Chapter 6.3—Wet Meadows

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Summary

Wet meadows help to sustain favorable water flows, biological diversity, and other values; consequently, restoration of degraded wet meadows is an important part of a strategy for promoting socioecological resilience. This chapter focuses on high-elevation wet meadows that are associated with streams; thus restoration of such meadows may be considered a subset of stream restoration. However, it is important to recognize that degradation of high-elevation meadows often reflects site-level impacts rather than watershed-scale impacts that degrade lower-elevation streams and rivers. For that reason, and because of the cascade of impacts associated with incision of wet meadows, restoration of wet meadows is often expected to deliver a wide range of benefits. Published evaluations of wet meadow restoration efforts within the synthesis area have demonstrated gains at specific sites in certain functions, including water quality, water quantity, and macroinvertebrate diversity. Broader reviews of stream and river restoration in the past decade indicate that restoration efforts have often fallen short in demonstrating anticipated benefits, especially in terms of wildlife and fishes. These shortcomings may reflect a variety of causes, including incomplete documentation of projects, inability of treatments to address limiting factors, and limitations on monitoring resources, experimental designs, and timeframes for evaluating responses, which may require over a decade to gauge. Because many of these challenges are also relevant to meadow restoration projects, these findings reinforce the need for continued and increased monitoring of treatment outcomes, use of rigorous experimental designs, and use of conceptual models when evaluating the potential for improving site conditions, designing treatments, setting restoration objectives, and evaluating outcomes. An important theme in the synthesis that applies to wet meadow restoration is an emphasis on restoring ecological processes, such as overbank flooding, sediment transport, and establishment of native wetland vegetation. Active site-specific restorations may be warranted where local factors have caused degradation to a point where natural recovery is likely to be extremely slow. Monitoring the rate and extent of channel incision is important to avoid losses of socioecological values in stream and meadow ecosystems associated with erosion and lowering of water tables. However,

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considering broader landscape influences on meadows may be more important over the next several decades, given that changes in hydrology, wildfire regime, and spread of nonnative species may affect key ecological processes in meadows. Meadow restoration offers productive ground for understanding interactions among a wide range of ecological, social, cultural, and economic values. Designing, conducting, and evaluating restoration strategies in an adaptive management framework will likely benefit from broad participation by resource managers, researchers, and community members to facilitate this integrated understanding.

Introduction

This chapter addresses wet meadows, and in particular, high-elevation wetlands that have fine-textured soils and shallow groundwater tables in the summer. These conditions support wetland vegetation, predominantly herbaceous plants, including sedges, other graminoids, and forbs, but also woody plants such as willows that can tolerate anaerobic conditions (Ramstead et al. 2012, Weixelman et al. 2011). This chapter focuses on meadows that are associated with defined stream channels (fig. 1). It does not focus on headwater fens and other peatlands, which are valuable but relatively uncommon in the synthesis area; recent publications provide guidance for assessing their conditions (Weixelman et al. 2011).

Jonathan Long

Figure 1—Trout Creek and adjacent wet meadow in the Lake Tahoe Basin Management Unit.

Stream restoration in general has been identified as an important part of the Forest Service's overall restoration strategy for the synthesis area (USDA FS 2011b). Restoration of wet meadows provides important opportunities to promote ecological resilience and benefit social values (Weixelman et al. 2011). Wet meadow restoration is expected to have an important role in securing favorable flows of high-quality water (Viers and Rheinheimer 2011) and mitigating emissions of carbon and nitrogen (Norton et al. 2011). By enhancing meadow wetness and enhancing diversity of meadow conditions, restoration could also promote biodiversity including pollinators (Hatfield and LeBuhn 2007) and nesting passerine birds (Cocimano et al. 2011). The final section of this chapter, "Integrated Socioecological Approaches to Stream and Meadow Restoration," considers further opportunities to link socioeconomic and ecological values to guide restoration of wet meadows.

Restoration of wet meadows provides important opportunities to promote ecological resilience and benefit social values.

Restoration of streams has been a focus of research across the Sierra Nevada region, the state of California, and the United States within the past decade. Earlier synthesis reports for the region, including the Sierra Nevada Ecosystem Project report (SNEP Science Team 1996b), the 1998 Science Review (Sierra Nevada Science Review Team 1998), and the 1999 report Sierra Nevada Ecosystems in the Presence of Livestock (Allen-Diaz et al. 1999), remain relevant and useful because they address a broader range of meadow ecosystems and related topics, including conservation of aquatic biodiversity, sustaining streamflows for wildlife and human uses, and grazing management on public lands. A more recent synthesis for Great Basin ecosystems by Chambers and Miller (2011) explained that strategies to restore streams and meadows should consider a wide range of watershed impacts, including roads, trails, grazing, and water diversions. Restoration strategies may be most effective if they consider where and when addressing these watershed influences is necessary to promote restoration, and in which cases active interventions are warranted and cost effective (Hobbs and Cramer 2008, Kauffman et al. 1997).

Promoting Resilience in Wet Meadow Ecosystems

Chapter 6.1, "Watershed and Stream Ecosystems," provides a definition of resilience and emphasizes the importance of restoring natural fluvial processes. Although these concepts apply generally to montane wet meadow systems, a strategy of relying on natural disturbance processes may be less effective in these less physically dynamic systems because they have relatively small watershed areas and reduced stream power. There is widespread recognition that channel headcutting in headwater systems can be indicative of a more persistent disequilibrium, in part because the process is difficult to reverse through natural deposition in such small systems. In the Great Basin, many streams have exhibited a tendency toward incision during

the past two millennia (Germanoski and Miller 2004). However, most meadow systems on the western slope of the Sierra Nevada appear to have been stable within the past three millennia, and in a few cases, as many as 10,000 years, apart from more recent incision associated with anthropogenic disturbances such as livestock grazing (Benedict 1982, Ratliff 1985). Reference erosion rates appear very low in many small headwater streams and in wet meadow systems that have intact streambank vegetation, as reported by studies in the Sierra Nevada (Micheli and Kirchner 2002, Simon 2008). As a consequence, high rates of incision and bank erosion generally appear outside the range of historical variation in these systems and strengthen the rationale for active intervention.

