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Patterns and dynamics of vegetation recovery following grazing cessation in the California golden trout habitat

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Abstract. In 1978, the Golden Trout Wilderness area was established to protect the California golden trout (*Oncorhynchus mykiss aguabonita*)—a vulnerable subspecies of the rainbow trout that is endemic to California—and its habitat, which is currently restricted to a few streams within high-elevation meadows in the Sierra Nevada Mountain Range. Because of the deleterious effects of livestock grazing on riparian vegetation in the golden trout habitat (occurring since the 1800s), meadow restoration activities were initiated in 1991, including cattle exclusion. There has been renewed discussion about re-opening these public lands to livestock grazing, and impact assessment studies are needed to inform decision makers about the potential consequences. Thus, we estimated the recovery potential of the golden trout habitat by measuring the height of riparian vegetation within areas that have been grazed vs. closed to grazing ("rested") since 1991. We found that cattle exclusion is effective at favoring riparian vegetation growth, but that vegetation recovery from grazing could take several decades in these sensitive habitats as some "rested" areas have yet to recover to full vegetation height, even after 25 yr of rest.

Key words: cattle; global change; Golden Trout Wilderness; grazing; livestock; *Oncorhynchus mykiss aguabonita*; protected area; public lands; riparian vegetation.

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Introduction

Humans now dominate the earth's ecosystems (Vitousek et al. 1997) and have radically altered land surfaces and land use, thereby triggering increased pressure on the environment (Foley et al. 2005). Some land-use activities, such as livestock grazing and crop farming, have legacy effects that may influence ecosystem structure and functioning for decades, even after their cessation (Foster et al. 2003). Moreover, land use can interact with climate change to exacerbate the effect of climate change on local ecosystems (Dale 1997, Hansen et al. 2001, Nussle et al. 2015).

One common land-use practice of growing concern is livestock grazing (Milchunas and Lauenroth 1993, Foster et al. 2003, Agouridis et al. 2005). As the demand for livestock follows the increased consumption of animal protein by humans in developed countries (Gill 1999), so does its consequences in terms of pressure on the environment (McMichael et al. 2007). In particular, many concerns have been raised with regard to the negative effects of livestock grazing on terrestrial and freshwater ecosystems (Belsky 1987, Fleischner 1994).

Livestock grazing has affected 70% of the land in the western United States (Fleischner 1994), including widespread grazing on protected public lands (Knapp et al. 1998, Beschta et al. 2013). Most streams in the western United States are considered damaged by livestock grazing (Belsky et al. 1999). As a consequence, the former President of the American Fisheries Society, Professor Robert Hughes, called for a great reduction in grazing on public lands (Hughes 2014). A fundamental issue with livestock grazing near streams is the impact of grazing on riparian vegetation (Kauffman and Krueger 1984), which has a central role in ecosystem functioning (Richardson et al. 2007). The riparian zone is defined as the interface between stream and terrestrial ecosystems and is considered a diverse, dynamic, and complex ecotone (Naiman and Decamps 1997). Riparian vegetation provides food and habitat for many terrestrial and aquatic species (Cummins et al. 1989) and is also a source of leaves and invertebrates that fuel river ecosystems and sustain aquatic consumers (Nakano and Murakami 2001, Ryan and Quinn 2016). Riparian vegetation is essential for stabilizing the river channel and river banks (Kauffman et al. 1997, Miller et al. 2014). Additionally, riparian vegetation provides shade that has a cooling effect on stream water temperature, which may ameliorate the expected water temperature increases linked to global warming (Naiman and Decamps 1997, Moore et al. 2005, Nussle et al. 2015, Ryan and Quinn 2016).

Due to the growing appreciation for the importance of the riparian zone to both terrestrial and aquatic ecosystems, it is now common practice in forest management to leave a buffer of riparian vegetation along the stream channel (e.g., Young 2000). Moreover, in areas that are actively grazed by livestock, mitigation measures often include habitat restoration coupled with livestock exclusion through fencing or complete exclusion to restore and protect the riparian zone (Schulz and Leininger 1990, Stromberg 2001, Brookshire et al. 2002). While excluding grazers can accelerate the rate of recovery, it may take at least 10 yr for the riparian zone to recover from grazing, and even longer in less resilient habitats (Moore et al. 2005). Consequently, Beschta et al. (2013) advocate for a careful documentation of the ecological, social, and economic costs of livestock grazing on public lands, and suggest that costs are likely to exceed benefits in sensitive ecosystems.

