, private growers).

Post-Restoration Management

Removal and revegetation are seldom successful without post-restoration management. Important aspects of post-restoration management include grazing deferral and management and monitoring. Most agencies defer grazing for two years after post-fire revegetation but, depending on site conditions, additional deferral or reduced grazing levels may be required for full recovery. Monitoring should be conducted over a long-enough period of time to evaluate recovery, normally three to five years. Monitoring measurements should be based on restoration goals and site conditions. Information should be included on the soil response, especially surface stability, and vegetation response including cover or biomass, species composition and species diversity. For areas with weed populations, monitoring should include information on the abundance (cover or biomass) and spatial distribution of all weed species. Where habitat restoration is a priority, monitoring also should include information such as population densities and turnover rates of the animal species.

REFERENCES CITED

Anderson J.E., Inouye R.S. 2001. Landscape-scale changes in plant species abundance and biodiversity of a sagebrush steppe over 45 years. Ecological Monographs 71:531-556.

Alpert, P. and J.L. Maron. 2000. Carbon addition as a countermeasure against biological invasion by plants. Biological Invasions 2:33-40.

Chambers, J.C. and J.R. Miller. 2004. Restoring and maintaining sustainable riparian ecosystems – the Great Basin Ecosystem Management Project. Pages 1-23, In J.C. Chambers and J. R. Miller (eds). Great Basin Riparian Ecosystems - Ecology, Management, and Restoration. Island Press, Covelo, CA

Chapin, F.S. III., M.S. Torn, and M. Tateno. 1996. Principles of ecosystem sustainability. The American Naturalist 148:1016-1037

Christensen, N.L., A. Bartuska, et al. 1996. The Scientific basis for ecosystem management. Ecological Applications. 63:1-34.

Davis, M.A., J.P. Grime et al. 2000. Fluctuating resources in plant communities: a general theory of invasibility. Journal of Ecology 88:528-534.

D'Antonio, C. and J.C. Chambers. 2005. Using ecological theory to manage or restore ecosystems affected by invasive plant species. In D. Falk, M. Palmer, and J. Zedler (eds). Foundations of Restoration Ecology. Island Press, Covelo, CA. *in press*.

D'Antonio, C. M. and P. M. Vitousek. 1992. Biological invasions by exotic grasses, the grass/fire cycle, and global change. Annual Review of Ecology and Systematics 23:63-87.

D'Antonio, C.M. and M. Thomsen. 2005. Ecological resistance in theory and practice. In Proceedings: Invasive Plants in Natural and Managed Systems: Linking Science and Mangement. *in press.*

Hemstrom, M.A., M.J. Wisdom, W.J. Hann, M.M. Rowland, B.C. Wales, and R.A. Gravenmier. 2002. Sagebrush-steppe vegetation dynamics and restoration potential in the Interior Columbia Basin, U.S.A. Conservation Biology 16:1243-1255.

Huenneke, L.R., S.P. Hamburg, et al. 1990. Effects of soil resources on plant invasion and community structure in California serpentine grassland. Ecology 71:478-491.

Levine, J., and C.M. D'Antonio. 1999. Elton revisited: a review of the evidence linking diversity and invasibility. Oikos 87:1-12.

Miller, R.F., and R.J. Tausch. 2001. The role of fire in juniper and pinyon woodlands: a descriptive analysis. Proceedings: The First National Congress on Fire, Ecology, Prevention, and Management. San Diego, CA, Nov. 27 - Dec. 1, 2000. Tall Timbers Research Station, Tallahassee, FL.

Monaco, T.A., D.A. Johnson, J.M. Norton, T.A. Jones, K.J. Connors, J.B. Norton, and M.B. Redinbaugh. 2003. Contrasting resources of Intermountain West grasses to soil nitrogen. Journal of Range Management 56:282-290.

Monsen, S.B., Stevens, R., and N.L. Shaw, compilers. 2004. Restoring Western Ranges and Wildlands. Gen. Tech. Rep. RMRS-GTR-136. 3 volumes. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Paschke, M.W., T. McLendon, et al. 2000. Nitrogen availability and old-field succession in a short-grass steppe. Ecosystems 3:144-158.

Rau, B.M., R.R. Blank, J.C. Chambers, and D.W. Johnson. Pinyon-juniper expansion and prescribed fire effects on soil in Great Basin sagebrush ecosystems. Soil Science Society of America Journal. *in press.*

Sheley, R.L., and J. Krueger-Mangold. 2003. Principles for restoring invasive plant-infested rangeland. Weed Science 51:260-265.

Vallentine, J.F. 2004. Herbicides for plant control. Pages 89-100. in Monsen, S.B., Stevens, R., and N.L. Shaw, compilers. Restoring Western Ranges and Wildlands. Gen. Tech. Rep. RMRS-GTR-136. 3 volumes. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Vinton, M.A., and I.C. Burke. 1995. Interactions between individual plant species and soil nutrient status in shortgrass steppe. Ecology 76:1116-1133.

West, N.E and T.P. York. 2002. Vegetation responses following wildfire on grazed and ungrazed sagebrush semi-desert. Journal of Range Management 55:171-181.

of this Project is to increase seed supplies of native plant species, particularly forbs, for the Great Basin. Its components include plant selection (source identified seed sources, methods of propagation), seed and seedling technology (genetic variability, pollination requirements, seed predation, seed germination, seedling establishment), and seed production (federal and state nurseries, NRCS, private growers).