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To evaluate what kinds of interventions, if any, are warranted in a particular ecological system requires analysis to determine whether abiotic or biotic thresholds have been passed (Hobbs and Cramer 2008). In considering these questions, Sarr (2002) described how systems with intact soils and geomorphology demonstrated capacity to recover quickly and predictably, while others had shifted to alternative states marked by channel incision (discussed in more detail below), lowering of local water tables, reduced connectivity of channels to broad floodplains, and encroachment of nonhydrophytic woody plants (particularly conifer trees and sagebrush) in formerly wet riparian areas. Revegetation measures such as transplanting sedges tend to be more effective where groundwater tables are sufficiently high (Steed and DeWald 2003). In more degraded sites, much more active restoration efforts to remove woody vegetation, raise groundwater levels, and reestablish burning regimes may be needed to restore native herbaceous communities (Berlow et al. 2003). Sagebrush encroachment is addressed in detail by Chambers and Miller (2011). A report by Eagan et al. (2000) noted that a trail used by hikers and stock in a subalpine meadow required recontouring and restoration of topsoil after demonstrating little recovery following 30 years of closure. Because restoration potential appears to be very site-specific, studies of geology, hydrology, and soils attributes, as well as assessment tools discussed in the section on monitoring and evaluation near the end of this chapter, are important to determine site potential and to select appropriate treatments (Ramstead et al. 2012).

Channel Incision

Channel incision can cause a profound loss of productivity in wet meadow ecosystems. Shields et al. (2010) described incision as a syndrome that threatens many ecosystem services by triggering a cascade of geomorphic, hydrologic, and biological effects, including bank instability, channel erosion, perturbated

hydrology, non-point source pollution, conversions from wet to dry meadow vegetation, degradation of aquatic habitat, and reduced fish species richness. Causes of incision may be natural, such as geological uplift, lowering of channel base levels associated with changing climate, or extreme runoff events associated with wildfires or storms; or resulting from more specific human actions, such as blocked culverts that impair sediment movement or overgrazing that removes protective vegetation or substrates from stream channels. These influences result in excess capacity of a stream to transport sediment relative to the supply of sediment from upstream reaches (Simon and Rinaldi 2006). Reduced sediment supply resulting from the alteration of fire regimes, as well as loss of beaver activity, are additional potential influences that might have rendered meadows more vulnerable to incision (see "Research Gaps and Pending Research" at the end of this chapter).

Studies within the synthesis area have reinforced the importance of addressing channel incision. The potential for channel incision to pierce low-permeability layers and alter stream hydrology is a particular concern; such layers may be associated with peat or with compacted soils that are a legacy of historical heavy grazing (Hill and Mitchell-Bruker 2010). Local studies have also quantified some impacts from incision; for instance, a study of Monache Meadow in the southern Sierra Nevada found that banks without wet meadow vegetation are approximately 10 times more susceptible to erosion than banks with herbaceous wet meadow vegetation, such as sedges and rushes (Micheli and Kirchner 2002). Where channels have active headcuts, herbaceous vegetation may not be effective in preventing bank erosion (Zonge et al. 1996). Moreover, physical changes associated with channel widening or incision, including increased temperatures, are not readily changed through restoration of riparian vegetation alone (Poole and Berman 2001). Because of the profound losses in ecosystem functions that can occur as a result of incision (Sarr 2002), management strategies and monitoring would benefit from focusing on this process. Preventing incision and restoring incised meadows could be important components of a landscape strategy to promote system resilience to climate change (Seavy et al. 2009) and sequester carbon and nitrogen (Norton et al. 2011). Although incision is likely to be a predominant problem of concern, other processes in meadows are important, such as channel widening (Loheide et al. 2009).

Chambers and Miller (2011) proposed a general framework for addressing incised meadows based on the degree of incision (table 1). Their synthesis is particularly useful for considering issues that are important for east-side systems, such as sagebrush encroachment and management of the fire-adapted, invasive cheatgrass.

Table 1—Framework for addressing incision within wet meadow systems by Chambers and Miller (2010)

Condition	Indicators	Treatment approach
Low to moderately incised	Channel has incised to 0 to 2 times bankfull channel depth	In-stream structures and bank stabilization measures to prevent knickpoint migration and maintain meadow vegetation
Highly incised	Channel has incised to >2 times bankfull channel depth	Careful design of in-stream structures to minimize further incision of the main channel and to maintain springs
Fully incised	Channel has previously incised but is no longer actively incising	Actively manage area to maintain meadow vegetation based upon knowledge of groundwater tables and riparian vegetation

In-Stream Structural Approaches

Because waiting for streams to stop incising may result in extensive erosion, structural interventions are often proposed for incising systems, and as shown in table 1, may be particularly warranted for early stages of incision. Such treatments include various kinds of grade control features and streambank or channel armoring (see Ratliff [1985] and Chambers and Miller [2011] for more extensive descriptions). In-stream structures have long been used to protect or enhance aquatic habitat, but there remain serious concerns about their potential for failure. For example, Stewart et al. (2009) concluded that resource managers should be circumspect in using in-stream engineered devices because evidence does not support their effectiveness. Failures, such as erosion around or under the structures, tend to be more common in larger, more dynamic streams but are still a concern for smaller meadow systems; consequently, structural treatments generally require careful design and installation as well as long-term monitoring and maintenance (Chambers and Miller 2011).

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An important trend in large river restoration strategies is to move from permanent structures toward temporary protection and enhancement that allows natural vegetation, sedimentation, and erosional processes to reestablish (Miller and Kochel 2010), as well as allowing streams access to a wider corridor to migrate (Kondolf 2011) (see chapter 6.1). Softer or "deformable" treatments may be somewhat more challenging to evaluate than harder in-stream structures because by their nature, they are intended to be overtaken by natural recovery processes. Although montane wet meadow systems are less dynamic than low-elevation riverine systems, the general principles of reducing constraints on historical floodplains (such as roads and culverts) and designing deformable treatments can extend to meadow treatments. For example, this principle is reflected in the use of natural rock and plant materials (rather than unnaturally large rip-rap or metal gabions) to construct grade control structures (e.g., riffle formations) and stabilize streambanks (see Chambers and Miller [2011] and Ramstead et al. [2012] for examples of such applications).

