Ecological Approach for Designing and Assessing Montane Meadow Restoration in California

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Abstract

Meadows in the mountains of California are ecologically important habitats that have become degraded following Euro-American colonization and the introduction of large herds of livestock in the 19th century. Their value has inspired a commitment from the U.S. Forest Service and others to increase the pace, scale and efficacy of meadow restoration in California. This increase in effort has exposed problems with widely applied restoration approaches such as pond-and-plug. Stream restoration science suggests reasons why some restored systems do not perform as well as comparable reference meadows. Here, we summarize the historical and current state of Sierra Nevada meadows, discuss current restoration practices, and propose ecologically-based restoration design standards and guidelines for Sierra Nevada meadow restoration projects. This approach: (1) views forest meadow ecosystems as three-dimensional landforms that have developed over long timespans through interactions between physical and biological processes, and (2) asserts that the main purpose of restoration is to reinvigorate and revitalize these processes. The underlying principles of the approach are to: (1) use the intrinsic energy of a site (e.g. the potential energy of streams and the solar energy captured by plants) to do the work of restoration where possible; (2) begin with minimally invasive procedures before attempting more heavily engineered and largely irreversible approaches; and (3) address the root causes of degradation and remove or modify human infrastructure that constrains fluvial processes, if possible.

Geomorphic History of Sierra Nevada Meadows

Mountain meadows provide ecologically important habitats throughout the Sierra Nevada. Mountain meadows typically occupy low-gradient geologic “benches” at elevations from 5,000 to 9,000 feet. Most Sierra Nevada meadows developed from floodplain and alluvial fan deposition, particularly during glacial outwash at the end of the Pleistocene, rather than infilling of lake basins (Wood 1975). Though they occupy less than 3% of the landscape, meadows provide habitat essential to numerous species (e.g. 50% of all vertebrate species in the region; Ratliff 1985, Murphy et al. 2004). Most Sierra Nevada meadows remained relatively stable habitats for thousands of years, until Euro-American settlement in the mid-19th century (Wood 1975, Benedict 1982). Wood's (1975) study of the development of mountain meadows in the southern Sierra Nevada revealed that downed trees and wetland graminoids modulated sediment transport rates and hydrologic processes to slowly build self-maintained mountain meadow ecosystems. He did not find stratigraphic evidence that beaver were instrumental in meadow development, though beaver dams were historically present in the Sierra and may have significantly contributed to soil accumulation in some meadows (James and Lanman 2012, Lanman et al. 2012). Typical soil depths in wet Sierra Nevada meadows range 4-6 feet, but can be much greater (Wood 1975). Thus the bulk of these ecosystems is below ground, composed of roots, decaying plant material and accumulations of mostly fine sediment, which form a rich organic soil horizon with high moisture retaining capacity. Sierran meadows showed little evidence of incision prior to Euro-American colonization and the introduction of large herds of livestock in the 19th century (Wood 1975).

Recent History of Sierra Nevada Meadows

For Euro-American settlers coming to California in the latter half of the 19th century, their large expanses of lush herbaceous vegetation made mountain meadows attractive for livestock grazing (Burcham 1957, Ratliff 1985). Unlike the vast prairies of the midwestern United States where large herds of bison ranged, the Sierra Nevada's meadow vegetation did not evolve in the presence of heavy grazing (Ratliff 1985). Though uncertainty remains about the relative contributions of different processes to the incision of Sierran meadows, intensive grazing and associated human manipulation of drainage patterns concentrated flow paths while also reducing the resistance of the meadow surface to erosional flow (Ratliff 1985, Kattlemann 1996). In some cases, portions of meadows were intentionally drained to increase grazing potential: sinuous, multi-threaded, sedge-lined flow paths were concentrated into single, often linear channels with exposed mineral banks. Later, to facilitate road construction, multi-threaded tributary flows were concentrated into single channels to reduce the need for culverts (Fig. 1). Thus, mountain meadows that had been aggrading for millennia quickly transitioned from sediment sinks to sediment sources due to incision through the organic horizon and into lower and more mobile mineral strata (Loheide and Booth 2011). Meadow vegetation no longer filtered and retained upstream sediment. Water tables dropped dramatically because incised channels can drain surface and ground water to the elevation of the new channel bed (Loheide and Gorelick 2005). Meadows altered in these ways no longer attenuate flood waters, maximize groundwater recharge, disperse flood flow, retain sediment, build organic-carbon-accumulating soils, or support diverse animal communities that can include species currently in widespread decline (Loheide and Gorelick 2007, Norton et al. 2011).

