Ratcheting up resilience in the northern Great Basin

By Dustin Johnson, Chad Boyd, Rory C. O'Connor, and Dustin Smith

On the Ground

- Rangeland resilience is influenced by a variety of ecosystem properties that fall into two broad categories, 1) abiotic and 2) biotic.
- Although important to consider in land management planning, abiotic properties cannot be directly influenced with management. In contrast, biotic properties of the ecosystem can be readily influenced by management.
- The formula for robust biotic resilience to wildfire and resistance to invasive annual grasses in the northern Great Basin sagebrush ecosystem is about maintaining and promoting perennial bunchgrasses.
- The management system must be resilient if we hope to promote ecosystem resilience in an ever-changing risk, seedling recruitment, and recovery environment. A successful strategy for promoting ecosystem resilience will require securing a resilient management system, and a shift in paradigm from random acts of opportunistic restoration to a sustained, organized, process-based approach for promoting ecosystem resilience.

Keywords: resilience, invasive annual grass, perennial bunchgrasses, adaptive management, degraded sagebrush, sagebrush rangeland.

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There has been significant focus on ecosystem resilience and how related principles can be used to inform rangeland management decisions. Land managers, practitioners, and researchers would agree in principle that sagebrush (*Artemisia* L.)-dominated rangeland management choices should promote ecosystem resilience to wildfire and related resistance to invasive annual grasses in the northern Great Basin. With any potentially unifying ecosystem management strategy, it is prudent to ensure a common vision of resilience and related principles are shared among affected stakeholders. A diverse group of over 200 western rangeland management practitioners, researchers, and educators were participants of the 2020 High Desert Partnership (HDP)/Oregon Sage-con Invasive Annual Grass Workshop and were asked to independently submit definitions for ecosystem resilience. Although different words were used by a diverse set of participants to describe ecosystem resilience (Fig. 1), most definitions, and the one we use in this article, center on concepts related to an ecosystem's capacity to recover structure, functions and processes,[1] and produce associated values[2] in the face of major stressors or disturbances. Such broad agreement suggests that promoting ecosystem resilience could be a unifying strategy in rangeland management for addressing major challenges like invasive annual grasses. In practice, however, a strategy focused on improving resilience requires an understanding of the basic factors conveying ecosystem resilience and identification of which of those factors can and should receive management attention.

The threat of interactive ecosystem disturbances and stressors of wildfire and invasive annual grasses, that challenge and can even comprise ecosystem resilience, varies within a highly fluctuating environment in the northern Great Basin. The threat of wildfire is strongly tied to weather patterns and the influence they have on fuel accumulations.[3] As an example of the variation in weather from year to year annual precipitation ranged from less than 127 mm (5 in) to more than 534 mm (21 in) from 1937-2007 at the Northern Great Basin Experimental Range (NGBER) in southeast Oregon. During that 70-year period, only about 1 out of every 4 years fell within 10% of the long-term average of 280 mm (11 in). Annual precipitation is a major driver of plant growth and biomass (fuels), especially in dry systems such as the northern Great Basin sagebrush ecosystem. Wet years may be highly productive, while plant growth may not be fully expressed during dry years. This annual variability in vegetation has important implications for management. Further complicating matters is that resilience is not static and can vary depending on the timeframe within which a disturbance like wildfire occurs. The ecosystem's ability to recover structure, functions, and processes following wildfire is highly influenced by weather conditions in the years preceding and following the disturbance.[4] Promoting resilience to wildfire is challenging in such an environment, particularly given the formidable threat

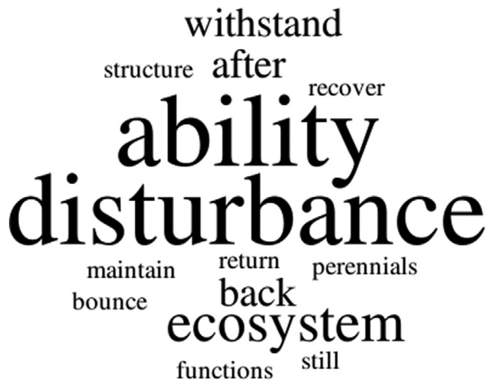

Figure 1. Word cloud developed from definitions of ecosystem resilience submitted by participants of the 2020 High Desert Partnership/Oregon Sage-con Invasive Annual Grass Workshop. Size and boldness of individual words indicate higher frequency of use by participants.