Channel filling and plugging—
Channel reconfigurations in the synthesis area have involved diversion, filling, or plugging of existing channels as well as excavation of new channels. Filling of incised channels has been conducted in a number of sites in the synthesis area (Loheide et al. 2009, Ramstead et al. 2012). For sites that are thought to have historically lacked defined channels, flows may be directed over the meadow surface (an example includes Halstead Meadow in Sequoia National Park, cited in Ramstead et al. [2012]). In other cases, they may be diverted into one or more remnant channels that have a more desirable geomorphic configuration and vegetation. Either approach requires careful attention to protecting or restoring native vegetation and hydrology to prevent re-incision. Where remnant conditions are not suitable for reintroducing flows, practitioners have often constructed new channels.

To reduce the volume of material needed to refill incised channels, practitioners have developed the "pond and plug method," wherein materials are excavated within the meadow, creating ponds, and then the channel is plugged at various locations using the excavated materials. This method has been the subject of studies in the Feather River watershed, which provide evidence that this method is effective in restoring many attributes of these systems (Loheide et al. 2009), as described further in the next section. However, researchers have also noted concerns about these treatments:

- Pond and plug creates novel conditions of deep ponds, which can become habitats for invasive aquatic species such as bullfrogs (*Rana catesbeiana*) and green sunfish (*Lepomis cyanellus*) (Adams and Pearl 2007, Ramstead et al. 2012).
- Channel reconstruction or pond and plug methods may be inappropriate in systems with fine-grained confining units, because the process of excavating alluvial materials could disrupt the meadow hydrology (Chambers and Miller 2011). Identifying low-permeability layers in meadows is an important component of a broader strategy for protection and restoration (see Hill and Mitchell-Bruker [2010] and the "Research Gaps and Pending Research" section).

Evaluating Benefits of Meadow Restoration

Water quantity and quality effects of meadow restoration have been undertaken at a relatively small number of sites in the Sierra Nevada within the past decade, with considerable emphasis on large, low-gradient meadows along tributaries of the Feather River and streams in the Lake Tahoe basin. Published studies suggest that active meadow restoration designed to remedy incised channels has increased

groundwater levels and subsurface storage, which in turn promotes wetland vegetation (Hammersmark et al. 2010); increased frequency and duration of floodplain inundation, which in turn may filter sediment and nutrients; attenuated peak flows and increased mid-summer baseflows (Hammersmark et al. 2008, Tague et al. 2008); and reduced maximum water temperatures (Loheide and Gorelick 2006). Streamflow below restored meadows may be affected by higher evapotranspiration rates in the rewetted meadows (and any created ponds) and increased subsurface storage (Hammersmark et al. 2008, Loheide and Gorelick 2005). Research has improved understanding of how site qualities influence response, including the presence of impermeable layers that can maintain high water tables but also inhibit groundwater from upwelling to the meadow surface (Booth and Loheide 2012). The water quality and water quantity benefits of wet meadow restoration are an important topic for which the National Fish and Wildlife Federation has initiated a major research initiative in Forest Service Region 5 (Viers and Rheinheimer 2011).

Restoration of meadow hydrology and vegetation is often expected to result in a cascade of higher order functions, including increases in soil carbon and improvements in fish and wildlife habitat (Ramstead et al. 2012). Nevertheless, a number of reviews have cautioned not to oversell higher order benefits without further monitoring and research to quantify them. This concern has emerged in light of the popularization and commercial expansion of stream restoration in parts of the United States (Lave et al. 2010). Several reviews have recommended a rigorous application of ecological theory and greater emphasis on monitoring outcomes (Palmer 2009, Ramstead et al. 2012). Bernhardt and Palmer (2011) noted that research on river restoration in recent years has progressed from asking "Why don't we know more about river restoration success?" to asking "Why aren't river restoration projects more effective?" This general trend also appeared to unfold in California, where Kondolf et al. (2007) highlighted a lack of information needed to evaluate projects. In a meta-analysis of effects of stream restoration projects on macroinvertebrates, Miller et al. (2010) did not include any studies from the Sierra Nevada, presumably because they did not find ones that met their criteria for a controlled research design. A recent evaluation of wet meadow restoration in the Southwest, which included studies of about a dozen projects from the synthesis area, concluded that although there has been significant progress in restoring morphology and vegetation, there remains a need for long-term and better designed monitoring programs (Ramstead et al. 2012). These reviews noted lack of controls and confounded treatments as a common problem in evaluating project effects. For example, changes in grazing management are often confounded with structural restoration treatments, and sites that have not been treated recently may have an older history of treatments. Others

have noted the potential for a publication bias in favor of reporting more successful projects (Ramstead et al. 2012, Stewart et al. 2009).

Demonstrating benefits of stream and meadow restoration becomes more challenging when evaluating benefits to higher order ecosystem services, including biodiversity. Researchers have criticized shortcomings of some restoration projects as overly relying upon the "field of dreams hypothesis" that "if you build it, they will come," in which "it" refers to physical structure, hydrology, or vegetation, and "they" refers to the desired biological community, usually wildlife (Hobbs and Cramer 2008, Palmer et al. 1997). Defenders of that approach may counter that projects that fell short may have lacked restoration of critical ecosystem processes, such as overbank flooding and fire, so in effect, they did not "rebuild it." Nevertheless, researchers contend that this hypothesis needs to be rigorously tested for different habitats and different species (Palmer et al. 1997). In recent years, researchers have reviewed stream restoration efforts nationwide to evaluate this hypothesis. Bernhardt and Palmer (2011) cautioned that channel reconfiguration efforts may reduce bank erosion and increase sinuosity, but that evaluations have found little evidence for benefits to sensitive taxa and water quality (in particular, reduction of nutrients). They noted that many projects in the United States are undertaken at sites where watershed degradation is a key factor, so reach-specific channel restoration treatments do not treat the underlying causes of degradation. However, their review included many urbanized streams and other sites in heavily altered watersheds. Sites on national forests in the Sierra Nevada are less likely to have experienced severe watershed-scale impacts (although dams may have significantly altered hydrologic processes in some watersheds), and many restoration projects have targeted streams and meadows that have been significantly affected by localized road, channelization, or grazing impacts. Therefore, meadow restoration projects in the synthesis area should generally be less vulnerable to those potential shortcomings. Nevertheless, this research firmly underscores the importance of long-term monitoring and research to evaluate more complex, higher order outcomes of restoration.

