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Research article

Seeding plants for long-term multiple ecosystem service goals

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ABSTRACT

The historical management of agroecological systems, such as California's rangelands, have received criticism for a singular focus on agricultural production goals, while society has shifting expectations to the supply of multiple ecosystem services from these working landscapes. The sustainability and the multiple benefits derived from these complex social-ecological systems is increasingly threatened by weed invasion, extreme disturbance, urban development, and the impacts of a rapidly changing and increasingly variable climate. California's grasslands, oak savannas, and oak woodlands are among the most invaded ecosystems in the world. Weed eradication efforts are rarely combined with seeding on these landscapes despite support for the inclusion of the practice in a weed management program. Depending on seed mix choice, cost and long-term uncertainty, especially for native seed, is an impediment to adoption by land managers. We investigated four seeding mixes (forage annual, native perennial, exotic perennial, and exotic-native perennial) to evaluate how these treatments resist reinvasion and support the delivery of simultaneous multiple ecosystem services (invasion resistance, native richness, nitrogen fixing plants, pollinator food sources, plant community diversity, forage quality, and productivity). We found the increase of exotic and native perennial cover will drive resistance to an invading weedy summer flowering forb *Centaurea solstitialis* but provides a mixed response to resisting invasive annual grasses. The resistance to invasion is coupled with little tradeoff in forage productivity and quality and gains in plant diversity and native cover.

1. Introduction

California annual rangelands — Mediterranean-type ecosystems that consist of annual-dominated herbaceous communities across California's grasslands, oak savannas, and oak woodlands — are some of the most highly plant-invaded systems in the world. These systems, which are global biodiversity hotspots (Myers et al., 2000; Roche et al., 2012), provide a critical forage source for a 3.2 billion USD cattle and calf livestock industry and a multitude of provisional, regulating, support, and cultural ecosystem services (CALFIRE-FRAP, 2010; MEA, 2005; National Agricultural Statistics Service (USDA NASS), 2012). The widespread invasion of these systems has led to significant losses of multiple economic and ecological benefits. For example, weed infestations can increase fire frequency and magnitude (Lambert et al., 2010), modify virus incidence in native bunchgrasses (Malmstrom et al., 2005), reduce native plant diversity (Davies, 2011; Parmenter and MacMahon, 1983), alter water resources (Gerlach, 2004), reduce livestock carrying capacity (Davy et al., 2015; Hironaka, 1961), and can alter ecosystem nutrient cycles and nitrogen fixation (Ehrenfeld, 2003; Liao et al., 2008). Efforts to control invasive annual grasses have generally elicited ineffective long-term results (e.g., James et al., 2015), often because these weeds can quickly recolonize bare areas from which they are extirpated through management.

In highly-invaded rangelands, seeding may play a crucial role for successful weed management. Seeding with desirable species is a strategy that is not widely used for weed management, and not common practice on California rangelands, despite evidence that supports its inclusion in weed management programs (James et al., 2015; Roche et al., 2015). This technique holds particular promise

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for managing invasive annual grasses and weedy summer flowering forbs because seeding has the potential to (1) create a barrier to weed establishment (Corbin and D'Antonio, 2004; Hierro et al., 2011; O'Dell et al., 2007); (2) sustain or enhance forage production (Briske, 2011); and (3) increase resistance to future invasions (Funk et al., 2008; Hulvey and Aigner, 2014). Resistance occurs because seeding desirable species that demonstrate functional similarity or equivalence in resource utilization to invasives increases the magnitude of resource interactions between natives, improved forage species, and/or non-native naturalized species as competition is strongest among individuals with similar resource requirements or similar resource acquisition efficiency (Connell, 1983). Seeding provides additional utility for managers because this strategy facilitates the direct reestablishment of multiple ecosystem services, such as increased forage production or enhanced biodiversity (Briske, 2011; Pellant and Lysne, 2005; Prober and Smith, 2009; Sheley and Half, 2006).