On several public lands within the Sierra Nevada Mountain Range in California, for example, streams and adjacent riparian vegetation in high-elevation meadows have been severely degraded by livestock grazing (Ratliff 1985, Knapp and Matthews 1996, Herbst et al. 2012, Purdy et al. 2012), reducing their potential to buffer increasing summer air temperatures. In a recent study, we found that reduced vegetation due to the combined effects of cattle activities can lead to river temperatures over 5°C higher in areas where cattle are present compared to ungrazed areas, where vegetation was both denser and larger due to cattle exclusion since 1991 (Nussle et al. 2015).

Several meadows in the Sierra Nevada (Fig. 1) provide habitat for the golden trout (*Oncorhynchus mykiss aguabonita*; Knapp and Matthews 1996), the state fish of California and a subspecies of rainbow trout that is endemic to California. Its native habitat is restricted to a few watersheds in the upper Kern River in the southern Sierra Nevada of California. Habitat degradation, grazing, in addition to competition and hybridization with non-native trout, have resulted in its listing as a species of high concern (vulnerable) by the California Department of Fish and Wildlife (Pister 2010, Moyle et al. 2015). To protect this species, the Golden Trout Wilderness area (Fig. 1) was established in 1978 within the Inyo National Forest and Sequoia National Forest, protecting the upper watersheds of the Kern River and South Fork Kern River (Stephens et al. 2004).

There is discussion about re-opening the meadows to livestock grazing in the Golden Trout Wilderness, and the Inyo National Forest will begin an environmental impact statement in 2019 under United States environmental law for grazing allotments on the Kern Plateau (Lisa Sims Inyo National Forest, *personal communication*). In order to provide managers and policy makers with information on the likely short- and long-term consequences of grazing, we estimated the time for riparian vegetation to recover to full heights from grazing by measuring the height of riparian willows (*Salix* spp.) in 1993 and in 2014/2015 in two meadows that have been managed differentially with regard to grazing: Ramshaw and Mulkey meadows. Both meadows have been partially protected from livestock grazing since 1991, when electric fences were installed to exclude livestock from their riparian zones. However, Ramshaw has been fully protected from grazing since 2001 when cattle were excluded entirely from the meadow, whereas Mulkey has continued to be grazed outside the exclusion area since 1991 to the present (summarized in Table 1). The differential management allowed us to characterize patterns of vegetation recovery in the two