Long-term monitoring and research are needed to evaluate the more complex, higher order outcomes of wet meadow restoration, including effects on wildlife.

Researchers have emphasized the importance of conceptual models to explicitly state and test the strength of linkages between various fundamental changes, such as modifying channels to reduce entrenchment and increase the areas flooded during frequent floods, to vegetative effects and higher order effects on fish, amphibians, and terrestrial wildlife. Through a national meta-analysis of two dozen studies, Miller et al. (2010) concluded that although habitat restoration may promote biodiversity and ecosystem resilience, its ability to increase biomass of macroinvertebrates for the benefit of higher tropic levels (e.g., fish, amphibians, and birds) was still uncertain. That study noted that channel reconfigurations yielded highly

variable invertebrate community responses. On the other hand, in a study from the Sierra Nevada, Herbst and Kane (2009) reported that active channel restoration yielded a rapid shift in macroinvertebrate communities toward reference conditions. Conceptually, restoration of wet meadow hydrology should yield benefits for a variety of wildlife species, including willow flycatcher (*Empidonax traillii*) (Cocimano et al. 2011). However, many of these higher order biological objectives may prove hard to achieve (or to demonstrate) in short timeframes because of confounding or limiting factors, including legacy effects of past management, including historical overgrazing, soil compaction, mining, and stocking of nonnative trout. For example, the stocking of trout into fishless systems has affected amphibians, reptiles, and birds by altering food webs in lakes and streams (Eby et al. 2006, Epanchin et al. 2010). A Sierra Nevada study by Purdy et al. (2011) found that fundamental indicators of vegetation and physical habitat tend to classify meadows as being in better condition than do aquatic indices, especially the native fish and amphibian index. This finding could reflect a variety of causes, including legacy effects, time lags in these indicators, and controlling influences that are beyond the site.

Grazing Management and Wet Meadow Restoration

Livestock grazing involves a complex interplay of social and ecological factors (see chapter 9.5, "Managing Forest Products for Community Benefit"). Although grazing is only one of many land uses that affect streams and wet meadows, grazing management and hydrogeomorphic condition appear to be critical determinants of meadow restoration outcomes (Ramstead et al. 2012). In a recently published review of rotational grazing from a broad socioecological perspective, Briske et al. (2011b) offered frameworks to promote effective management of grazed systems, including adaptive management with an emphasis on stakeholder participation (Fernandez-Gimenez et al. 2008) as well as targeted grazing that explicitly emphasizes management outcomes, such as weed control, fire hazard reduction, and wildlife habitat improvement. The latter approach suggests that grazing management could be an important tool for promoting socioecological resilience in systems that evolved with grazing animals. This approach embodies the logic of disturbance-based management as described in North and Keeton (2008), and recognizes that grazing, like fire, can be a tool for rejuvenating areas by reducing accumulated vegetation. It is important to recognize that because different kinds of domesticated livestock (i.e., cattle, horses, and sheep) have different grazing behaviors and influences, they are not interchangeable with each other or with the prehistorical assemblage that may have grazed particular landscapes. Researchers have discussed the utility of grazing in "novel systems," where grazing has a long history and nonnative species

have become dominant (Hobbs et al. 2009). In such systems, carefully managed livestock grazing may be a useful, albeit often controversial, tool for maintaining biodiversity and ecological services (Hobbs and Cramer 2008). For example, studying spring systems in Sierra Nevada foothills, Allen-Diaz et al. (2004) found that removing livestock grazing may allow dead plant material to accumulate, which in turn can increase levels of nitrate in wetland waters and decrease plant diversity. Similar findings have come from research in vernal pool systems (Marty 2005). The ecological benefits of grazing-based management approaches to less invaded, high-elevation wet meadows of the Sierra Nevada are less clear. A report by the Sierra Nevada Ecosystem Project indicated that it was unknown whether grassland ecosystems in the Sierra Nevada were adapted to disturbance by prehistoric megafauna, and suggested that more intensive grazing practices, such as active herding, could avoid many undesirable impacts (SNEP Science Team 1996a).

A recent comprehensive report on riparian management practices provides an overview of prescribed grazing effects on a wide range of resource values, including wildlife habitat, water quantity and quality, streambank and soil stability, carbon storage, plant and animal diversity, composition and vigor of plant communities, forage for grazing and browsing animals' health and productivity, riparian and watershed function, soil condition, and fine fuel loads (Briske et al. 2011a). In a companion chapter on riparian management practices, George et al. (2011) found that grazing practices that result in heavy use of riparian vegetation, are too long in duration, or are poorly timed can be detrimental to aquatic values such as fisheries and streambank stability. They found support for grazing exclusion as a restoration strategy for degraded riparian systems because it promotes recovery of riparian plant community composition. However, they noted that other techniques for manipulating livestock distribution, including herding, supplement placement, water development, and fences, are effective in reducing livestock residence time and utilization in the riparian zone. Both direct effects (such as trampling) and indirect effects (reducing vegetation) of grazing on streambanks and channels within the riparian zone remain critical considerations for meadow resilience because of their potential to induce stream incision and other threshold changes (Ramstead et al. 2012, Trimble and Mendel 1995).

Studies have also examined effects beyond the streamside zone, including impacts on water quality, soils, nutrients, and vegetative composition. For example, Blank et al. (2006) reported that cattle grazing under short-term, high-density stocking conditions did not affect composition and root length density, but that the treatment deposited nutrients and altered soil pH at the edge of a wet meadow in the synthesis area. Also from the synthesis area, a recently completed 5-year study

addressed the effectiveness of excluding cattle from breeding areas of Yosemite toads (*Bufo canorus*). The researchers found no detectable differences in toad occupancy, toad density, or water quality between grazed and nongrazed meadows when livestock grazing met current standards, including 30 to 40 percent use (Roche et al. 2012b). In addition, they found that meadow hydrology there influences occupancy by toads, and cattle grazing intensity does not (Roche et al. 2012a). Recent studies on national forests of the Sierra Nevada have reported exceedances in levels of fecal coliform bacteria (*Escherichia coli*, specifically) in several meadow streams with cattle grazing as well as recreational use in some cases (Derlet et al. 2012, Myers and Kane 2011, Myers and Whited 2012). Additional research on a number of sites in the synthesis area should help to put these studies within a broader context of national forest management (see box 6.3-1).