The historical management of rangeland systems has been criticized for singular focused production goals, while society is increasingly demanding multiple ecosystem services from these landscapes (Briske, 2011). However, achieving desired multiple objectives in annual rangeland systems, especially invaded systems, could be difficult due to a variety of reasons including conflicting practices, non-adaptive management, and lack of fiscal rewards for non-traditional ecosystem services. Further, most efforts to intervene, restore, or enhance these grazed ecosystems are considered prohibitively expensive and often lack evidence for long-term success (Briske, 2011; Hardegree et al., 2012). Seeding demonstrates high utility for maximizing reestablishment of multiple ecosystem services while reducing continued need for capital inputs and efforts required for successful invasive species control (Bullock et al., 2011). For example, seeding of native species on working grasslands can potentially enhance water quality (Blignaut et al., 2010), while reducing invasives, thus providing the opportunity for ranchers to achieve multiple goals of relatively high priority to annual grassland managers (Roche et al., 2015). However, limited supply and the high cost native seed mixes relative to non-native commercial mixes may be a barrier to their use in post intervention seeding strategies. Despite the promise of achieving multiple management goals with the integration of seeding into rangeland vegetation priorities, formal investigations that quantify the utility of seeding to reestablish multiple ecosystem services is extremely uncommon.

We conducted a study to understand the multiple outcomes associated with restorative range seeding practices following a weed control program in a highly invaded grassland habitat. In order to assess the long-term effectiveness of rangeland seeding within heavily invaded rangeland plant communities, we established a long-term study to investigate how native and non-native seedings influence multiple management goals, including (1) reduction of three dominant invasive plants: *Aegilops cylindrica* Host (jointed goatgrass), *Centaurea solstitialis* L. (yellow starthistle), and *Elymus caput-medusae* L. Nevski (medusahead grass); (2) response of species diversity and native richness; (3) response of forb diversity and relative abundance of nitrogen fixing legumes; and (4) potential tradeoffs of forage quality and quantity. Seed treatments included one native perennial grass mix, one exotic perennial grass mix, one blend of native and exotic perennial grasses, and one mix of an annual grass and annual forage legume. We expected greater resistance to noxious weed re-invasion between all perennial grass treatments compared to the annual seed mix and the control treatments. We expect the native seeding has the potential to resist invasion through supporting the cultivation of a diverse and native rich plant community. Exotic perennials employed in this study are improved varieties that have historically been imported and used for range improvement objectives on California landscapes. We expect them to be major competitors in resisting invasion, and a highly productive and quality source of forage given they have been engineered and imported for success. Additionally, we expect the annual seeding, which includes a leguminous species, to support a community rich in nitrogen fixing legumes and forb diversity. Overall desirability of each treatment is a subjective evaluation based on how well treatments meet management goals given their quantifiable benefits (resistance to weed invasion, forage quality and quantity, species diversity) and the restoration costs.

2. Methods

2.1. Study site and species

Our study was conducted on a working cattle ranch in the oak woodland-annual grassland interior coastal range of Northern Napa County, California, USA. The Mediterranean-type climate is characterized by nearly all the 75 cm of annual precipitation falling as rain during the mild wet winters and no measurable precipitation during the hot dry summers with mean annual minimum temperature of 8.4 °C and maximum annual temperature of 23 °C. These attributes translate into a thermic soil temperature regime and a xeric soil moisture regime. The soils are rated to support any climatically adapted plant species and are similar in productive capacity across the study site. The soils are classified taxonomically as Typic Haploxeralfs (Tehama series) and Mollic Xerofluvents (Yolo series) with a small portion of the plots described as Aridic Haploxertes (Diablo series). The soil textures are mostly loams followed by silt loams and silty clay loams. All plots were located across toeslope and terrace landscape positions with soil depths ranging from 45 cm to depths greater than 60 cm. The herbaceous plant community of this area typically consists of naturalized annual non-native grasses (e.g. *Avena fatua* and *Festuca perennis*) and forbs (e.g. *Erodium botrys* and *Trifolium hirtum*) with occasional remnant native grasses, primarily *Stipa pulchra*.

The focal weeds of our study are foreign invaders to the ecosystem and include *Aegilops cylindrica* (jointed goatgrass), *Centaurea solstitialis* (yellow starthistle), and *Elymus caput-medusae* (medusahead). While medusahead and yellow starthistle are dominant invaders in California's annual rangeland systems, jointed goatgrass is much less common than *Aegilops triuncialis* (barb goatgrass), but is equally problematic. Jointed goatgrass and medusahead are late-maturing annual grasses, both of which are high in silica content and often create a competition-suppressing persistent thatch and monoculture (DiTomaso and Healy, 2007). Yellow starthistle is a long-lived, late maturing summer annual forb that can out-compete and survive well after the shallow-rooted cool-season grasses and forbs have senesced when soil moisture is limited at the near soil surface but, soil moisture further down in the soil profile can be advantageously utilized by the deeper (>1 m) yellow starthistle rooting system (DiTomaso and Healy, 2007).