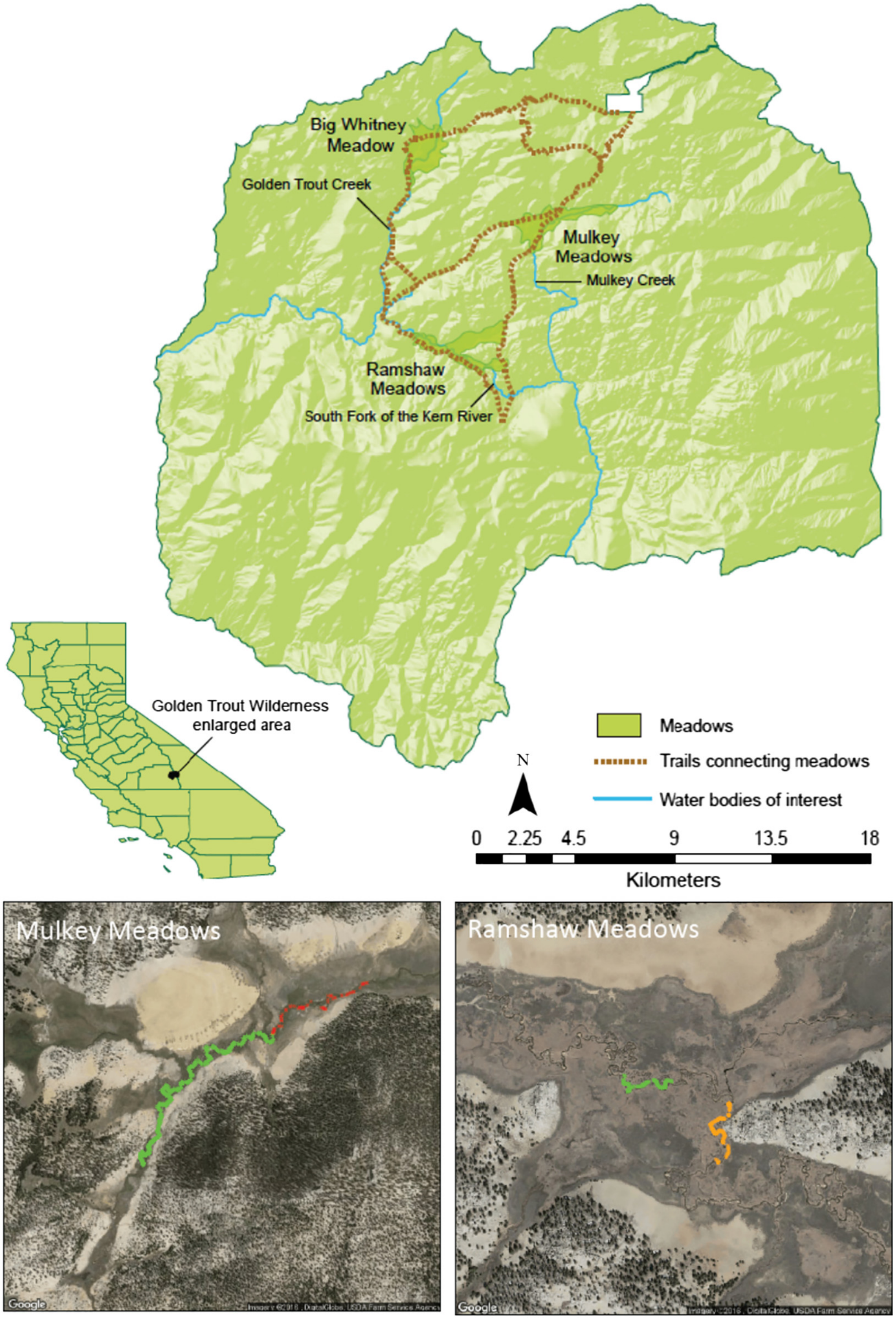

Fig. 1. Data were collected in two meadow systems of the Golden Trout Wilderness, California, a protected

(Fig 1. *Continued*)
area within the Inyo National Forest in the Sierra Nevada Mountains, which is the last remaining habitat of the golden trout (*Oncorhynchus mykiss aguabonita*). Riparian willow height was measured in 1993 and 2014 in Mulkey Creek, within Mulkey Meadows, in two areas: inside an exclosure established in 1991 and ungrazed since that time (individual willows sampled in 2015 are marked in green) and outside the exclosure where cattle have been permitted (individual willows are marked in green). In Ramshaw Meadows, in the South Fork of the Kern River, willow height was measured in 1993 and 2015 in two areas: inside an exclosure set in 1991 (individual willows sampled in 2016 are marked in green) and outside an exclosure set in 1991, but where cattle have been excluded entirely since 2001 (individual willows are marked in orange).

meadow systems and to address four specific objectives: (1) short-term and (2) long-term impacts of cattle exclusion, (3) partial (i.e., within-meadow) cattle exclusion efficiency, and (4) the time needed for riparian vegetation to recover to full heights after complete cessation of grazing.

Methods

This study was conducted in two meadows of the Golden Trout Wilderness: Ramshaw and Mulkey meadows (Fig. 1). These meadows are located at high elevations (>2000 m) in the southern end of the Sierra Nevada, California (118°15′ N, 36°22′ W), a semi-arid region with 50–70 cm annual precipitation, mostly in the form of snow during the winter (Knapp and Matthews 1996). Such climatic characteristics result in shallow ground water, fine-textured superficial soils, and a dominance of herbaceous vegetation, such as sagebrush (*Artemisia cana*) in the meadow and sedge (*Carex* spp.) and willow (*Salix* spp.) in the riparian zone (Weixelman et al. 1997, Viers et al. 2013). Our analyses focused on willow (*Salix* spp.). While we do not know the exact willow species, historical CalFlora records (www.calflora.org) indicate that *Salix geyeriana* is the most frequently observed willow species in the Golden Trout Wilderness area, whereas the second most frequent species, often use in restoration projects (Uchytil 1989), is a closely related species (*Salix lemmonii*).

Table 1. Summary of restoration measures in Mulkey and Ramshaw meadows.

Measures	Mulkey meadows	Ramshaw meadows
Pre-restoration grazing	Before 1991	Before 1991
Meadows restoration	1991	1991
First willow measurements	1993	1993
Partial cattle exclusion	Since 1991	1991–2001
Total cattle exclusion	. . .	Since 2001
Second willow measurements	2014	2015

Because riparian vegetation and stream banks were severely degraded by livestock, the Inyo National Forest initiated a restoration program between 1990 and 1991 in several meadows (Knapp and Matthews 1996). Restoration involved planting thousands of young willows along stream banks and protecting them from cattle grazing with electric fences (Fig. 2). Cattle continued to graze the meadows outside of the fenced riparian zone. In 2001, cattle were completely removed from some meadows (Stephens et al. 2004), including one of our study meadows (Ramshaw Meadows).