Much of the research on grazing has had limitations on experimental design that constrain the range of inference to contexts that may not necessarily match conditions on national forest lands. Many studies of grazing impacts are difficult to translate to grazing management strategies when they lack details such as stocking rates or utilization levels (Briske et al. 2008). Many studies of grazing in the Western United States, including the Sierra Nevada, have provided a dichotomous view of grazing by comparing differences or trajectories of vegetation and channel morphology inside and outside of exclosures (examples from the Sierra Nevada include Kondolf [1993] and Knapp and Matthews [1996]). Studies have commonly reported that where physical thresholds had not been exceeded (e.g., channel incision that had lowered water tables below the rooting zone), long-term grazing exclusion or reduction has facilitated substantial growth of native wetland herbaceous and woody vegetation such as willows (Ramstead et al. 2012). A review of exclosure studies on the Kern Plateau by Sarr (2002) noted that particular vegetative and channel responses to exclusion differ owing to a host of factors, including watershed stability, climate, subsurface moisture availability, soil organic content, proximity of willow propagule sources, and degree of channel incision. A study of bumblebees at 20 meadow sites on the Tahoe National Forest (Hatfield and LeBuhn 2007) reported variable impacts associated with cattle and sheep grazing that suggested an important interaction between grazing and flower availability, but it did not quantify the level of grazing use.

Variation in responses has also been reported in some studies on higher order responses within the past decade. Studies assessing the impacts of cattle on amphibians have often been correlative and have yielded mixed results; for example, Bull and Hayes (2000) found no evidence of negative effects of grazing on the Columbia spotted frog (*Rana luteiventris*), but they noted their inability to control for wide

variation in grazing intensity and other landscape variables. More experimental studies using cattle exclosures have also reported mixed results with specific implications for particular taxa. For example, reporting from a study in Tennessee, Burton et al. (2009) suggested that fencing cattle from wetlands may benefit ranid frogs, and controlled grazing may benefit toads in the genus *Bufo*.

Quantifying the influence of livestock grazing in stream and meadow ecosystems has been difficult because experimental designs may not sufficiently address ecological variation. Sarr (2002) identified common problems in evaluating responses to livestock grazing and exclusion, including lack of proper controls and the small size of exclosures. Research experiments are often conducted at too small a scale to properly evaluate effects (Briske et al. 2008). In response to these challenges, Sarr (2002) suggested that resource managers evaluate treatments at watershed scales on experimental rangelands, and in modest-sized exclosures as part of an ongoing adaptive management process. This strategy is reflected in the recent study by Herbst et al. (2012), which suggested that treatments at broader scales may yield different outcomes than smaller riparian exclosures. Specifically, they reported greater macroinvertebrate diversity and measures of habitat quality after 4 years of rest from grazing at the allotment scale, but more limited differences within local riparian exclosures that had been in place over a decade.

Monitoring and Evaluation

Recent stream restoration research indicates that monitoring remains very important in evaluating whether restoration is achieving desired objectives and in improving practice. The Forest Service Watershed Condition Framework set a goal of establishing a comprehensive monitoring effort by 2016 (USDA FS 2011a). Effort-based performance metrics, such as number of stream miles restored or enhanced, may create an unintended incentive for intervention, particularly in reaches that may have lower per-unit treatment costs. It is important to measure performance in terms of changes in ecological condition and associated benefits. Furthermore, metrics based primarily on physical structure (such as high sinuosity and low width-depth ratios) may underemphasize ecological functions (Bernhardt and Palmer 2011). Consequently, measurements of ecological processes (such as overbank flooding) and services (e.g., improved water quality, changes in seasonal water tables, dampened floods, and improvements in the diversity or abundance of target taxa) may be more appropriate for tracking progress (Bernhardt and Palmer 2011). The emphasis on process-based indicators is an important theme of this synthesis (see chapter 1.2, "Integrative Approaches: Promoting Socioecological Resilience"). In addition, monitoring is important in evaluating project outcomes

over a long period during which floods and vegetative development are expected to alter conditions. Finally, adopting a landscape perspective may be important in promoting socioecological resilience by giving increased weight toward meadows with greater potential to yield desirable outcomes. For example, stream reaches that are located close to less disturbed areas are more likely to be successful in reestablishing aquatic organisms (Bernhardt and Palmer 2011).

The Watershed Condition Framework considers channel incision within criteria for channel shape and function. Developing more specific quantitative criteria for this critical threshold of ecological function may be possible in different regions within the Sierra Nevada; for example, Micheli and Kirchner (2002) suggested that a bank height of 1 m in a southern Sierra Nevada meadow represents a threshold for shifting to dry meadow species and less stable streambanks, and Chambers and Miller (2011) suggested a threshold of incision occurs when channel depths exceed twice the bankfull depth.

A recent study in the Sierra Nevada concluded that soil properties correspond with rapid assessments of meadow condition using the Proper Functioning Condition methodology; specifically, they found that meadows categorized as "properly functioning" have greater nitrogen and dissolved organic nitrogen than "nonfunctioning" or "at-risk" meadows, and greater carbon than "nonfunctioning" meadows (Norton et al. 2011). To evaluate grazing management in wet meadows, Blank et al. (2006) suggested using root-length density as an indicator of ecological function. Root depth is another useful indicator of functional condition, and these types of qualities can be related to vegetation cover and composition data that is collected more routinely (Weixelman et al. 1999). Collectively, these studies provide a basis for using rapid assessments that focus on channel incision and shifts in vegetation away from native wet meadow graminoids; however, they also point to more quantitative metrics and possible threshold values for monitoring.

Post-project evaluation, monitoring, and adaptive management beyond 3 years is important for advancing stream restoration.