Post-Restoration Management

Removal and revegetation are seldom successful without post-restoration management. Important aspects of post-restoration management include grazing deferral and management and monitoring. Most agencies defer grazing for two years after post-fire revegetation but, depending on site conditions, additional deferral or reduced grazing levels may be required for full recovery. Monitoring should be conducted over a long-enough period of time to evaluate recovery, normally three to five years. Monitoring measurements should be based on restoration goals and site conditions. Information should be included on the soil response, especially surface stability, and vegetation response including cover or biomass, species composition and species diversity. For areas with weed populations, monitoring should include information on the abundance (cover or biomass) and spatial distribution of all weed species. Where habitat restoration is a priority, monitoring also should include information such as population densities and turnover rates of the animal species.

REFERENCES CITED

Anderson J.E., Inouye R.S. 2001. Landscape-scale changes in plant species abundance and biodiversity of a sagebrush steppe over 45 years. Ecological Monographs 71:531-556.

Alpert, P. and J.L. Maron. 2000. Carbon addition as a countermeasure against biological invasion by plants. Biological Invasions 2:33-40.

Chambers, J.C. and J.R. Miller. 2004. Restoring and maintaining sustainable riparian ecosystems – the Great Basin Ecosystem Management Project. Pages 1-23, In J.C. Chambers and J. R. Miller (eds). Great Basin Riparian Ecosystems - Ecology, Management, and Restoration. Island Press, Covelo, CA

Chapin, F.S. III., M.S. Torn, and M. Tateno. 1996. Principles of ecosystem sustainability. The American Naturalist 148:1016-1037

Christensen, N.L., A. Bartuska, et al. 1996. The Scientific basis for ecosystem management. Ecological Applications. 63:1-34.

Davis, M.A., J.P. Grime et al. 2000. Fluctuating resources in plant communities: a general theory of invasibility. Journal of Ecology 88:528-534.

D'Antonio, C. and J.C. Chambers. 2005. Using ecological theory to manage or restore ecosystems affected by invasive plant species. In D. Falk, M. Palmer, and J. Zedler (eds). Foundations of Restoration Ecology. Island Press, Covelo, CA. *in press*.

D'Antonio, C. M. and P. M. Vitousek. 1992. Biological invasions by exotic grasses, the grass/fire cycle, and global change. Annual Review of Ecology and Systematics 23:63-87.

D'Antonio, C.M. and M. Thomsen. 2005. Ecological resistance in theory and practice. In Proceedings: Invasive Plants in Natural and Managed Systems: Linking Science and Mangement. *in press.*

Hemstrom, M.A., M.J. Wisdom, W.J. Hann, M.M. Rowland, B.C. Wales, and R.A. Gravenmier. 2002. Sagebrush-steppe vegetation dynamics and restoration potential in the Interior Columbia Basin, U.S.A. Conservation Biology 16:1243-1255.

Huenneke, L.R., S.P. Hamburg, et al. 1990. Effects of soil resources on plant invasion and community structure in California serpentine grassland. Ecology 71:478-491.

Levine, J., and C.M. D'Antonio. 1999. Elton revisited: a review of the evidence linking diversity and invasibility. Oikos 87:1-12.

Miller, R.F., and R.J. Tausch. 2001. The role of fire in juniper and pinyon woodlands: a descriptive analysis. Proceedings: The First National Congress on Fire, Ecology, Prevention, and Management. San Diego, CA, Nov. 27 - Dec. 1, 2000. Tall Timbers Research Station, Tallahassee, FL.

Monaco, T.A., D.A. Johnson, J.M. Norton, T.A. Jones, K.J. Connors, J.B. Norton, and M.B. Redinbaugh. 2003. Contrasting resources of Intermountain West grasses to soil nitrogen. Journal of Range Management 56:282-290.

Monsen, S.B., Stevens, R., and N.L. Shaw, compilers. 2004. Restoring Western Ranges and Wildlands. Gen. Tech. Rep. RMRS-GTR-136. 3 volumes. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Paschke, M.W., T. McLendon, et al. 2000. Nitrogen availability and old-field succession in a short-grass steppe. Ecosystems 3:144-158.

Rau, B.M., R.R. Blank, J.C. Chambers, and D.W. Johnson. Pinyon-juniper expansion and prescribed fire effects on soil in Great Basin sagebrush ecosystems. Soil Science Society of America Journal. *in press.*

Sheley, R.L., and J. Krueger-Mangold. 2003. Principles for restoring invasive plant-infested rangeland. Weed Science 51:260-265.

Vallentine, J.F. 2004. Herbicides for plant control. Pages 89-100. in Monsen, S.B., Stevens, R., and N.L. Shaw, compilers. Restoring Western Ranges and Wildlands. Gen. Tech. Rep. RMRS-GTR-136. 3 volumes. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Vinton, M.A., and I.C. Burke. 1995. Interactions between individual plant species and soil nutrient status in shortgrass steppe. Ecology 76:1116-1133.

West, N.E and T.P. York. 2002. Vegetation responses following wildfire on grazed and ungrazed sagebrush semi-desert. Journal of Range Management 55:171-181.

Whisenant, S.G. 1999. Repairing Damaged Wildlands. A Process-Oriented, Landscape-Scale Approach. Cambridge University Press, Cambridge, UK.

Woo, I., and J.B. Zedler. 2002. Can nutrients alone shift a sedge meadow towards invasive *Typha x glauca*? Wetlands 22:509-521.