To estimate the time for vegetation recovery following resting, we measured the riparian vegetation height along two streams: (1) Mulkey Creek, within Mulkey Meadows, between 2827 and 2844 m in elevation, and (2) the South Fork of the Kern River within Ramshaw Meadows, between 2629 and 2648 m (Fig. 1). Data were collected at three different time points after the start of the restoration program. A first assessment of the vegetation height was made in 1993, after two years of partial cattle exclusion (Knapp and Matthews 1996). Then, 23 yr after cattle exclusion (in 2014), Mulkey Meadows, which has partial protection via a cattle exclosure, was sampled again in both the grazed part of the meadow (i.e., outside the exclosure) and the rested part of the meadow (i.e., inside the exclosure). Finally, in 2015, Ramshaw Meadows, where cattle have been excluded completely since 2001, was sampled in the area rested since 1991 (i.e., inside the initial exclosure, 24 yr of rest) and the area rested since 2001 (i.e., outside the initial exclosure, 14 yr of rest) (Fig. 1).

We sampled the meadows by walking parts of the river and measuring the willows within 2 m of the stream bank with a measuring rod: The height

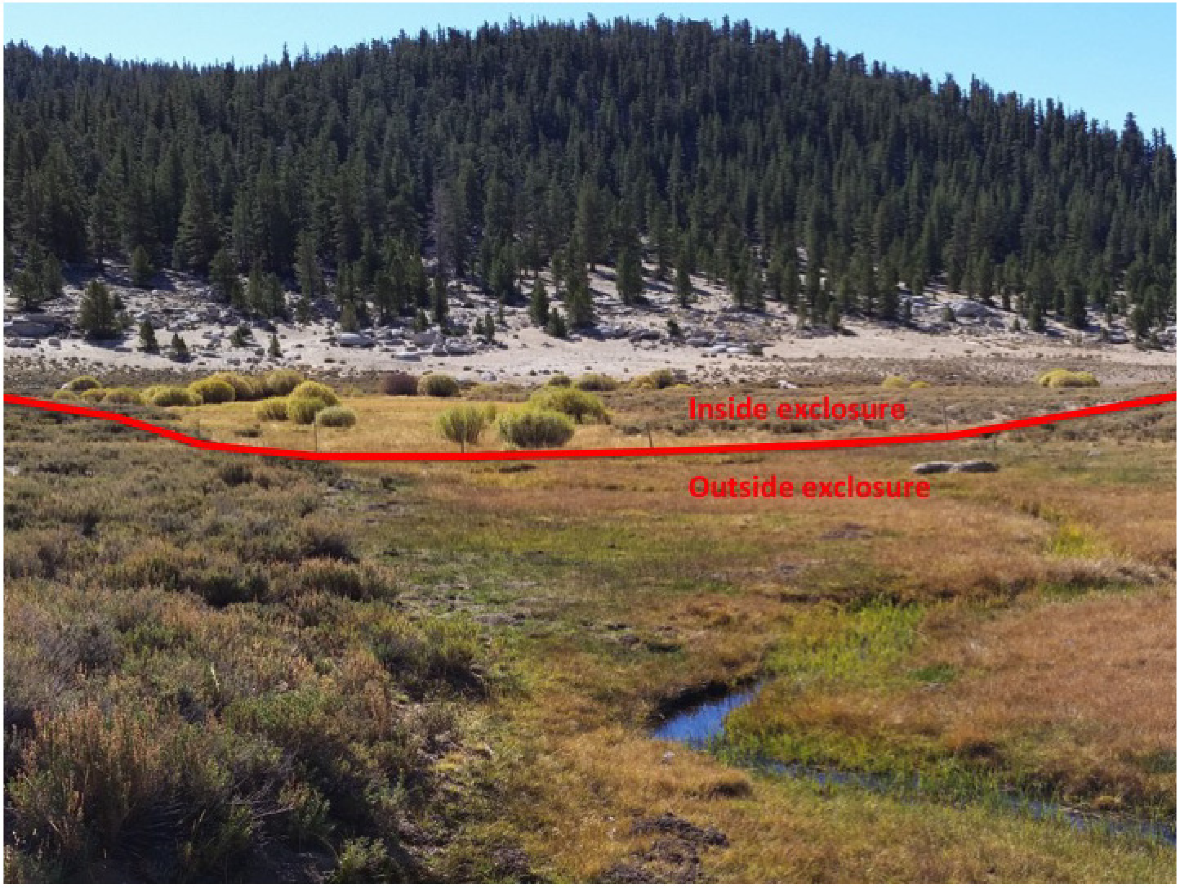

Fig. 2. Photograph highlighting the effect of the cattle exclosure in Mulkey Meadows. The red line represents the electric fence delineating the cattle exclosure. The bottom of the photograph (front) shows the zone where cattle are present and willow are scarce. The back plan highlights the zone where cattle are absent as well as the locations of willows along the streambed.