Stewart et al. (2009) contended that more research-based information about in-stream structural treatments is needed before widespread use can be recommended. Kondolf et al. (2007) pointed to the importance of post-project evaluation, monitoring, and adaptive management for advancing stream restoration and learning from both successes and failures. They further noted that restoration projects in California rarely provide for monitoring beyond 3 years, which is likely inadequate to observe effects of large, infrequent events. They also argued that projects do not always meet the standards needed to evaluate the restoration outcomes articulated by Bernhardt et al. (2007), including a clearly defined goal, objective success criteria, and use of controlled monitoring designs. Ruiz-Jaen and Aide (2005) recommended including measures of diversity, vegetation structure, and ecological

processes, and monitoring more than one reference site, to account for the temporal and spatial dynamics of ecosystems. Identifying suites of streams and watersheds that are in reference condition or could be brought into reference condition would facilitate evaluation of restoration potential and success in the face of anticipated stressors.

Because recovery of stream channels and floodplains may be limited by the episodic nature of flood disturbances, pulsed monitoring to coincide with climate and flood dynamics has been proposed as an efficient way to evaluate stream condition.

Monitoring frameworks need to consider temporal scale to account for effects of disturbances on key indicators (Berkes and Folke 2002, Bryant 1995). Because recovery of stream channels and floodplains may be limited by the episodic nature of flood disturbances (Sarr 2002), pulsed monitoring to coincide with climate and flood dynamics has been proposed as an efficient way to evaluate stream condition (Bryant 1995). Furthermore, interpreting indicators of stream condition relative to flood dynamics may be more appropriate than evaluating annual trends in systems where less frequent floods drive key ecological processes. The idea of quantifying a threshold to aid determination of when geomorphic monitoring is warranted was proposed by Florsheim et al. (2006) for dynamic lowland rivers. Even in relatively stable wet meadow ecosystems, environmental conditions can vary significantly from one year to the next, so reliable evaluations need a relatively long timeframe for monitoring, including pre- and posttreatment data, to demonstrate trends (Kiernan and Moyle 2012, Ramstead et al. 2012). These temporal dynamics further complicate efforts to evaluate impacts of grazing and rest, so one strategy is to consider long rest periods that provide opportunities to evaluate influences of grazing from multiple perspectives (Briske et al. 2011b).

Standardized monitoring and classification protocols could facilitate collection and comparison of data at larger spatial scales. Katz et al. (2007) provided a number of recommendations to facilitate evaluation of project effectiveness, including standardized metrics and a common reporting system for tracking restoration projects that includes common semantics for project type, location, timing, and magnitude. Stein et al. 2009 validated the utility of a rapid assessment tool, the California Rapid Assessment Methodology (CRAM) for lower elevation systems, although testing of a CRAM module for high-elevation meadow systems has not yet been published. Validation is important to ensure that the methods are effectively capturing important information about condition and trend. However, as Purdy et al. (2011) explained, variation across different biological indices within sites pose challenges for rapid assessments to concisely summarize the various dimensions of stream and meadow condition.

Classification systems are helpful in addressing heterogeneity within the large areas. A field key by Weixelman et al. (2011) provides a tool for classifying meadow types based on several hydrogeomorphic factors, including soils, water source, and gradient. Loheide et al. (2009) developed a framework for predicting potential

benefits of restoration based on several factors, including elevation, soil texture, and the degree of stream incision. Use of these classifications in project reporting and evaluation could help evaluate restoration treatment effectiveness across the synthesis area by identifying geomorphic settings and hydrologic characteristics that appear particularly sensitive to threats or responsive to treatments.

Research Gaps and Pending Research

A host of pending research projects will help to fill some of the important gaps in knowledge regarding wet meadow restoration (see box 6.3-1 below). Many of the key cause-and-effect questions and information gaps identified in the Sierra Nevada Forest Plan Amendment Appendix E (USDA FS 2004) focused on impacts of livestock grazing practices. These questions will likely remain at the center of meadow management, although thorough review of long-term monitoring data on rangelands, streams, and meadows should provide better information on which to base decisions and to revisit the questions in Appendix E.

Long-term studies of effects of meadow restoration on higher order values, such as favorable water flows and aquatic life, remain a topic for further research, particularly in light of anticipated effects of climate change.

Many topics that influence the outcomes of meadow restoration warrant further research, especially groundwater interactions between meadow aquifers and surrounding systems and the effects of meadow properties and various treatments on hydrologic responses (Hill and Mitchell-Bruker 2010, Loheide et al. 2010). Long-term studies of effects of meadow restoration on higher order values, such as favorable water flows (Loheide et al. 2010) and aquatic life, remain a topic for further research, particularly in light of anticipated effects of climate change. The Sierra Nevada watersheds with the largest amount of mountain meadows are the Mokelumne, Tuolumne, and Stanislaus; these three basins, along with the American and Merced, have been projected to have longer periods of low flows, which threaten mountain meadows and the services they provide (Null et al. 2010).

The introduction of beaver (*Castor canadensis*) has been suggested as a strategy for restoring wet meadows through their potential to induce sediment deposition, raise water tables, and alter relatively large habitat patches (Johnston and Naiman 1990). Beaver introductions in Yellowstone have shown potential to promote increased water surface area, wetland herbaceous vegetation, and riparian shrubs (McColley et al. 2012). However, the complex interactions between beaver activity, wetland hydrology and vegetation, and human infrastructure have to be considered, especially given the potential impacts of beaver dam failures (Beier and Barrett 1987, Butler and Malanson 2005). Recently published evidence that beaver were native to at least some watersheds in the Sierra Nevada suggests that other areas warrant more indepth investigation (James and Lanman 2012, Lanman et al. 2012). These findings heighten the importance of research to determine the conditions under which beaver reintroductions may promote meadow restoration.