2.2. Site preparation & management practices

In late spring 1999 and 2000, the entire site was treated with the broadleaf herbicide Transline® (clopyralid) sprayed at a rate of 7.7 ml/l H_2O per hectare; followed by an application of 2–4 D Amine 4 sprayed at rate of 61.8 ml/l H_2O per hectare in spring of 2006. In early summer 2003 and 2004, the entire site was also treated with prescribed fire, specifically timed for jointed goatgrass control. The plots were then drill seeded in fall 2004 (seeding rates and mixes described below). Beginning in the year 2005, cattle (75–150 head) were rotated through the pastures twice annually to graze for approximately 10–14 days during the growing season.

2.3. Experimental design

The experiment was a randomized complete block design with four blocks and five treatments per block. Each block was approximately 2.63 ha and the treatments within block were seeded across 0.52 ha sections. We used five seeding treatments: exotic annual species, native perennial species, exotic perennial species, mixed native and exotic perennial species, and an unseeded control. The annual seed mix was *Lolium rigidum* ("Wimmera 62" Italian rye) and *Vicia villosa* spp. *Daciacarpa* ("Lana" woolly-pod vetch) seeded at a combined rate of 21.13 kg ha^{-1}. The native perennial seed mix was *Bromus carinatus* (California brome), *Elymus glaucus* (blue wild rye), *Melica californica* (California onion grass), and *Stipa pulchra* (purple needlegrass) seeded at a combined rate of 16.05 kg ha^{-1}. The exotic perennial seed mix was *Dactylis glomerata* (Orchard Grass) and *Phalaris tuberosa stenoptera* (Harding Grass) seeded at a combined rate of 4.66 kg ha^{-1}. The mixed native and exotic perennial seed rate was 10.40 kg ha^{-1}. The seeding rates, approximately 355 seeds m^{-2} for each treatment, follow recommendations from the USDA-NRCS Lockeford Plant Materials Center (CAPMC) and exemplify typical of rates used throughout California rangeland.

2.4. Data collection

Plots were sampled via line-point intercept every 0.61 m across 15.24 m transects with four transects in each treatment (Bonham, 2013; Coulloudon et al., 1999). Each point was identified to the plant species level (including designations as native, non-native, and non-native invasive) or ground cover type (i.e. bareground), which enabled the calculation of native species cover, forb cover, total diversity, forb diversity, nitrogen fixing symbiont cover, and invasive plant species cover. Total plant and forb diversity were calculated using the Shannon-Wiener diversity function. Plant community sampling was conducted in 2005, 2006, 2007, and 2015. The precipitation, reported as percentage of normal, for sampling years was 2004-126%, 2005-137%, 2006-43%, 2014-63%, 2015-72%, and 2016-78%. We measured peak forage production in May of 2016 via the comparative yield method (Inter Agency Technical Team (ITT), 1996) by clipping, oven drying at 60 °C for 48 h, and weighing two of the three 0.3-m square quadrats placed at equal intervals and evaluated across a transect in each treatment of each block. We selected two 0.3 m square quadrats per treatment per block to process for forage quality metrics (i.e. crude protein analysis AOAC, 2006).

2.5. Estimating costs

In order to provide an estimate of treatment costs, we accounted for the prescribed burning and herbicide applications, and the cost of seeding with a range drill. The actual cost of the two herbicide applications was 100 USD ha^{-1}. The prescribed burn was conducted at no cost because it was an agency training. A typical prescribed burn for this region would potentially cost 346 USD ha-1 for the 16 ha field based on rates for bulldozer, 6 person crew for 6 h and 2 fire engines for 6 h. The seed cost was calculated based on the actual retail value of each seed mix (annual 184 USD ha^{-1}, native perennial 949 USD ha^{-1}, exotic perennial 186 USD ha^{-1}, mixed perennial 567 USD ha^{-1}). We estimated the cost of drill seeding at 84 USD ha^{-1}, which includes 62 USD ha-1 for the seed drill rental, 22 USD ha-1 for tractor rental. The tractor cost rate is based on 218 USD local daily rental rate for a tractor and using a 1.8 m wide drill seeder running at 8 kph for 8 h of operation per day, covering 1.2 ha per hour.