(cm) and the GPS (global positioning system) location of each willow were recorded in the 2014–2015 samplings, but only the height class (20 cm bins) of the trees was measured in 1993. We used these data to test questions regarding the temporal dynamics of vegetation recovery and to estimate the recovery time until maximal vegetation heights. The differential management allowed us to characterize patterns of vegetation recovery in the two meadow systems and to address four specific objectives: (1) short-term, (2) long-term impacts of cattle exclusion, (3) partial (within-meadow) cattle exclusion efficiency, and (4) the time needed for riparian vegetation to recover after complete cessation of grazing.

In both 1993 and 2014/2015, we compared the height of vegetation in both zones (inside vs. outside exclosures) with Welch's tests (*t*-tests with correction for heteroscedasticity). To measure short-term impacts of cattle exclusion (Objective 1), we compared the height of vegetation in 1993 (two years after cattle exclusion). We compared willow height inside exclosures (cattle absent) vs. outside exclosures (cattle present) in both Mulkey and Ramshaw meadows. We also binned the 2014/2015 data and compared the tests on raw and binned data to confirm that binning does not affect height comparisons. To measure long-term impacts of cattle exclusion (Objective 2), we compared the height of vegetation in 2015 between the two areas in Ramshaw, that is, 14 vs. 24 yr after cattle were excluded (recalling that part of the meadow has been rested since 2001 and another part has been rested since 1991). To estimate partial within-meadow cattle exclusion efficiency (Objective 3), we focused on Mulkey Meadows and compared the height of vegetation in 2014 between the actively grazed region vs. a region that has been ungrazed for 23 yr. Finally, to investigate the time needed for vegetation height recovery after complete cessation of grazing (Objective 4), we first compared vegetation height in both areas of Ramshaw: one area that had been rested since 1991 and the other area that had been rested since 2001. Then, we reconstructed the growth trajectories of willows based on the height data from three treatments since the cattle exclusion: (1) Ramshaw, (2) Mulkey ungrazed, and (3) Mulkey grazed. For the Ramshaw treatment, since sampling was performed in 1993 and in 2015, we were able to estimate the growth of willow after four periods of cattle exclusion, that is, 24 yr after cattle removal in the Ramshaw exclosure, 14 yr after cattle removal outside the former Ramshaw exclosure (1993–2001 with cattle present, 2001–2015 with cattle absent), two years after cattle removal within the Ramshaw exclosure in 1993, and zero years after cattle exclusion in the grazed part of Ramshaw in 1993. In Mulkey Meadows, cattle were never excluded completely from the meadow; therefore, we measured willow height only in three periods after exclosure in the ungrazed area (0, 2, and 23 yr) and two in the grazed area (2 and 23 yr).

We used quadratic models to model the willow growth trajectory in Ramshaw and Mulkey meadows because willow growth trajectories in sensitive habitats and under active grazing have been shown to increase, reach a maximum height, and then decrease (den Herder et al. 2008). Such growth trajectories can be modeled with quadratic models, that is, with a multiple regression with average height as a function of time (in years) and time-squared. More elaborate models exist for willow growth, such as models with age-specific growth (Marshall et al. 2014), but such models require size-at-age data that we lacked. Using a quadratic function to mimic willow growth has two advantages compared to a linear regression: *First*, modeled willow height will grow at a slower pace until it reaches a maximum, which is expected as willow grow in three directions and we only measured one (height); *second*, it will eventually reach a maximum (see also den Herder et al. 2008), which may be understood as the recovery time to maximal height.

Results

By comparing vegetation height in the grazed and ungrazed zones after two years of rest (in 1993), we could estimate the short-term effects of cattle exclosures after habitat restoration in the two meadows (Objective 1). In 1993, in Mulkey, vegetation height was 20.0   13.0 in the grazed area vs. 29.8   25.4 in the ungrazed area (Welch's test: $t_{26.1} = 2.4$, $P < 0.05$; Fig. 3A). Similarly, in 1993, the average height of the vegetation in Ramshaw was 33.1   11.5 cm in the grazed area, while it was 45.9   35.4 in the rested area (Welch's test: $t_{81} = 4.9$, $P < 0.001$; Fig. 3A).