Large-scale restoration efforts are increasingly seeking to better incorporate understanding of disturbance regimes and multiple successional states (Lake et al. 2007). As noted in chapter 1.5, "Research Gaps: Adaptive Management to Cross-Cutting Issues," proposals to study landscape-scale effects of forest treatments on multiple resource values would benefit from including aquatic resources, especially to evaluate effects of managing riparian areas and impacts from wildfires. Ratliff (1985) noted a wide range of potential wildfire impacts to meadows, including reduced encroachment by conifer trees; increased flows of water, sediment, charcoal, and woody debris; consumption of peat layers in meadow soils by intense fires; and consumption of wood structures that serve as check dams. However, a more formal examination of outcomes would help to evaluate whether there are thresholds of existing meadow instability or wildfire severity that leads to undesirable outcomes, as well as under what conditions and timeframes wildfires promote desirable developments in wet meadows.

Box 6.3-1

Current and Pending Research

These studies are included for reference although they may have not been published in peer-reviewed outlets.

Golden trout and climate change adaptation—

- The U.S. Forest Service Pacific Southwest Research Station (PSW) has a current project funded by the National Fish and Wildlife Foundation to examine the resiliency of stream habitats in the Golden Trout Wilderness to future climate warming. This project will spatially analyze stream temperatures and shading in restored and degraded sections of Mulkey and Ramshaw meadows to estimate what proportion of the habitat will be resilient to climate change and what proportion should undergo restoration treatments. The project is using peak temperature threshold values of 23 °C to trigger management responses, with a long-term goal of keeping streams below 20 °C so they will be resilient to future climate warming. Monitoring of degraded and recovering stream sections will enable comparisons of temperature, dissolved oxygen, stream depth and width, and shading, and it will be used to guide restorative management actions.

Grazing management in national forests—

- Researchers at the University of California–Davis (UC Davis), led by Kenneth Tate, are completing a study across several national forests to determine whether grazing best management practices avoid exceedance of water quality standards.

(continued on next page)

(*from page 357*)

- A joint Forest Service Region 5 and UC Davis project, also led by Kenneth Tate, will publish long-term (1999 to present) rangeland condition and trend monitoring data on more than 800 permanent plots from throughout the state.

Hydrologic effects of meadow restoration—

- Barry Hill, Region 5 Hydrologist, is preparing an assessment of meadow restoration and meadow hydrology for the Sierra Nevada.

Meadow restoration guide and economic effects—

- "A guide for restoring functionality to mountain meadows of the Sierra Nevada" (Stillwater Sciences 2012) provides an overview of restoration strategies in the synthesis area.
- "An Economic Analysis of Sierra Meadow Restoration" (Aylward and Merrill 2012) synthesized both peer-reviewed studies and unpublished reports in evaluating potential economic impacts of meadow restoration in the synthesis area.

Evaluation of meadow restoration—

- A recent PSW meadow restoration study included sites from the southern Cascade Range to the Stanislaus National Forest (fig. 2). Response variables of interest included basic physical and vegetative indicators of wetland condition, including soil moisture, soil carbon, vegetation cover and biomass, channel depth, and presence of headcuts.

Meadow restoration and native trout reports—

- Researchers at UC Davis published a report titled "Meadow Restoration to Sustain Stream Flows and Native Trout: a Novel Approach to Quantifying the Effects of Meadow Restorations to Native Trout" (Henery et al. 2011).
- American Rivers produced a report titled "Evaluating and Prioritizing Meadow Restoration in the Sierra" that documented a rapid assessment methodology based on six attributes (bank height, gullies, bank stability, ratio of graminoid to forb vegetation, bare ground, and encroachment) and a framework for prioritizing restoration activities (Hunt and Nylen 2012).
- UC Davis researchers have released a study that examined the number and size of meadows in the Sierra Nevada: "Sierra Nevada Meadow Hydrology Assessment" (Fryjoff-Hung and Viers 2013).
- UC Davis researchers have prepared reports on effects of climate change on fishes and amphibians associated with meadows: "Projected Effects of Future Climates on Freshwater Fishes of California" (Moyle et al. 2012) and "Montane Meadows in the Sierra Nevada: Changing Hydroclimatic Conditions and Concepts for Vulnerability Assessment" (Viers et al. 2013).