of invasive annual grasses, and restoration efforts rarely occur as planned on paper and success often requires iterative attempts. As such, a successful strategy for promoting ecosystem resilience requires a sustained adaptive management effort to address everchanging risk and recovery conditions. The management system itself must possess properties of resilience if we hope to promote ecosystem resilience in a dynamic risk and recovery environment. Therefore, a successful strategy for promoting ecosystem resilience will first require securing the necessary components of a resilient management system. Resilient management systems have a set of core qualities aptly covered elsewhere in this special issue including sustained investment, implementation at appropriate scales, and enabling policy (see Smith et al.; Maestas et al.; Cahill this issue).[5–7] We focus on properties of the northern Great Basin sagebrush ecosystem contributing to resilience, with a particular focus on factors that can be influenced through land management and should be incorporated into a strategy for promoting resilience to wildfire and related resistance to invasive annual grasses.

The hand we are dealt

Resilience is influenced by a variety of ecosystem properties that fall into two broad categories, 1) abiotic and 2) biotic. The first category includes the properties of the ecosystem shaped by the geologic and climatic history of the region. These abiotic factors influencing ecosystem resilience represent the hand we are dealt as land managers.

These abiotic properties take in factors influencing rangelands soil temperature and moisture regimes including elevation, latitude, soil depth and texture, and solar exposure.[8] Generally, ecosystem resilience decreases with decreasing elevation (Fig. 2). Other factors that influence a site's soil moisture and temperature regime, such as solar exposure, soil texture and depth also play important roles, whereby warmer, drier sites inherently offer lower resilience to disturbances than cooler moister sites.[9] These abiotic factors have a large bearing on where threats are expressed within the ecosystem (Fig. 2), and such knowledge can be used to inform related management priorities for promoting ecosystem resilience.[10] However, it is important to understand that the abiotic properties that influence ecosystem resilience are not static, especially those associated with weather and climate. For example, a system can respond very differently depending on the weather conditions occurring before and after a fire.[4] Specifically, lower elevation sites that normally offer lower resilience to disturbance may behave more like higher elevation areas in response to wildfire during cool, wet climatic cycles favoring perennial plant reestablishment. The reverse is also true. Therefore, it is important to pay attention to climatic conditions associated with disturbance events and the implications they have for ecosystem response and recovery. In addition, it is better to know than to guess. Monitoring ecosystem response (e.g., perennial bunchgrass abundance and survival, and invasive annual grass presence and cover) post-disturbance is critical to ensure the recovery trajectory is in-line with desired management outcomes and to know if or when management intervention is necessary.

Knowledge of abiotic properties influencing ecosystem resilience can be used to inform selection of appropriate land treatments.[8] For example, application of prescribed fire might represent a completely reasonable vegetation treatment (e.g., conifer control) for higher resilience (usually higher elevation) areas, while it is generally discouraged for less resilient rangelands prone to invasion by annual grasses.[11,12] Knowledge of the influence of abiotic properties on resilience can be used to prioritize management attention and associated resources. For instance, knowledge and mapping of abiotic factors influencing ecosystem resilience can be used proactively to inform a fire suppression strategy within a Potential Operational Delineations framework (PODs, see Wollstein et al. this issue),[13] whereby PODs comprised of rangelands prone to annual grass invasion might be prioritized for suppression efforts. Alternatively, PODs with higher wildfire resilience might receive lower suppression priority, especially if fire may actually promote values identified within the area (e.g., areas prone to conifer expansion). Although it is extremely important to account for abiotic properties impacting ecosystem resilience when making management decisions, they are not factors we can directly influence from a practical sense.

Biotic resilience – it's about bunchgrasses baby!

The other category of factors playing a major role in shaping ecosystem resilience includes the biotic properties of the ecosystem. Biotic conditions, especially vegetation, have a large influence on the ecosystem's capacity to recover from