Accounting for the large variability in vegetation height, long-term effects of cattle exclosure (Objective 2) could be estimated by comparing vegetation height in both areas of Ramshaw in 2015: The area that was rested since 2001 had smaller willows (112.7   73.8 cm) than the area that was rested since 1993 (140.8   75.9) (Welch's test: $t_{239} = 2.9$, $P < 0.01$; Fig. 3B). These results indicate that recovering after cattle exclusion, that is, attaining maximum willow height, can take over a decade.

In Mulkey, the partial within-meadow cattle exclusion efficiency (Objective 3) was estimated by comparing vegetation height in both areas in 2014. The actively grazed area had significantly smaller willows (41.6   25.3 cm) than the area ungrazed since 1991 (92.2   57.0 cm; Welch's test: $t_{137.9} = 14.6$, $P < 0.001$; Fig. 3C). This result indicates that active grazing prevents riparian vegetation from reaching its maximal potential height.

Finally, in order to estimate the resting time for recovery to maximum willow height after grazing cessation (Objective 4), we used the height data collected in Ramshaw and Mulkey meadows to estimate the willow growth trajectory. Assuming no growth in the grazed area (see *Discussion*) between 1991 and 2015 and a quadratic growth function for height, we estimated the growth trajectory of the riparian vegetation as the average height of the willows as a function of time (Fig. 4). In Ramshaw: Willow height = 29.5 + 7.76 × time   0.13 × time^2. In Mulkey: Willow height = 20.0 + 5.09 × time   0.085 × time^2. Given these relationships, we estimated the time to recovery of willow