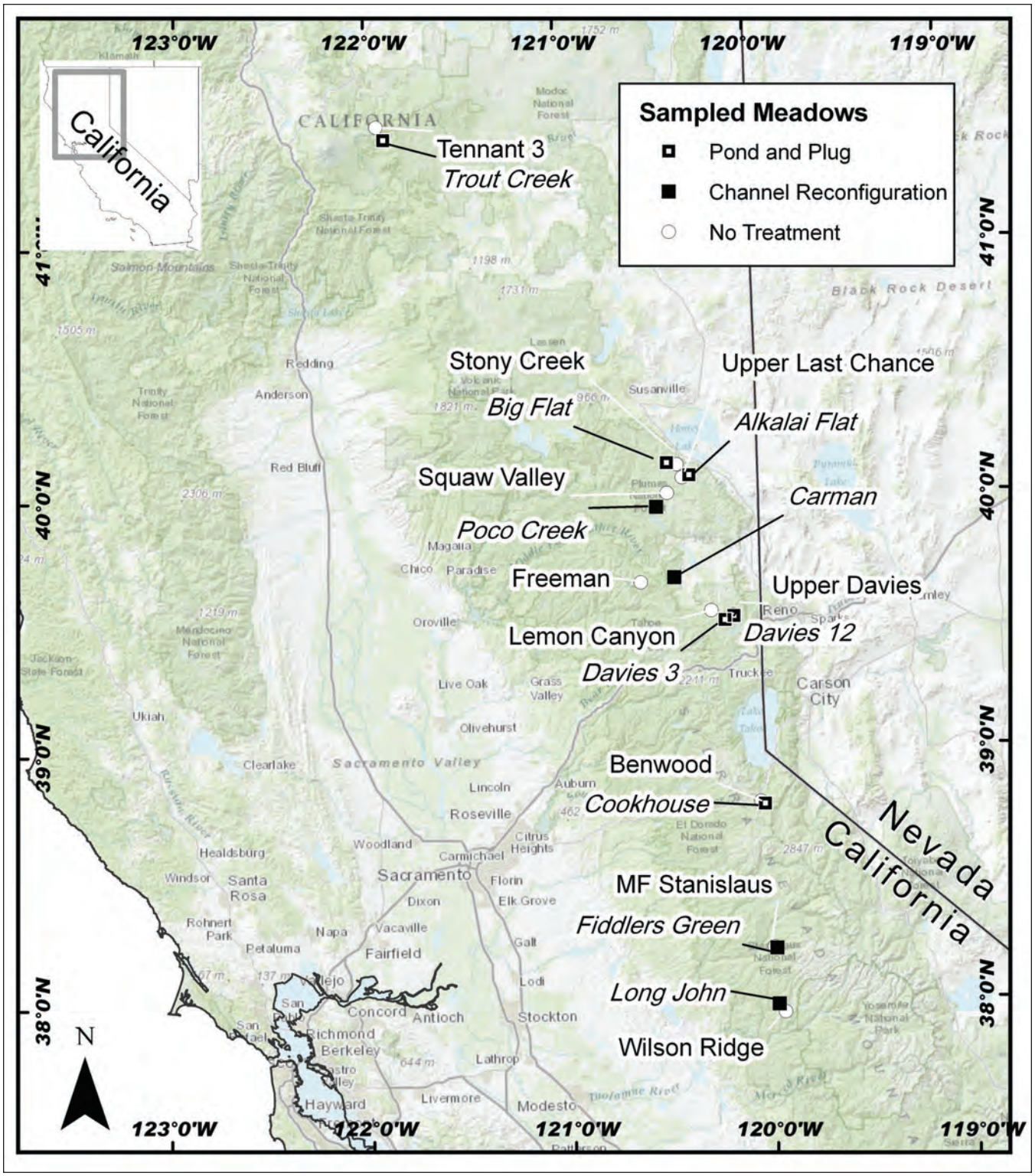

Figure 2—Map of sites in the meadow restoration study led by the Forest Service Pacific Southwest Research Station. Map by Diane Sutherland.

Integrated Socioecological Approaches to Stream and Meadow Restoration

Because streams and meadows provide important ecological services and other sociocultural values, they present opportunities to promote ecologically and socially integrated restoration consistent with the broader approaches in this synthesis.

Because streams and meadows provide important ecological services and other sociocultural values (fig. 3), they present opportunities to promote ecologically and socially integrated restoration consistent with the broader approaches in this synthesis (see chapters 1.2, "Integrative Approaches: Promoting Socioecological Resilience"] and 9.1, "Broader Context for Social, Economic, and Cultural Components"). Advancing management may increasingly depend on a participatory or collaborative adaptive management program that accounts for both social and ecological objectives and promotes learning to meet those objectives (see chapter 9.6, "Collaboration in National Forest Management," as well as Briske et al. [2011b] for a discussion in the context of grazing management). Bernhardt et al. (2007) observed that the most effective stream restoration projects tend to involve local community members and advisory committees throughout all stages, and they hypothesized that those interactions promote accountability in ways that improve outcomes. Golet et al. (2006) also found that community participation in planning may also help to increase the success and social benefits of stream restoration. Chapter 9.1 explains that participation in restoration activities can be empowering for individuals and enhance social capital. Recognizing the importance of social benefits builds upon the distinction drawn by Higgs (1997) between "effective restoration" that is focused on meeting technical performance criteria and "good restoration," which addresses the value of restoration in sociocultural contexts.

Increasing interest in the idea of payments for ecosystem services through restoring montane meadows of the Sierra Nevada has generated excitement about the potential to accelerate the pace of restoration (Viers and Rheinheimer 2011). Rising interests and concerns about these approaches are discussed more generally in chapter 9.2, "Ecosystem Services." Market incentives have fostered interest in treating degraded streams and developing stream restoration as an applied science; however, the increasing importance of stream restoration as a private industry and potential market for ecosystem services could have unintended consequences as complex ecosystem functions are translated into specific credits (Lave et al. 2010). Kondolf et al. (2007) pointed out that although quantitative criteria are important measures of success, projects may also have broader goals regarding stakeholder involvement. Many meadow sites have strong cultural value to tribes and may have been managed by Native American tribes (Ramstead et al. 2012). A strategy discussed in chapter 4.2, "Fire and Tribal Cultural Resources," focuses on partnering with tribes to reestablish more frequent fire regimes and enhance growth of

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Figure 3—Fly-fishing along Trout Creek, Lake Tahoe Basin Management Unit, represents one of the socioeconomic opportunities afforded by well-functioning stream/wet meadow ecosystems.

culturally desirable plants, such as sedges, willows, and various geophytes, including beargrass, that are commonly associated with riparian or wet meadow habitats.

Relationships between meadow condition and broader social values are a topic that invites further study, particularly to reconcile potential tensions in meadows between scenic views and more complex ecological aesthetics based upon ecological integrity (Gobster 1999, Gobster et al. 2007). For example, wildflower viewing is an important and burgeoning recreational activity (see chapter 9.1). However, Ratliff (1985) reported that maintaining wet meadows in good hydrologic and vegetative condition favors graminoid species that are less showy than many forbs. On the other hand, maintaining wet meadow hydrology may promote production of late-season wildflowers for the benefit of pollinators (Hatfield and LeBuhn 2007) as well as human visitors. Furthermore, because meadow degradation can stimulate dramatic shifts from vegetative reproduction by sedges to production of pollen and seeds by grasses and forbs (Klimkowska et al. 2009), evaluating production of allergens could present another opportunity to relate meadow integrity to social considerations.

Management Implications

- Wet meadows can be vulnerable to transformations that result in diminished socioecological value. The flip side of that coin is that restoration of these systems holds great potential to provide multiple ecological and social benefits, despite their small share of the landscape. Research to date suggests that projects can promote important benefits; however, additional long-term monitoring and research would help to evaluate those benefits and prioritize investments in restoration.
- In particular, long-term studies of effects of stream and meadow restoration on higher order values such as water flows and aquatic life remain a topic for further research, particularly in light of anticipated effects of climate change.
- Assessments of the number, size, location, current condition (especially extent of incision), and recovery potential of degraded wet meadows in the synthesis area will help target and prioritize structural interventions, changes in grazing practices, or other restoration treatments.
- In addition to site-specific assessments and treatments, examination of disturbances (e.g., wildfire) and management practices (e.g., prescribed grazing practices) on a larger, watershed scale, could aid the design of more effective strategies to promote long-term resilience of these valuable systems.

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