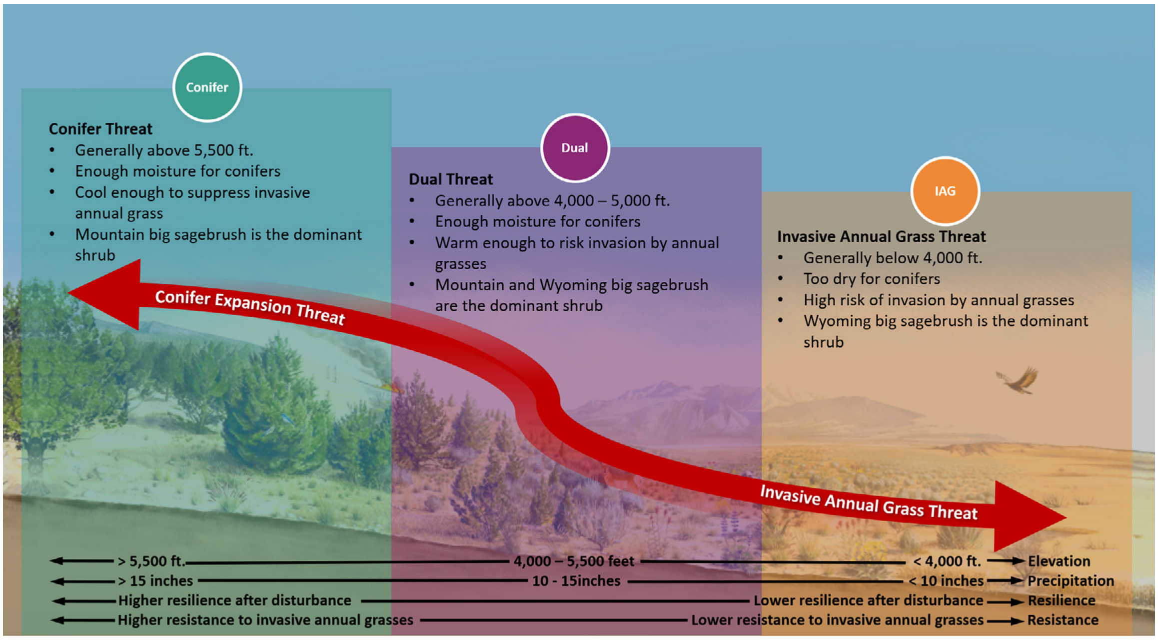

Figure 2. Environmental and biotic indicators of ecosystem susceptibility to the primary threats of conifer expansion and invasive annual grasses in the northern Great Basin sagebrush steppe region (adapted from Johnson et al.).[10]

disturbances like wildfire and to resist invasion by annual grasses.[14–18] In contrast to abiotic properties, biotic factors that convey ecosystem resilience can be influenced with management.

Managing biotic (vegetation) conditions in ways that promote ecosystem resilience first requires an understanding of relevant ecology and, specifically, which ecological properties should receive attention as part of a strategy for ratcheting up resilience. Sagebrush steppe vegetation in the northern Great Basin region can be broadly classified into different groups based on their ecological functions within plant communities.[19] Plant functional groups within this region commonly include shrubs (predominantly big sagebrush - *Artemisia tridentata Nutt.*), large perennial bunchgrasses (e.g., bluebunch wheatgrass -*Pseudoroegneria spicata* (Pursh) Á. Löve), small perennial bunchgrasses (e.g., Sandberg bluegrass - *Poa secunda* J. Presl), annual and perennial forbs, and annual grasses (usually non-native invasives; Fig. 3). Plant functional group composition is a key determinant of biotic resilience of the ecosystem.[14] It is important to note, even with completely filled niches (i.e., all available soil resources are utilized by desired plants), sagebrush plant communities will often consist of bare ground areas that appear empty and invasible. Native vegetation in these semi-arid shrublands is discontiguous because sparse perennial bunchgrasses and shrubs compete for limited water and nutrients, resulting in barren interspaces between plants.[20] A large portion of this ecosystem usually receives <300 mm (11.8 inches) of precipitation a year and has a high evaporative rate.[21] As such, fewer plants can grow per unit area in this resource limited environment than in areas with higher annual precipitation. However, in resilient sagebrush plant communities, the soil profile is "occupied" by the roots of perennial plants beneath these bare areas – principally large perennial bunchgrasses – that are utilizing nutrients and water and making those resources unavailable to undesirable invasive annual grasses (Fig. 4; see Maestas et al. and Boyd this issue for related discussions).[6,22] Therefore, although the above-ground area near bunchgrasses might appear barren, by taking an underground view, it becomes obvious the plants' root masses fully occupy the space. Conversely, in plant communities where bunchgrasses are reduced or lacking, niches are left unfilled, leaving a soil profile unoccupied by roots of desired functional groups and susceptible to invasion by annual grasses. Although shrubs also occupy space and utilize resources within these plant communities, the near surface root density of shrubs is much less than bunchgrasses.