2.6. Analysis

We used generalized linear mixed effects models to investigate how the fixed effect of seeding treatment type, and the random effects of block and year (to account for repeated measures) affected multiple outcome variables, specifically: native species cover, forb cover, total diversity, forb diversity, nitrogen fixing symbiont cover, forage production, forage quality, and invasive plant species cover. Invasive species responses over time were analyzed after a log transformation using a generalized linear mixed effects model in R with the lme4 package in the R environment. We also utilized descriptive statistics with the 2015–2016 monitoring data to visualize the tradeoffs and benefits of the seeding strategy outcomes.

We used structural equation modeling (SEM) to elucidate the potential mechanisms by which seeding treatments influence long-term invasive species outcomes. For this analysis, we analyzed the 2015 plant community data and calculated change in cover of jointed goatgrass and yellow starthistle populations (medusahead cover was limited across study site even though it was present before intervention). SEM is a statistical tool that employs path and factor analyses to investigate complex multivariate relationships between variables (Grace, 2008; Grace and Bollen, 2008). A conceptual SEM was constructed based on *a priori* hypothesized pathways linking treatment implementation to actual changes in invasive cover (Fig. 1). Seeding treatments tested were exotic annual species, native perennial species, exotic perennial species, mixed native, and exotic perennial species; the unseeded control was used as the reference treatment. The SEM evaluated seeding treatment effects on final (2015) percent cover of three plant functional groups – native perennials, exotic perennials, and annual species—as well as subsequent effects on changes in invasive species cover over the duration of the experiment (2005–2015). Analysis was performed using the Stata 13.1 structural equation modeling command with the standardized reporting option to obtain standardized coefficients, which allows for direct comparisons. We implemented parsimonious model selection by eliminating pathways that were not significant at $p < 0.10$. Model goodness of fit was evaluated via multiple fit statistics, including root mean squared error of approximation, AIC, and BIC (estat gof command; (StataCorp, 2013)).

3. Results

3.1. Invasion resistance

Across the three target invasive weeds, responses to treatments across time were markedly different. We initially observed rapid colonization of yellow starthistle across all seeding treatments, with the exception of the exotic and mixed perennial treatments, which exhibited high levels of invasion resistance across all study years (Fig. 2). Over the course of the 11-year experiment, invasive species frequency was significantly less in both the exotic perennial seeding ($p < 0.01$) and the mixed native and exotic perennials seeding ($p < 0.01$) compared to the control seeding treatments. In contrast to the response we observed to yellow starthistle and medusahead grass, we found jointed goatgrass to be a strong invader across treatments and over time with no detectable difference in resistance to invasion of the seeded communities and control treatment (Fig. 3). Finally, we observed limited medusahead grass cover (< *0.01%* of experiment wide total plant hits) across all treatments and the control for the entire duration of the study despite its occurrence in the surrounding landscape and before

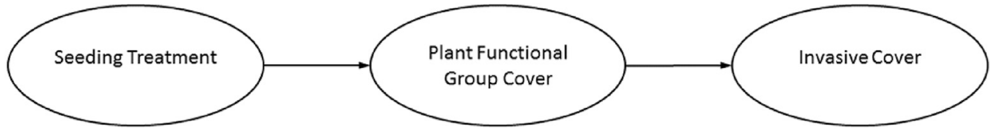

Fig. 1. A conceptual SEM based on *a priori* hypothesized pathways linking treatment implementation to functional group cover to actual changes in invasive plant cover.

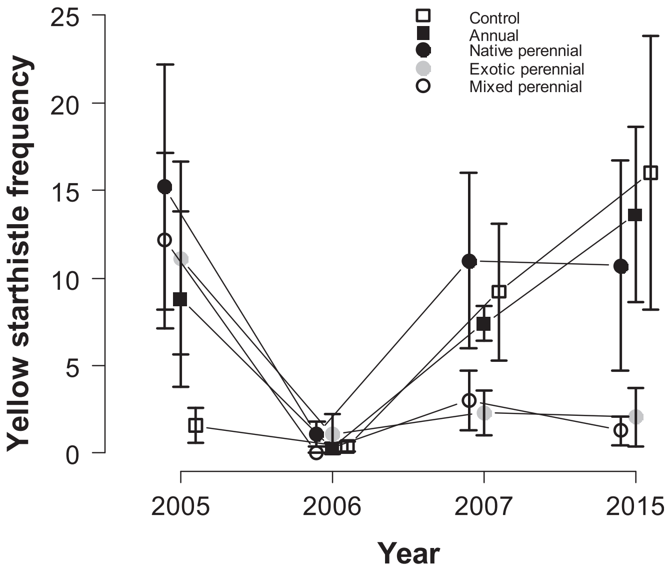

Fig. 2. Mean ± SE of Yellow starthistle (*C. solstitialis*) frequency by seeding treatment across the four sampling periods.