Mountain Meadow Restoration

For more than 80 years, ranchers and land managers have attempted to arrest meadow channel incision and restore meadow function on a trial-and-error basis (Hunsaker et al. 2015). Only recently have professional restoration practitioners begun to increase the pace and scale of restoration. For example, the Sierra Meadow Restoration Strategy of the Sierra Meadows Partnership (Drew et al. 2016) has a goal of restoring 30,000 acres of meadow habitat in 15 years. A strong focus on channel morphology has led to approaches that involve major earth-moving activities to reconfigure channels with the assumption that ecological restoration will follow (Palmer et al. 2014b). "Pond-and-Plug" meadow restoration projects currently predominate in the Sierra Nevada (Hunsaker et al. 2015). This technique uses earthen check dams to "plug" incised trenches and redirect flow across meadow surfaces. The technique often obtains the plug material from borrow pits ("ponds") dug from meadow soils. These borrow pits usually fill with water, creating permanent ponds. Repeated down the length of a project area, the technique results in a series of ponds and channel plugs that can cover acres of former mountain stream and meadow habitats (Fig. 1). Often, flow is redirected into historical or newly created channels on the meadow surface. The technique can quickly raise water tables, typically to the meadow surface elevation, and in that specific way "restore" the hydrologic conditions that existed prior to incision (Loheide and Gorelick 2006, Hammersmark et al. 2009). The raised water table may increase plant productivity, and the resultant increased organic material combined with persistent soil saturation may result in additional storage of soil carbon (Feng et al. 2012, Moyano et al. 2013). Although one of the primary selling points of pond-and plug restoration is increased late-summer stream flow, physically-based quantitative modeling indicates that contributions to streamflow from drainage of meadows are negligible. Nash and others (2018) found that wet meadows, regardless of whether they were restored or incised, contributed less than 0.01% to stream discharge per kilometer of meadow, for a stream with a summer discharge of 0.1 cms (3.5 cfs). This is consistent with empirical measurements by Hunsaker and others (2015), who found no effect of pond-and-plug restoration on water storage losses, replenishment, or discharge. Similarly, Pope and others (2015) found that most ecosystem functions did not improve at pond-and-plug restoration sites relative to nearby unrestored meadows. In addition, the restored meadows showed more indicators of channel instability compared to the unrestored meadows (Pope et al. 2015).

Concerns with Current Restoration Practices

Restoration efforts have too often degraded aquatic ecosystems due to inadequate consideration of their landscape context, hydrological drivers, or geomorphology (Beechie et al. 2010). Most meadow restoration projects include alteration of stream channels, but most meadow restoration planning has ignored the extensive literature on ecological restoration of streams. Current restoration practices mostly view meadows as wetland systems rather than fluvial systems. Indeed, for much of the year the majority of meadow surfaces support shallow, still water habitat similar to wetland environments and some meadows do not interact with streams. However, as described above, most meadows are formed and maintained through fluvial processes that deliver water and sediment (Gosselink and Turner 1978), which interact with meadow vegetation to maintain dynamic depositional and erosional processes. Altering stream energy and sediment carrying capacity through installation of ponds or hard “control structures” may quickly raise the water table but it also alters the fluvial processes that yield diverse, dynamic, depositional habitats. Meadows downstream of such structures tend to follow the successional trajectory of hydrologically stable wetlands, leading to less diverse and denser vegetation (Pollock et al. 1998), except in new stream channels where down-cutting begins anew. Redirecting streamflow away from the constructed ponds and dams maintains unnaturally concentrated flows and favors sediment transport over retention.

Figure 1. Pond-and-plug meadow restoration in Tásmam Kójum (Humbug Valley) on Yellow Creek, Plumas County, CA. Note the isolated ponds dug from the meadow surface that provided the source material to plug the incised channel. The main channel remains single threaded above, through, and below the project area while a road crossing continues to constrain flow at the downstream edge of the project. Photo by Brian Cluer.

