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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