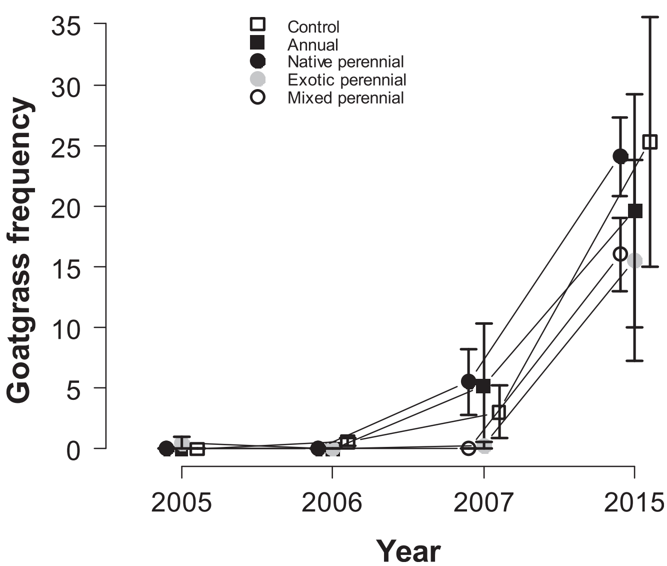

Fig. 3. Mean ± SE of Jointed goatgrass (*A. cylindrica*) frequency by seeding treatment across the four sampling periods.

weed control efforts (data not shown). The findings from the structural equation model illustrate that seeding native, exotic, and exotic-native mix of perennials does facilitate the integration of desired species into the plant community, which subsequently drive resistance to yellow starthistle invasion via increases in native and/or exotic perennial cover relative to the control (Fig. 4). The mixed perennial seeding reduced non-native annual species cover, however, this had no effect on the invasives (Fig. 4). The annual

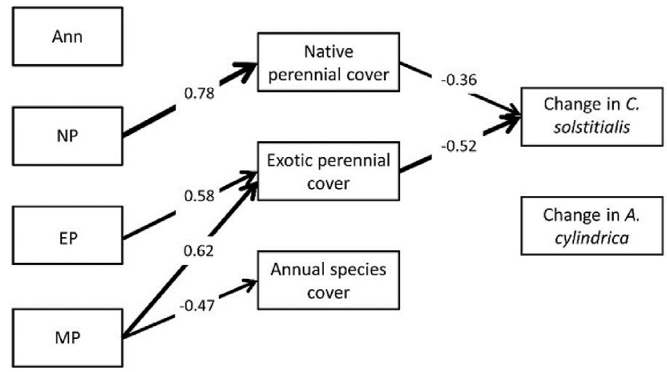

Fig. 4. Structural equation model. Only significant ($p < 0.1$) pathways shown. The relative strength of the effects are indicated by the standardized coefficients and thickness of arrows. Seeding treatments are represented by Ann = exotic annuals; NP = native perennials; EP = exotic perennials; MP = mixed native and exotic perennials, and are compared to the unseeded control.

seeding treatment had no effect on invasive cover change relative to the control (Fig. 4).

3.2. Benefits and tradeoffs

We observed differences in native species and nitrogen-fixing species cover, forbs diversity, and total species diversity. In the native perennial seeding treatment, we observed more native plant cover compared to all other treatments and control ($p < 0.05$; Fig. 5 and Table 1). Native perennial seeding treatments provided higher level of total plant species diversity (Shannon-Wiener index) compared to all other treatments and control ($p < 0.05$; Fig. 5 and Table 1). We observed more nitrogen fixing plant cover in the annual and control plots than in the exotic perennial, mixed native and exotic perennials, and native perennial plots ($p < 0.01$). Furthermore, we observed more nitrogen fixing plant cover in the annual treatment plots than in the control plots ($p < 0.05$).