Understanding differences in root structures and their functions among plant functional groups gives clues to why sagebrush plant communities change in response to disturbance when certain groups of plants are lost from the community and what managers should pay attention to in order to avoid unwanted changes. The optimum management strategy for promoting rangeland function and productivity includes preventing the loss of established perennial bunchgrasses. The more bunchgrasses on a landscape, the greater the ability of the rangeland to resist invasive annual grasses.[14–17] Bunchgrasses also improve the resilience of the ecosystem to wildfire. The deep roots and location of growing plants allows many species of bunchgrasses to more readily regrow after fire[23] (Fig. 5), compared to other important, but fire intolerant species such as sagebrush. This regrowth can limit open niches and unoccupied bare ground, reducing the potential for invasion by annual grasses.

Though bunchgrasses play a dominant role in maintaining biotic resilience of sagebrush-dominated rangelands to wildfire and resistance to invasive annual grasses, other plant func-

Plant functional groups

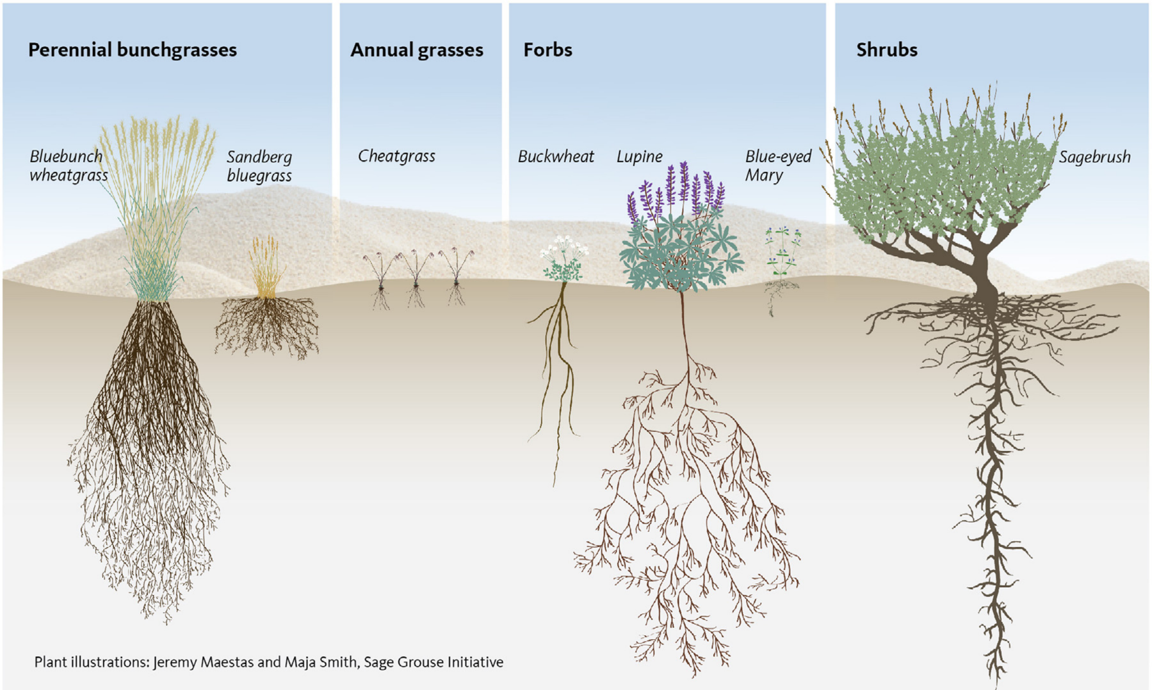

Figure 3. Primary plant functional groups comprising northern Great Basin sagebrush plant communities.

Figure 4. Plant display showing the rooting morphology of the primary plant functional groups comprising northern Great Basin sagebrush plant communities including, from left to right, small perennial bunchgrass (i.e., Sandberg bluegrass - *Poa secunda* J. Presl), large perennial bunchgrass (e.g., bluebunch wheatgrass - *Pseudoroegneria spicata* (Pursh) Á. Löve, shrub (e.g., Wyoming big sagebrush - *Artemisia tridentata* Nutt. Ssp. *wyomingensis* Beetle & Young), and perennial forb (e.g., whitewoolly buckwheat – *Erigonum ochrocephalum* S. Watson). Perennial bunchgrasses have the highest root mass among the plant types and effectively take nutrients and water from the soil, reducing available resources for invasives.