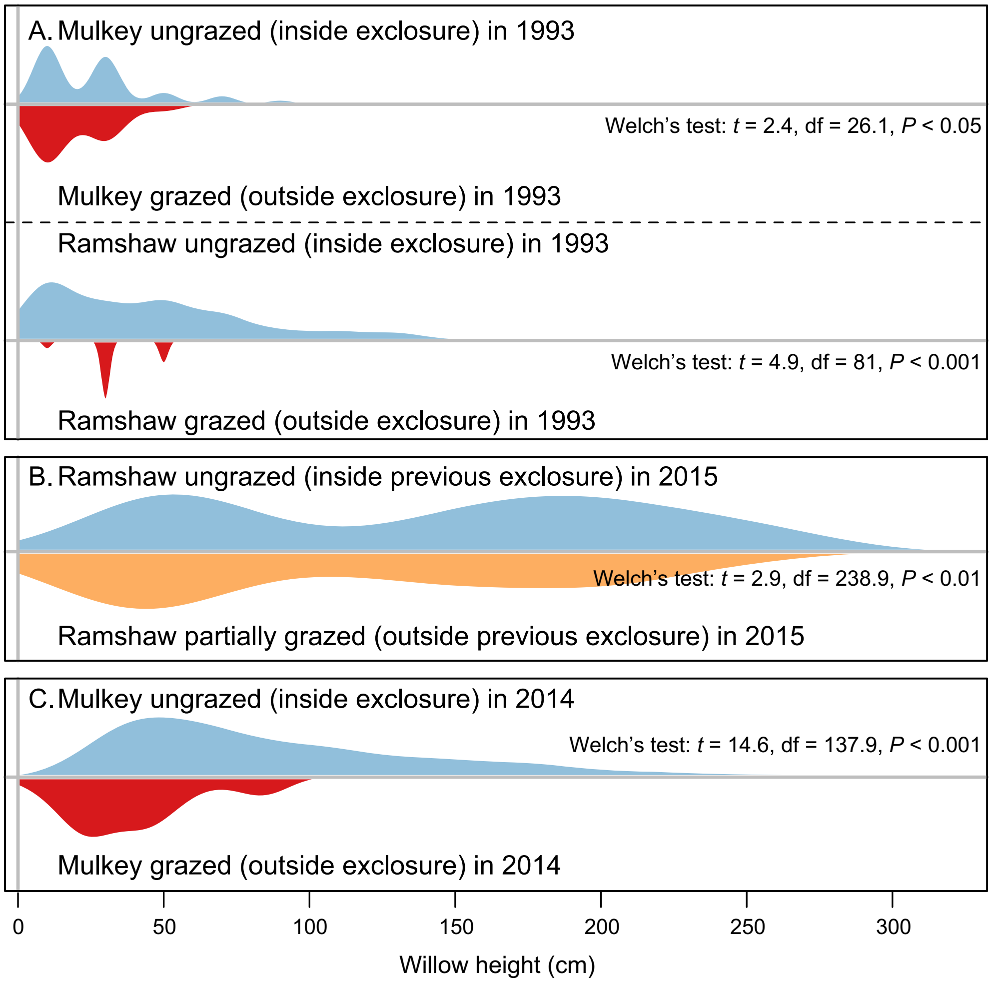

Fig. 3. Comparisons of willow height distributions in the two meadows at the three different periods (A) 1993, (B) 2015, and (C) 2014. The ungrazed treatment is reported in blue, the grazed treatment in red, and the partially grazed treatment in Ramshaw in orange. We used Welch's tests that account for heteroscedasticity to test for differences in average willow height between the different areas (see *Methods*). In 1993, the peaks are artifacts due to the binned data for willow height.

heights in both meadows to be ~30 yr (specifically, 29.8 yr in Ramshaw and 30.0 yr in Mulkey).

Discussion

Livestock grazing has strong impacts on vegetation, including in the riparian zone (Brookshire et al. 2002). Our study demonstrates the importance of cattle exclusion as means of mitigating against the effects of livestock grazing on riparian vegetation in the high-elevation meadows of the Golden Trout Wilderness, while also emphasizing the dynamics of vegetation recovery.

There is a consensus that cattle exclusion can rapidly improve riparian zones, within a few years, as many studies have demonstrated rapid increases in riparian vegetation size and density following cattle exclusion (reviewed in Sarr 2002). Our results suggest that in high-elevation meadows, removing livestock—either with fences or through complete exclusion—is beneficial for riparian vegetation growth, and such benefits are evident after only two years of rest. Through a comparison of willow heights after two years of rest (i.e., 1991 vs. 1993), we found that willows in the ungrazed area were larger, on average, than in

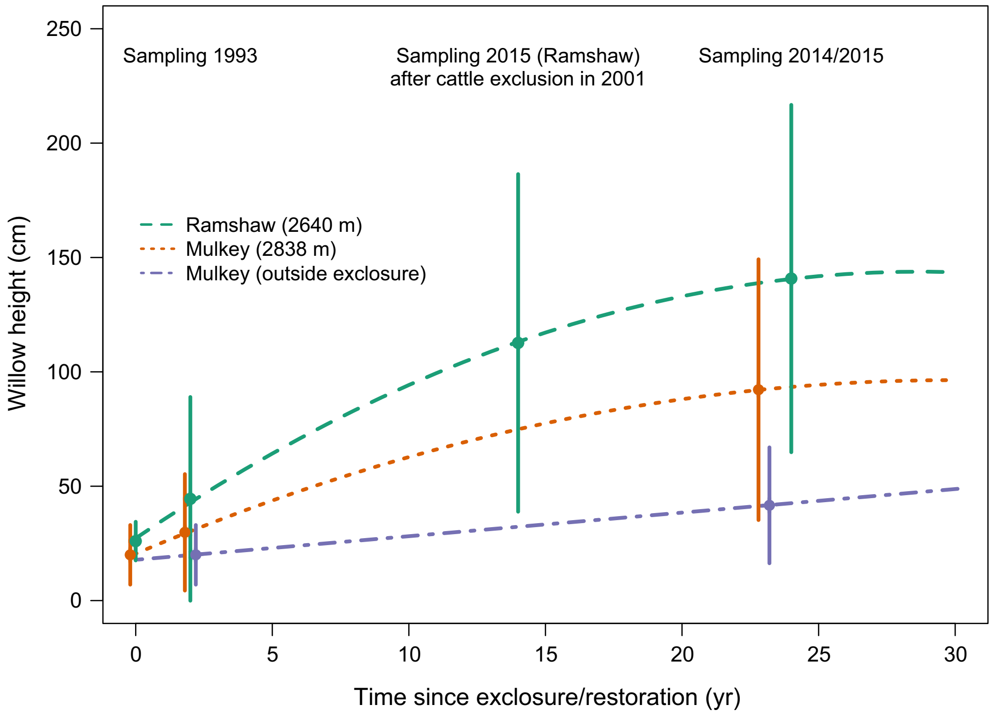

Fig. 4. Willow growth patterns following restoration (i.e., cattle exclusion). Reconstructed growth trajectories based on the data collected in three areas: Ramshaw Meadows, Mulkey Meadows within exclosure, and Mulkey Meadows outside exclosure. Points represent the average willow height, and straight lines represent the standard deviation of the willow height.

the grazed area of both Ramshaw (15 cm larger) and Mulkey (10 cm larger) meadows (see Fig. 3A).