The annual, native perennial, and exotic perennial seeding treatments harbored herbaceous plant communities that were not significantly different in productivity from the control at peak standing crop (Fig. 5 and Table 1). The annual treatment was apparently the most productive at peak standing crop, and the mixed native and exotic perennials seeding treatment were the least productive and significantly less productive than the control (Fig. 4 and Table 1). The exotic perennial and the mix of native and exotic perennial seeding treatments provided a similar forage quality (percent protein content at annual peak standing crop) and they were not significantly different from the control (Fig. 4 and Table 1). The annual and control plant communities' protein levels were not significantly different from each other.

Range drill seeding and weed control cost on a per hectare basis were estimated at: 714 USD —annual, 1479 USD —native perennial, 716 USD — exotic perennial, 1097 USD — mixed perennials, and 530 USD —non-seeded control.

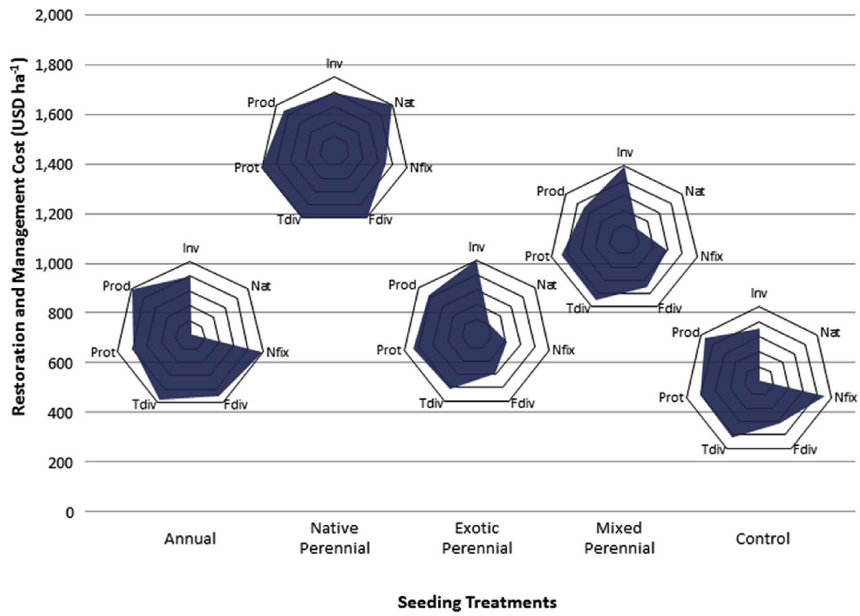

Fig. 5. Response of ecosystem services, across seeding treatment levels (x-axis) by cost of seeding and weed control (y-axis), based on 2015–2016 data 11 years after drill seeding. Each radar diagram is comprised of seven axes for each of the seven ecosystem service goals measured (Inv = invasion resistance; Nat = Native Richness; Nfix = Nitrogen fixing plant cover; Fdiv = forb diversity; Tdiv = total diversity; Prot = herbaceous vegetation crude protein; Prod = forage production). The center of each radar chart represents the minimum of zero and the outer edge represents 100% of the maximum mean value observed. The extent of plot coverage on the axis represents the percentage of the maximum mean observed among all treatments and control. For purposes of direct comparison on the radar diagrams, we used non-invasive percent cover as an indicator of resistance to invasion.

Table 1
Responses of plant community, invasion, and forage quantity and quality indicators to seeding treatments and non-seeded control. Means and standard error of means reported for 2015/2016 data.

	Non-invasive (percent cover)	Native (percent cover)	Nitrogen Fixer (percent cover)	Forb Diversity (H′)	Total Diversity (H′)	Protein ($g \cdot 0.1\ kg^{-1}$)	Forage Biomass ($g \cdot 0.3m^{-2}$)
Annual	65.6 ± 10.93	0.4 ± 0.43	16.3 ± 6.75	1 ± 0.14	1.62 ± 0.08	6.1 ± 0.11	59.4 ± 1.63
Native Perennial	65.2 ± 7.27	26.1 ± 9.37	11.5 ± 1.01	1.11 ± 0.04	1.71 ± 0.09	7.78 ± 0.64	51.84 ± 4.13
Exotic Perennial	82.4 ± 7.87	5.6 ± 5.65	6.8 ± 3.26	0.65 ± 0.23	1.38 ± 0.23	6.85 ± 0.74	49.59 ± 10.56
Mixed Perennial	82.7 ± 3.34	6.1 ± 3.95	9.6 ± 4.86	0.77 ± 0.13	1.53 ± 0.11	6.78 ± 0.37	41.14 ± 3.58
Control	58.3 ± 9.79	0.4 ± 0.42	14.9 ± 5.62	0.7 ± 0.2	1.43 ± 0.13	6.35 ± 0.18	55.53 ± 2.78