In pond-and-plug restoration efforts, failure to address the causes of degradation (on- or off-site), creation of single-thread channels, and erosion at constructed diversion, plug, and control points can all contribute to unnatural channel instability. Some pond-and-plug projects place ponds at the base of incised alluvial fans at the upstream edge of meadows (Fig. 1). As tributaries flow into such ponds, sediment is deposited in the ponds instead of moving into the channel or onto the meadow floodplain, where it can contribute to soil-building processes. Channels incise when sediment supply does not meet the capacity of the channel to transport sediment. Thus, upstream ponds exacerbate the physical problem that pond-and-plug seeks to repair and prevents or slows the aggradation required for ecosystem recovery. A common misconception is that streams entering mountain meadows are limited in sediment supply and therefore would not allow for process-based channel rebuilding. Indeed, such streams can be “supply limited” in relation to the large capacity of the incised channel, but they often still transport plenty of sediment that can be captured for restoration purposes. We might note this point does not conflict with the fact that contemporary sediment supply is low relative to sediment supply during glacial retreat (Weissmann et al. 2002).

Pond-and-plug restoration creates several other problems that retard the recovery of wet meadow ecosystems. The construction of the plugs themselves modifies the soil profile of the material used, altering hydraulic properties including permeability, conductivity, and storage capacity, while also damaging the native seed and propagule bank. The technique also often creates pools too deep for meadow vegetation to recolonize. Thus the plugs and the ponds become disturbed sites unfavorable to re-establishment of native meadow vegetation and conducive to invasion by non-native species. Ponds provide deep, still-water habitat suitable for non-native animals, including the American bullfrog and signal crayfish, which can endanger native Sierra Nevada amphibians that use montane meadow habitats (Pope et al. 2015).

Ecological Restoration Approach

Ecologically-based restoration seeks to remove impediments to physical and biological processes that hold the impaired area in poor condition and accelerate natural processes that lead to recovery (e.g., Fig. 2). Practitioners use low-risk approaches that can be expanded if proven effective before resorting to actions that cause significant disturbance to existing habitat and risks to natural processes (Thorp et al. 2010, Kondolf 2011, Kondolf et al. 2013). For example, in this approach practitioners often first install temporary, biogenic in-stream barriers to encourage flow dispersion and determine the amount of within-system sediment available to fill incised channels, before assuming inadequate sediment supply and filling the channel with sediment collected from borrow pits. Ecologically-based restoration enables practitioners to affect positive change over time and across large areas. It encourages habitat heterogeneity because recovery within the system occurs at variable temporal and spatial scales. That said, the approach has the potential to yield rapid system-wide recovery because affordable, low-intensity restoration efforts that use natural processes can be widespread.

High-priority restoration actions reconnect physical and biological processes to restore and enhance meadow function. Major engineering efforts and construction disturbance, if any, focus on modifying human infrastructure to increase lateral and longitudinal connectivity and increase the exchange of surface and groundwater (Al-Chokhachy et al. 2016, Raiter et al. 2018). Potentially beneficial infrastructure modifications range from providing off-meadow water sources for cattle to removing or restructuring roads, ditches, or levees that constrict flow paths (Chambers and Miller 2011). If timed correctly, the construction disturbance associated with infrastructure improvements can provide sediment for capture by in-channel sediment traps created by restoration.