While excluding cattle (i.e., "resting" a meadow) can have a rapid effect on willow height, the time required for full willow height recovery—as indicated by a stable vegetation cover (Hupp 1992)—can take much longer. However, long-term studies investigating the complete recovery of riparian areas after cattle exclusion are scarce (but see Dobkin et al. 1998, Beschta et al. 2014, Batchelor et al. 2015). In this study, we demonstrate that even in areas where >1000 willows have been replanted (Matthews, pers. obs.) and have been rested from grazing for 25 yr, riparian vegetation has not recovered completely in terms of height (Fig. 4). Using a simple model to explore the growth trajectories of willow using data collected at different times since cattle were excluded, we estimate that willow height recovery after cattle exclusion could take up to 30 yr. We should note that this is a conservative estimate because of the assumptions made to model growth trajectories. In order to calculate the growth trajectory in Ramshaw Meadows, we assumed that the vegetation height measured in 2015 in the previously grazed area was equivalent to what it would have been in 2005 in the ungrazed area, that is, after 14 yr of exclosure. In other words, we assumed no vegetation growth when cattle are present, which is unlikely as shown in the Mulkey grazed area (Fig. 4). This simplification has the consequence of *overestimating* the growth capacity, and therefore *reducing* the expected time needed to reach the recovery height. Examining the distribution of willow height in Ramshaw Meadows supports this hypothesis; the average willow height in the ungrazed part of Ramshaw is 140 cm, but the highest tree measured was 280 cm and the largest 10% of trees were all above 240 cm, which leaves considerable opportunity for further recovery. The time needed for recovery is tightly linked to environmental features, which reflect both the potential for willows to outgrow its grazer, and the density of grazers that will determine the pressure exerted on the plants (Schulz and Leininger 1990, Case and

Kauffman 1997, Brookshire et al. 2002). For instance, in a harsh tundra ecotone, willows stopped growing after two to four years (and even decreased in height) because of grazing (den Herder et al. 2008). Moreover, vegetation recovery after channelization might take even longer—>65 yr—according to Hupp (1992).

Our results suggest that the long-term impacts of grazing and the time needed for recovery after habitat restoration can be very long in sensitive high-elevation meadows (multiple decades, see Fig. 4). Moreover, it is important to note that while we focus on willow height in the present study, grazing also reduces willow density (Knapp and Matthews 1996, Belsky et al. 1999, Nussle et al. 2015). Beyond impacts from cattle grazing on vegetation recovery, riverbanks have collapsed and erosion is severe in the most affected part of Mulkey Meadows (Fig. 5). Previous work indicates that montane meadows are also likely to suffer from increased erosion and xerification due to the presence of cattle (Fig. 5), which may require even longer recovery periods than the vegetation (Ratliff 1985, Viers et al. 2013).

In a recent companion study, we demonstrated that vegetation reduction due to grazing interacts with climate change to increase water temperature beyond that expected due to climate change alone (Nussle et al. 2015). In a warming climate, reduced riparian vegetation, combined with the naturally dry and warm conditions of the Kern Plateau, could raise water temperatures to levels that might be harmful for the California golden trout and the aquatic invertebrates they feed on (Knapp and Matthews 1996, Poff et al. 2002, Durance and Ormerod 2007, Nussle et al. 2015). Moreover, the recovery of willow height has the potential to influence several aspects of golden

Fig. 5. Photographs showing (A) degraded habitat with trampled soil in front, eroded stream bank in back, and scarce herbaceous vegetation (*Carex* sp.) and (B) recovered habitat with high banks and dense willow vegetation.

trout ecology beyond their thermal experience (e.g., via roots and more complex banks that provide shelter, via infall of terrestrial invertebrate prey), and indirect effects of grazing on fish ecology deserve further study.

Since global climate change is likely to continue due to the inertia of climate as well as political decisions (Peters et al. 2012, Stocker et al. 2013), management strategies should focus on minimizing additional stressors in order to protect freshwater ecosystem integrity and biota under a changing climate (Ficke et al. 2007). In sensitive ecosystems such as these high-elevation meadows, restoration measures should be taken to reduce the environmental stressors that further accentuate the impacts of climate change (Heller and Zavaleta 2009, Hunter et al. 2010, Prato 2011, Beschta et al. 2013). There is mounting evidence that protecting pristine ecosystems might be both the least expensive and most effective defense against climate change (Martin and Watson 2016). Therefore, any cattle grazing on sensitive habitats in public lands should be carefully considered for the sake of conserving imperiled California golden trout and its habitat.

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