4. Discussion and conclusion

4.1. Discussion

The invasion of Mediterranean-type rangeland ecosystems by several noxious weeds has led to declines in the multiple benefits agricultural and conservation society derives from these working landscapes. Land managers are increasingly interested in vegetation management approaches that simultaneously achieve multiple goals and effectively fit into the broader scheme of typically low margin, low return rangeland dependent agricultural operations. In terms of ecosystem services, not all desired benefits can be simultaneously maximized through management activities, and tradeoffs between multiple services may be inevitable (Fig. 5). Incorporating seeding of desirable species into management strategies has shown promise in achieving many desired outcomes. This study focused on assessing seeding mix strategies to (1) resist invasion of prominent weeds, medusahead grass, jointed goatgrass and yellow starthistle; and (2) provide insight to the resulting synergies and tradeoffs among multiple ecosystem service management goals ranging from agricultural productivity to plant community diversity.

Our results suggest the exotic perennial and mixed perennial seedings, and, to a lesser extent, the native perennial seeding, provide barriers to invasion more so than the annual seeding and control (no seeding) (Fig. 4). We found increasing exotic or native perennial cover was effective at inhibiting yellow starthistle, which can employ annual, biennial, and even perennial life history strategies (Fig. 4). The driver for resistance to invasion is potentially created by seeding species functionally redundant with respect to a multitude of resource interactions and competition for overlapping niche occupation of light, water, and nutrients. However, we found evidence for competitive suppression by perennial grasses with yellow starthistle, but did not observe this in the jointed goatgrass response (Fig. 4). Resistance to suppression by the perennial grass treatments suggests that for jointed goatgrass, different competitors with alternative timing of resource use should be tested. The annual seeding and control plots were largely composed of annual-dominated plant communities, which typically use resources early in the California growing season. Since these plots did not experience a decline in invasion, these results suggest that timing of resource interactions of perennial grasses and poor competition from the annual-dominated communities play a role in the resistance to re-invasion (Figs. 1–4). The exotic and native perennials have the ability to utilize water and nutrient resources after most cool-season annuals have senesced, but while the annual invasives are in periods of active vegetative growth and flowering during the late spring and into the dry summer season. This strong competitive effect among phenologically overlapping plants to suppress invasion has been documented in similar systems in California (e.g. Hooper and Dukes, 2010). However, more work needs to be done to determine the traits and specific resource interaction mechanisms at play here. As has been suggested elsewhere (Funk et al., 2008; Gornish and Ambrozio dos Santos, 2015), managers should consider using a trait-based approach to grassland management when invasion resilience is a key goal. For example, managers can choose easy-to-identify traits such as flowering date to determine when desired species might overlap in resource use with targeted non-desirable invasive species.

We also found that native perennial seedings supported the greatest native plant cover and most diverse plant communities, which aligns with expectations that the native seeding had the potential to resist invasion through the cultivation of a diverse and native rich plant community. For example, studies in alternative vegetative states of the oak woodland-annual grassland have found that plant communities with more native cover and less invasives are associated with higher levels of plant species diversity (e.g. Eastburn et al., 2017). The ability of the native perennial seeded plant community to resist invasion, albeit not as effective as the exotic perennials, and support a more diverse plant community provides further justification for inclusion in weed management strategies that target diversity and native richness as ecosystem service goals.

We included metrics of forb diversity and nitrogen fixing plant cover in our study to gain insight into potential differences in the supply of pollinator and soil ecosystem services across seeding strategies. In the annual and native perennial seeding plots, forb diversity was significantly greater than the other seeding treatments and controls. These seeding practices may be a potential strategy to enhance pollinator services through increasing and managing for forb diversity and cover in these systems. Increasing and maintaining forb component of a plant community often aligns with management goals that target forage quality. Our study provides evidence that the use of seeding is feasible to improve pollinator forage sources and potentially enhance forage quality at different periods of the growing season. Seeding mixes that support or include nitrogen fixing plants can significantly influence nitrogen cycling dynamics (Wedin and Tilman, 1990). In our study, we found the annual seeding, which included a nitrogen fixing legume, maintained significantly more nitrogen fixing plant cover over the long-term. Seeding and managing for nitrogen fixing plants can increase above ground biomass production, while accelerating and increasing nitrogen cycling with favorable outcomes for soil fertility (Craine et al., 2002).