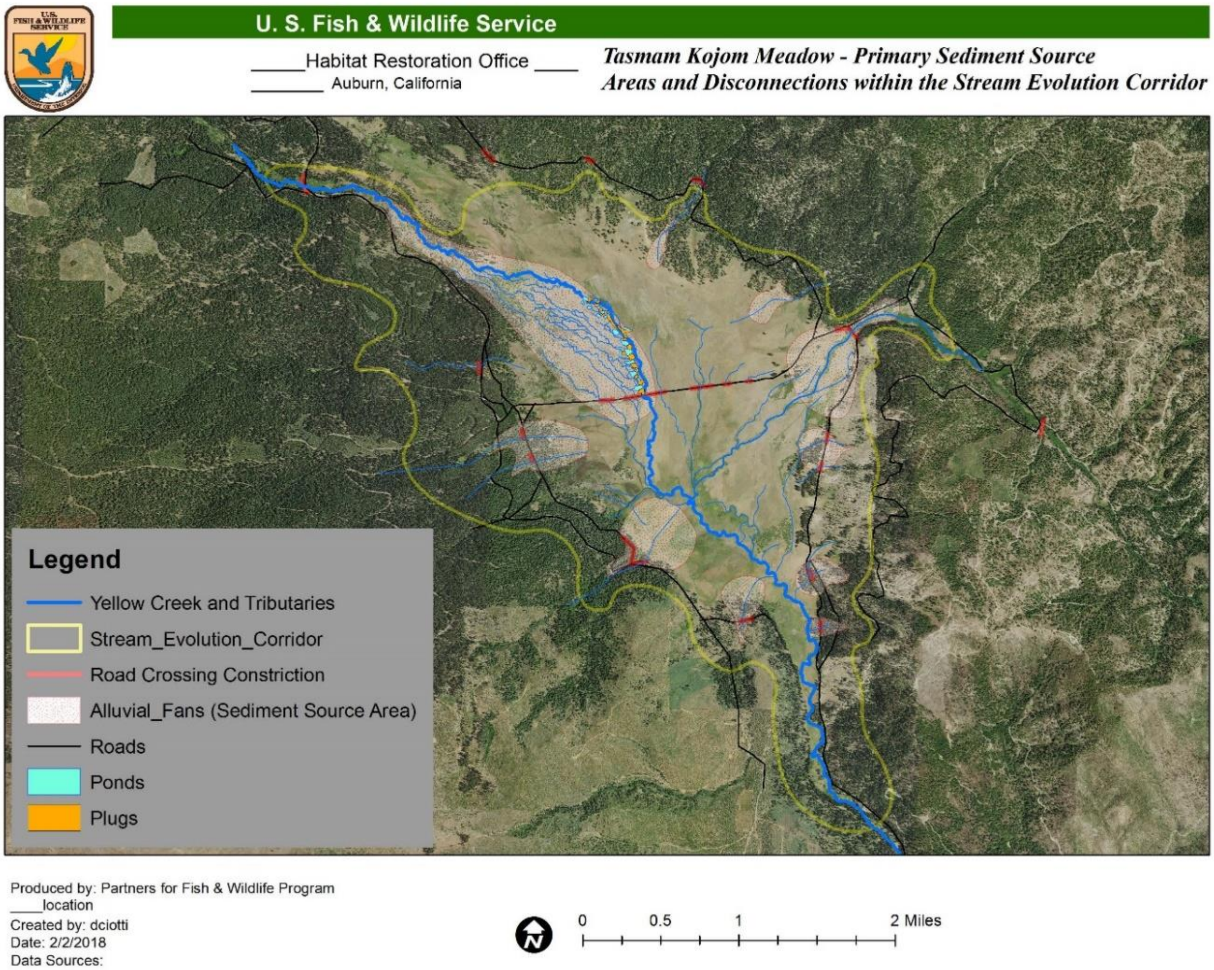

Figure 2. Example identification of sources of degradation and sediment source areas. Analysis conducted by D. Ciotti and J. McKee.

Restoration of incised channels usually requires techniques to raise streambed elevation and disperse streamflow. Ecologically-based restoration accomplishes these goals by trapping sediment through direct reductions in stream power, distributing stream power by removing barriers to flow and encouraging multi-threaded channel formation, and creating conditions favoring the growth of emergent and riparian vegetation that can resist erosive flows. The technique reduces and distributes stream power through placement of large wood, beaver dam analogs (BDAs) and other natural materials in positions determined by the existing arrangement of landforms, stream energy, and sediment sources (Harvey and Watson 1986, Shields et al. 1995, Brooks et al. 2004, Beechie et al. 2010, Pollock et al. 2014). In particular, BDAs have been shown to halt and reverse incision, raise groundwater tables, attenuate flood flows, re-invigorate desiccated riparian and wetland areas, and improve habitat for salmonid fishes (Pollock et al. 2014, Bouwes et al. 2016, Weber et al. 2017). Re-introduction of beaver or the creation of conditions that favor natural colonization by beaver are additional potential elements of ecologically-based restoration. Recently developed geospatial models that assess sites for their potential to support beaver facilitate these possibilities (Dittbrenner et al. 2018). In-channel alterations can be combined with riparian vegetation restoration actions, such as willow planting and cattle exclosures. Partial or complete livestock removal from meadows can dramatically increase total below-ground biomass, increase soil infiltration rates, and increase net potential nitrification (Kauffman et al. 2004).