Figure 5. Post fire photo of surviving large perennial bunchgrass (bottlebrush squirreltail - *Elymus elmoides Raf.*). Photo Credit: Lori Ziegenhagen.

tional groups also contribute vital ecosystem functions and related values. For example, sagebrush is critical to providing many habitat requirements of sagebrush obligate wildlife species, and forbs are essential for monarch butterflies, other pollinators, greater sage grouse (*Centrocercus urophasianus*), and other wildlife species.[24] As such, maintaining or restoring the full diversity of sagebrush plant community structure and composition is important. Doing so, however, requires bunchgrasses in annual grass prone rangelands, because without them, invasion by annual grasses,[18] frequent fire,[3,25,26] and declines in fire intolerant sagebrush and plant biodiversity[27] will occur.

Bolstering badass bunchgrasses

Despite the importance of bunchgrasses to ecosystem resilience, their dominance is tenuous, and dependent on recruitment of new seedlings into the population at least every

10 or 15 years.[28] Their dominance is made even more tenuous by the increasing frequency of wildfire; a single wildfire can kill 20 – 60% of bunchgrasses within a plant community.[29] Indeed, wildfire is the primary disturbance challenging the resilience of the northern Great Basin sagebrush ecosystem and is inextricably linked to declines in bunchgrasses and expansion of invasive annual grasses. As such, management promoting bunchgrasses as the primary biotic property of ecosystem resilience must consider the interplay between pre-fire biotic (vegetation) conditions and wildfire severity. In this context, the term wildfire severity refers to the net impact of a fire on plant community resistance to annual grass invasion and the associated ability of the ecosystem to recover a perennial bunchgrass-dominated plant community.

Research has shown extreme temperatures during a wildfire, and the duration of those extreme temperatures are a function of the amount of woody (i.e., shrub) fuels present in sagebrush plant communities.[29,30] Thus, as shrub fuels increase in abundance, fire severity has a corresponding increase. This is important, because shrubs are an energy dense fuel and combustion of shrub fuels is necessary to create the head load (amount and duration of elevated temperature) that kills perennial bunchgrasses.

If we want to promote ecosystem resilience to wildfire, then should we eradicate shrubs? No, not only would such an approach be ecologically and socially unacceptable, it is simply not the message here. Our point is that strategic brush management will be needed as part of an approach to promote resilience to wildfire in the sagebrush ecosystem given the interplay between wildfire, shrub abundance, and perennial bunchgrass mortality, especially in areas experiencing long-term exclusion of disturbance and with high shrub cover.[31] More research is needed, however, to better understand the potential interactive thresholds in shrub abundance and understory herbaceous fuel amount and continuity as they relate to perennial bunchgrass mortality and wildfire resilience in sagebrush plant communities. Such thresholds could identify and prioritize locations for management action based on readily available remote sensing information, such as plant functional group cover available via the Rangeland Analysis Platform (https://rangelands.app/). Further research is needed to build on existing knowledge (see Archer et al.)[32] in order to inform decisions regarding appropriate shrub reduction objectives and related tactics that do not promote invasive annual species among sites with varying abiotic and/or biotic resilience attributes.