The production benefit from nitrogen fixing plants may be the reason we observed similar forage production in the annual seeded plots compared to the other treatments. However, the control plots and each of the seeding mixes were all relatively productive across seeding mixes and the control; ranging from a mean of 4428 kg ha-1 to 6394 kg ha-1 at peak standing crop. Invasive plants on rangelands, such as yellow starthistle, negatively influence plant community productivity and forage quality leading to agricultural and other non-market ecosystem service losses (Duncan et al., 2004). In California, restoring the loss of primary production services or managing for agricultural productivity goals, will likely be incorporated into invasive control and range seeding strategies and a priority for land managers in these largely privately owned working landscapes (Huntsinger et al., 2010; Roche et al., 2015). We observed no significant, only apparent, differences in forage production. This suggests the tradeoffs of forage production among different seeding mixes may not be as large of a barrier to adoption of native and/or more invasive resistant exotic seedings as commonly suggested. This potentially opens a path to manage for synergies among multiple ecosystem service goals, (e.g. optimize between forage production, biodiversity, and invasion resistance). Interestingly, we also found comparable forage quality among the plant communities supported by the various seeding mixes we tested. Poor forage quality of native and naturalized plant communities has been suggested as another barrier to inclusion in agricultural producer and land manager forage seeding practices on rangeland. Our findings suggest including natives into seeding mixes may not be coupled with the often-assumed opportunity cost, however, the capital cost of seeding natives is still a considerable barrier to adoption (Gornish et al., 2016). Accounting for the cost of invasive control efforts and seeding, the native mix was by far the most expensive treatment in our study, which provides a demonstration for the cost and inputs required to restore native and biodiversity ecosystem services. However, we generally expect a positive association that more diverse plant communities of vegetative states, or phases, are more stable and potentially better suited to adapt to a changing climate (Elmqvist et al., 2003; Mace et al., 2012; Tilman et al., 2006). Depending on management goals, the seeding strategies we examined such as the native perennial, exotic perennial, and the exotic-native mix can provide a means to achieving multiple ecosystem service goals but barriers of adoption and the constraints of cost need to be addressed by policy makers and further economic assessment.

5. Conclusion

Reseeding for restoration or range improvement holds potential to simultaneously achieve a multitude of management goals, including forage production, enhanced forage quality, plant diversity, and reduction of invasive plant cover. This is especially important following management activities such as herbicide and prescribed fire applications, which can promote reinvasion of ecologically sensitive habitats and economically sensitive social-ecological systems. As a hot spot of biodiversity, pollinator habitat, and livestock production, it is imperative Mediterranean-type rangeland systems are managed with an awareness of potential tradeoffs and especially when the management goal is supplying multiple ecosystem services over singular focused goals, such as agricultural productivity or native plant community restoration. In order to attain the multiple goal outcome an objective to strive for is an optimal balance (e.g. Pareto efficiency) of ecosystem services management to maintain functioning, resilient, and sustainable working landscapes. Clearly, long-term research must be more commonly employed to ultimately provide managers more realistic recommendations of long-term outcomes of agricultural technologies. This study followed the response of plant community over an 11-year period, which highlighted the value of considering seeding treatments in both the short and long-term. The majority of range seeding studies evaluate outcomes within or one year subsequent to the planting year (Briske, 2011). In this experiment, if we considered our seeding treatments only in the short-term, we would have reached different conclusions and potentially not recognized the potential for exotic and native perennials to resist yellow starthistle invasion after eradication efforts. Incorporating seeding into restoration strategies must also take site potential into account, our study plots were located on soil types well suited for planting. We may have reached different conclusions, if seeding on different topographic positions with more marginal soil types. In addition, various grazing management strategies could lead to different restoration and agricultural outcomes. Finally, a critical knowledge gap to address with further study is the influence reseeding actions and choice may have on the soil microbiome, soil health, and the potential as a tool for increasing soil carbon stores and regulating climate.

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