Principles of Ecological Restoration

Below we outline six basic principles for ecological restoration as applied to mountain meadows:

1. Respect site characteristics in restoration designs

The ecological restoration approach recommended here should not be interpreted as a one-size-fits-all prescription. Successful restoration requires an in-depth understanding of each site and restoration designs based on that understanding. We recommend undertaking thorough pre-project assessments to identify the state and causes of degradation. Topographical surface analysis tools such as LiDAR allow accurate interpretation of the pre-manipulation surfaces of the meadow and evaluation of the level of departure exhibited in the current condition. They can help determine potential sediment sources and sinks, as well as infrastructure that impedes sediment delivery or constricts stream energy.

2. Include Support for Restoration Maintenance

Some projects fail due to poor design or flaws in implementation, but others fail when successful changes or practices are not maintained (Moore and Rutherfurd 2017). Emphasis in restoration funding has been on initiating restoration projects and implementation monitoring. Yet project success relies as much on post-implementation monitoring and maintenance as on initial design and implementation. Some projects will require lengthy ongoing maintenance; others will become self-sustaining in a few years. Common maintenance activities include weeding, replanting, and modifying BDAs in response to geomorphic responses that occur during floods.

3. Use a Collaborative Restoration Process

Restoration efforts require a range of skills, expertise, creativity, and commitment from practitioners and stakeholders. Partnerships with Tribal governments, local communities, and private organizations can greatly improve design, planning, monitoring and maintenance efforts and provide much of the workforce necessary to implement projects and assist in their success.

4. Monitor project effectiveness

Many project proponents and funders (including the Forest Service) have adopted linear or areal evaluation measures, such as area of riparian habitat or length of stream restored. Such metrics do not distinguish high-quality from low-quality habitat and do not address mechanistic links between processes and habitat. These standards encourage practitioners to maximize the restoration footprint, but not to ensure resilience or quality. For example, change in groundwater elevation is a common metric used in meadow restoration monitoring, yet the link between restoration of hydrologic process and groundwater is not addressed. By filling incised channels and redirecting flow onto the meadow surface, goals for the metric can be achieved temporarily without addressing the causes of the overall problem. By shifting restoration goals from systems to services, such as increasing water storage and carbon sequestration, we shift practices to interventions that differ substantially from ecological restoration in that they do not focus on recovery of self-sustaining living systems characteristic of past landscapes (Palmer et al. 2014a). Validation monitoring that seeks to understand the mechanisms responsible for system changes is urgently needed for meadow restoration. Because properly designed and executed evaluations can be expensive, they may only be possible in some cases and through pooling of resources (Rubin et al. 2017). In addition to better understand hydrological processes affecting meadow restoration, spatially explicit models that can link restoration outcomes to the responses of species of special concern, such as steelhead/rainbow trout and Sierra Nevada yellow-legged frog, are becoming more accessible. These models allow for long-term projections of restoration effects on populations of interest (Railsback et al. 2016).

5. Consider that Large Problems may Require Multiple Interventions

Deeply incised channels may not be repaired by one intervention. A series of grade lifts may be an effective and minimally disruptive approach, perhaps requiring a few years between interventions. This approach conflicts with current restoration funding and practice, which unrealistically seeks to immediately "fix" problems that have developed over decades or centuries with a single intervention.

6. Develop Training in Process-Based Design

We recognize restoration practitioners need guidance for applying ecological principles to restore dynamic and self-sustaining stream and meadow ecosystems. There is no easy recipe for applying scientific knowledge to practice. Federal agency practitioners hope to start a training effort in 2018 to provide practitioners with the background, tools, and experience to apply ecosystem science to restoration design.

Conclusions

Applying the principles of ecological restoration will help managers ensure the success of publicly-funded meadow restoration programs. Broad application of ecological restoration principles will allow the restoration community to do more with less and operate at the landscape scale of restoration needs. These principles also embody a long-term stewardship approach to mountain meadow management. In this sense, ecological restoration can be thought of as more of a sustainable management strategy that enhances the multiplicity of benefits that mountain meadows provide, rather than a restoration action isolated in time and space. By working with natural processes, ecological restoration leads to a self-sustaining recovery trajectory that maximizes the diversity of ecological goods and services that these systems provide.

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