Additionally, fine fuel management can play a critical role in determining the level and nature of shrub combustion during a wildfire event. Davies et al.[15] found that combustion of woody fuels is directly linked to fine fuel abundance and continuity; as fine fuel abundance and continuity increase, the percentage of shrubs combusting during a fire event also increases, which in turn increases heat energy output of the fire. So, while fire severity is largely a function of the amount of shrub fuel combusted, the percentage of shrub fuels becoming engaged in a fire is dependent on the amount and continuity of fine fuels. From a pragmatic standpoint, the functional "role" of fine fuels (be they perennial or annual) in a fire is to provide the fuel structure necessary to carry fire from shrub to shrub, while shrubs produce the heat load necessary to kill perennial bunchgrasses. As such, another part of an approach to promoting ecosystem (i.e., perennial bunchgrass) resilience may involve managing fine fuels in a manner consistent with limiting shrub combustion, which indirectly improves perennial bunchgrass survival when wildfire occurs (see Boyd).[22] Extreme fire weather conditions, particularly in areas of heavy woody fuels, controls fire behavior[33] and may override the effects of fine fuels management head load[34]; however, many rangeland fires ignite or burn during periods of lesser fire weather severity when fine fuels management may aid suppression efforts or reduce spread and fire behavior of unsuppressed fires.[35] Fine fuel management may also more directly influence perennial bunchgrass survival following wildfire. In a southeast Oregon study, Davies et al.[36] found that long-term livestock grazing exclusion increased risk of annual grass invasion following a fall burn compared to areas moderately grazed over the same time period. Moderate livestock grazing was defined as approximately 40% annual use by weight of available forage and periodic growing season rest for perennial bunchgrasses. The increase in invasive annual grass density in areas that had been protected from livestock grazing persisted for 14 years following fire. Davies et al.[36] suggested moderate levels of livestock grazing reduced litter accumulation of perennial bunchgrasses, which in turn resulted in more vigorous plants that experienced less self-shading and reduced fuel loading atop grass crowns (Fig. 6). A reduced amount of fuel loading on the crowns of bunchgrasses facilitated higher fire survival of bunchgrasses in areas moderately grazed. Greater survival and density of mature perennial bunchgrasses in grazed areas following fire, reduced post-fire resource availability for invasive annual grasses compared to areas afforded long-term protection from livestock grazing and experienced high perennial bunchgrass mortality. We suggest that strategies for reducing fine fuel accumulation and maintaining vigor of perennial bunchgrasses should be incorporated into management plans for sagebrush-dominated rangelands at risk of annual grass invasion. Likely, the only practical means of reducing litter accumulation on extensive rangelands is through well-managed livestock grazing (see Davies et al.).[37] "Well-managed livestock grazing" is a key term here as not all forms of grazing – such as heavy and/or continuous season-long use – will promote bunchgrasses and ecosystem resilience. Some information is available for informing fine fuel treatment (often grazing) objectives, however, more research is required to define management-scale (usually pasture) thresholds in fine fuel cover and abundance to aid in interpretation of available remote sensing data to inform the needs, locations and objectives for management actions.

Likely, the factors contributing to fire-induced bunchgrass mortality have always existed. Sagebrush has been part of the system for several millennia,[38] and it is unlikely that northern Great Basin rangelands experienced high grazing pressure (fine fuels modifications) prior to European settle-

Figure 6. Litter accumulation associated with grazed and ungrazed large perennial bunchgrasses (Thurber's needlegrass - *Achnatherum thurberianum* (Piper) Barkworth) in northern Great Basin sagebrush-dominated rangelands. Photo Credit: Kirk Davies.

ment.[39] High perennial bunchgrass mortality was likely a common outcome after periodic rangeland wildfire.[40] What has changed is the introduction of invasive annual grasses, which necessitates perennial bunchgrass recovery within a compressed timeframe compared to ecosystem recovery periods in the past. Indeed, conversion to a persistent annual grass state is practically assured in the absence of perennial bunchgrass recovery, especially in areas with lower abiotic resilience. Prior to the introduction of invasive annual grasses, recovery of sagebrush-dominated rangelands may have been slow depending on conditions, but the trajectory was largely secure. Invasive annual grasses have fundamentally changed the rules, requiring rangeland managers to consider alternative forms of management to promote bunchgrass survival and establishment after fire (see Boyd this issue).[22]

Rehabbing beleaguered bunchgrasses

Large tracts of sagebrush-dominated rangelands have been degraded through historical overgrazing by sheep, cattle, and horses, resulting in communities with few large perennial bunchgrasses, perennial forbs, and often an increased dominance of shrubs.[41] West[42] estimated that 25% of the sagebrush ecosystem was composed of sagebrush plant communities with degraded herbaceous understories and increased shrub dominance. Perhaps even more concerning is the majority of land in a degraded condition likely occurs in lower resistance and resilience (warmer, drier) areas supporting Wyoming big sagebrush (*Artemisia tridentata* Nutt. Ssp. *wyomingensis* Beetle & Young).[8,18,41] A wildfire under such conditions ensures a trajectory toward invasive annual grass dominance. Restoration of these plant communities has become a critical management imperative because of their value as wildlife habitat, as well as to increase resistance to invasive annual grasses and improve ecosystem resilience to wildfire.[41]

Restoration of degraded Wyoming big sagebrush communities has proven to be exceedingly difficult. Intermediate-term (5-10 years) rest from grazing in degraded Wyoming big sagebrush rangeland produced no evidence of recovery in understory herbaceous species in southeast Oregon.[31] Using fire or mechanical methods to promote perennial herbaceous plants by reducing Wyoming big sagebrush dominance has encouraged increases in invasive annuals and resulted in trivial responses from native perennial bunchgrasses and forbs.[43,44] Seeding native perennial bunchgrasses after mechanically reducing Wyoming big sagebrush also generally fails, with negligible increases in native bunchgrasses but large increases in invasive annual grasses and forbs.[45] Such a high failure risk might suggest that restoration attempts in degraded Wyoming big sagebrush-dominated rangelands should not be attempted; particularly since these areas still support sagebrush and offer related ecosystem services. However, it is not all bad news as some studies have demonstrated positive responses to management treatments under favorable environmental conditions,[46] especially when desired perennial vegetation is not entirely depauperate. In addition, degraded Wyoming big sagebrush-dominated rangelands have and will continue to burn in wildfires, with conversion to invasive annual grassland nearly guaranteed as a consequence. As such, defaulting to a strategy of passive management, motivated by a fear of failure, is probably not a viable long-term strategy for addressing the problem. At the same time, the land stewardship equivalent to the Hippocratic Oath suggests we should not knowingly do harm in the actions we take.

Restoration of degraded sagebrush rangelands is a problem that firmly places land managers between a rock and a hard place. We are unlikely to solve this problem here and now, but would like to offer a few ideas for productive future directions. First, it is important to recognize restoration of degraded sagebrush rangelands is indeed a complex problem. In arid ecosystems, relationships are highly variable over space and time in accordance with a multitude of biotic and abiotic factors such that restoration outcomes depend not only on where practices were applied, but also on when they were applied.[47] Successful restoration in such an environment therefore requires a process-, rather than an event-based approach. Increasingly, sustained effort within an adaptive management process is viewed as a requisite approach for addressing these types of complex problems,[47] which stands in stark contrast to traditional project planning focused on carrying out point-in-time restoration events. In fact, we would argue placing all hope in an event-based approach to restoration is functionally equivalent to playing the lottery as a primary investment strategy for retirement. You might get lucky, but the odds are stacked against you. Specific to our topic at hand, it is highly unlikely a singular treatment will be effective, so the problem should be managed with that in mind. Therefore, management planning, from the onset, should provide for ongoing, regular monitoring of results and modification of approach with timely interventions when necessary. Inaction may represent a better approach for degraded Wyoming big sagebrush-dominated rangelands if a commitment to ongoing management cannot be confidently made from the outset of the adaptive management process.

Next, given the inherent risk of failure associated with restoration treatments in degraded sagebrush plant communities, a potentially appealing restoration strategy might include implementing smaller scale treatments every year. Such an approach reduces costs associated with failure and follow-up treatments and increases the probability restoration attempts will occur under favorable conditions associated with certain years. Smaller scale efforts might also facilitate innovation through experimentation with techniques that could be scaled up pending their effectiveness.[48] Untested treatments are often viewed as carrying higher risk than conventional techniques, even if conventional treatments often fail, particularly when conducted over large areas. Experimenting with different treatments at smaller scales would likely reduce perceived risk compared to treating larger areas. In addition, smaller scale treatments can potentially be accomplished with equipment (e.g., ATV sprayers or seeders) that is lower in cost and easier to own/operate, which may alleviate logistical barriers and facilitate more timely follow-up management interventions. Staging restoration treatments over multiple seasons or years also represents a strategy that may fit within the annual operating budgets of land management agencies and landowners. For these reasons, we feel an approach involving deployment of smaller scale restoration treatments staged over multiple years is worth considering. Degradation of sagebrush-dominated rangeland did not happen overnight and we should not expect reversing it will either.

Lastly, and with some trepidation, we would like to touch on the subject of plant materials used in restoration efforts for degraded sagebrush plant communities (See Baughman et al. this issue for a related discussion).[49] Those who have been involved in management of western rangelands have likely engaged in conversation involving seemingly intractable debate over the merits and perils of crested wheatgrass (*Agropyron cristatum*). Frankly, such conversations are intellectually draining, and predictably playout like most arguments over tools, where in fact some folks love the tool and would like to see it used everywhere, while others' disdain for the tool is palpable. This is an oversimplification, as yet others are in the middle, but you get the point. If we consider the facts, crested wheatgrass is able to establish and persist under a wider range of environmental conditions compared to native perennial bunchgrasses.[50–52] This is an important attribute because, given the pressures exerted by invasive annual grasses and related changes to the ecosystem effected by their dominance, perennials plants have but a short window of opportunity for establishment following treatment or disturbance (see Boyd this issue).[22] Given the choice, many individuals engaged in management of sagebrush-dominated rangelands would rather see native bunchgrasses present. So instead of continuing to debate the appropriateness of using crested wheatgrass in restoration efforts, why not use what we learn about what physiological traits make it successful and find ways to promote expression of similar traits in desirable native species? For example, Hammerlynck and O'Connor[50] found crested wheatgrass, which has evolved to withstand herbivory, has increased reproductive potential compared to bottlebrush squirreltail (*Elymus elmoides Raf.*) because it produced seeds with higher specific mass. This translates to increased success in crested wheatgrass seed germination and seedling emergence, even during stressful abiotic conditions. Crested wheatgrass is resilient to herbivory from the seedling to the adult stage which allows it to persist while other native bunchgrasses decline.[51] These crested wheatgrass traits make it an ideal candidate for planting in stressful environments, but also make it an ideal candidate to use as a model to identify successful traits for native bunchgrass plant materials programs.[53] If we want to have successful restoration it is time for a paradigm shift regarding how we select, breed, and seed native bunchgrasses to keep up with a climatically variable and fire-prone management environment. Indeed, badass native bunchgrasses need to become a little "badder-ass" to keep pace within a highly fluctuating environment vulnerable to invasive annual grasses. In the meantime, it will be important to continue to carefully consider where and when it is appropriate to plant crested wheatgrass, given the potential relative permanency of such plantings[54–56] and related impacts to biological diversity.[57–59]

Recapping resilience

Ratcheting up sagebrush-dominated rangeland resilience to wildfire and promoting a related resistance to invasive annual grasses requires a firm understanding of the ecosystem properties contributing to resilience. Such properties can be broadly classified into two categories 1) abiotic and 2) biotic. Abiotic properties include factors influencing a rangeland's soil temperature and moisture regimes including elevation, latitude, soil type and texture, and solar exposure. Knowledge of how these factors influence resilience is critical for understanding vulnerability to the ecosystem threat of invasive annual grasses, and for informing appropriate management expectations and responses. However, abiotic properties cannot be influenced with management, and largely represent the hand land managers are dealt. The other category of factors playing a major role in shaping ecosystem resilience includes the biotic properties of the ecosystem. In contrast to abiotic properties, biotic properties of the ecosystem can be influenced by management.

The formula for robust biotic resilience in the northern Great Basin sagebrush ecosystem is largely about those badass bunchgrasses! Bunchgrasses, however, merit this designation only if they are mature plants and occur in sufficient abundance to preclude invasive annual grasses. As such, bunchgrasses need to successfully recruit new seedlings into the population and survive wildfire (and other disturbances) in order to fend off an ever-present onslaught from invasive annual grasses. Meeting these imperatives in a highly variable, annual grass-prone environment modifies the very nature of the problem from seemingly simple, to a highly complex one, particularly in areas where bunchgrasses are beleaguered rather than badass. Success in such an environment requires a process rather than an event-based approach. A singular management treatment is unlikely to be effective, so, management planning, from the onset, should provide for ongoing, regular monitoring of results and timely interventions when necessary. The management system itself must also possess properties of resilience if we hope to promote ecosystem resilience in an ever-changing risk, seedling recruitment, and recovery environment. As such, a successful strategy for promoting ecosystem resilience will first require securing the necessary components of a resilient management system, such as sustained investment, preemptive ecosystem planning (e.g., PODs), implementation at appropriate scales, and enabling policy.

To conclude, rangeland science is making strides toward informing tangible strategies for promoting ecosystem resilience. Recent work has facilitated an improved understanding of the relationship between fuels (amount, continuity, and composition) and perennial bunchgrass mortality. Organization and communication of near-real time information about related biotic properties of the ecosystem has and continues to be greatly enhanced. Rangeland scientists are also narrowing in on plant traits that promote native bunchgrass establishment and persistence under a wider range of ecological conditions. Although these are exciting developments, it is unlikely they will produce anything resembling a silver bullet, which further highlights the need for a paradigm shift from random acts of opportunistic restoration to a sustained, organized, and regional process-based approach for promoting ecosystem resilience.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests. DJ is a Guest Editor for this Special issue but was not involved with the review or decision process for this manuscript. The authors certify that they have no financial interest in the subject matter discussed in the manuscript. The content of sponsored issues of *Rangelands* is handled with the same editorial independence and single-blind peer review as that of regular issues.

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