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Grassland compost amendments increase plant production without changing plant communities

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Abstract. Compost amendment to grassland is a novel strategy proposed and demonstrated to increase ecosystem carbon (C) storage. However, the effects of compost applications on biomass production and plant diversity are not well known. We assessed impacts of a one-time compost amendment over 4 yr on plant dynamics in two grazed grassland ecosystems in California: a coastal prairie and valley grassland. The valley grassland was dominated by exotic annual grasses and had significantly lower species diversity than the coastal prairie, which consisted of a mix of perennial and annual grasses and forbs. We observed large and persistent increases in aboveground biomass. Over the 4 study years, aboveground biomass from compost-amended plots increased by $76\% \pm 21\%$ at the valley grassland and $41\% \pm 21\%$ at the coastal prairie, compared with controls. Plant N content was also greater from compost-amended plots. There were no major shifts in species richness or abundance at either grassland site. Overall, plant communities at both grasslands were relatively resistant to the compost addition, but responses of some individual species were observed. Notably at the valley grassland, the abundance of forbs decreased slightly, while the abundance of grasses increased. The abundance of two noxious weeds did not change as a result of the compost amendment. Our results suggest that a single application of composted organic matter used to sequester C provided cobenefits to grassland plant dynamics. The compost amendments produced sustained increases in plant productivity and forage production as well as plant N content without greatly affecting the diversity of these exotic annual grasslands.

Key words: annual grasslands; carbon sequestration; *Carthamus lanatus*; compost amendment; diversity; *Elymus caput-medusae*; grazing lands; Mediterranean climate.

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INTRODUCTION

Grasslands provide a multitude of ecosystem services, including forage production for live-stock grazing, soil carbon (C) sequestration, and

floristic diversity (Sala and Paruelo 1997, Herrero et al. 2009, Huntsinger and Oviedo 2014). There has been appreciable interest in managing rangelands for C sequestration as a climate change mitigation strategy (Betts 2003, Conant et al.

2011, Dean et al. 2012, DeLonge et al. 2013, Derner and Schuman 2007, Lipper et al. 2010, Morgan et al. 2010, Ryals and Silver 2013, Smith 2004, Srivastava et al. 2012). The addition of composted organic material has been recommended as strategy to sequester C in managed grasslands (Ryals and Silver 2013, Haden and De Gryze 2014). Organic matter additions to grasslands have been shown to stimulate net primary production and lead to ecosystem C sequestration (Eghball and Power 1999, Ippolito et al. 2010, Kowaljow et al. 2010, McFarland et al. 2010, D'Hose et al. 2012, Powlson et al. 2012, Ryals and Silver 2013, Ryals et al. 2014). Yet, few studies have explored potential trade-offs or cobenefits associated with management strategies that promote C sequestration (Olander et al. 2012).

Grassland plant communities of the far western USA are dominated by exotic annual grasses. These ecosystems have undergone major changes in plant community composition due to intensive grazing, severe drought, and the introduction of species from European Mediterranean regions in the 19th century (Bartolome et al. 2007a). Perennial grasses are thought to have dominated wetter coastal regions, and annual forbs may have dominated the drier foothill regions prior to species introductions (D'Antonio et al. 2007). Introduced annual grass species were opportunistic and thrived in resource-pulse-driven environments. These invasibility traits led to their persistence and altered nutrient cycling that prevent establishment or recovery of perennial grasses (D'Antonio et al. 2007). In more recent decades, secondary invaders have spread throughout exotic annual plant communities and comprise the economic viability of rangelands by reducing forage production and nutritional quality (Norton et al. 2007).

Two prominent species of aggressive secondary invaders of grasslands in the western USA are *Carthamus lanatus*, an annual forb (common name: woolly distaff thistle), and *Elymus caput-medusae*, an annual grass (common name: medusahead; previously *Taeniatherum caput-medusae*). The grass species *E. caput-medusae* is an abundant, aggressive competitor. It is fast growing and produces a thick thatch layer that slowly decomposes due to its high silica content (DiTomaso et al. 2008, Hironaka 1994). While it has adapted to germinate in its own thatch, the germination and survival of

other plant seeds is inhibited by lack of light, inability to reach the soil surface, and immobilization of nutrients caused by the thick thatch layer (Kyser et al. 2014). Reduction of plant diversity and subsequent impacts on ecosystem function are severe with the invasion of *E. caput-medusae*. It is also a low-quality forage for cattle and other grazers (Young et al. 1969, 1971). The high silica content and stiff, spiny awns of *E. caput-medusae* foliage make it relatively unpalatable to grazing animals (Kyser et al. 2014). For these reasons, *E. caput-medusae* is classified as high impact and a serious risk to native ecosystems by the California Invasive Plant Council (www.cal-ipc.org) and classified as a noxious weed (List C) by the California Department of Food and Agriculture (www.cdffa.ca.gov).

The forb, *C. lanatus*, also poses threats to grassland plant communities. Like *E. caput-medusae*, *C. lanatus* produces a thick, persistent thatch layer that can severely alter the structure and function of grassland ecosystems (Cal-IPC 2015). Although it has adequate forage nutrition for grazing animals, *C. lanatus* is a problematic forage. When mature, the tall and spiny structure of *C. lanatus* can cause mouth ulcerations, penetrate hooves, and limit mobility of grazing animals (Kessler 1987). Common management includes treatment with herbicides to prevent competition with other forages and to eliminate physical obstructions that restrict cattle movement. *C. lanatus* is classified as moderate impact and a serious risk to native ecosystems by the California Invasive Plant Council and classified as a noxious weed (List B) by the California Department of Food and Agriculture.

Nutrient inputs may change species diversity and the abundance of noxious weeds (DiTomaso 2000, Lemaire 2012). Excessive loading of inorganic N to grassland ecosystems has been identified as a primary mechanism responsible for the overall loss of plant species (Stevens et al. 2004, Bobbink et al. 2010, De Schrijver et al. 2011) and increased abundance of invasive species (Young et al. 1998, DiTomaso 2000, Corbin and D'Antonio 2004a, Blumenthal 2005, D'Antonio et al. 2007). Noxious plant species decrease the sustainability of rangelands (DiTomaso 2000) and generally reduce the capacity of these ecosystems to provide other goods and services (Masters and Sheley 2001). Inorganic N inputs can drive plant

invasions and reduce diversity (Clark and Tilman 2008), but it is not clear whether the effects are the same for composted organic N inputs. Composted organic matter releases N slowly due to slow N mineralization and decomposition (Ryals et al. 2015). Recent work suggests that the form of N addition plays a key role in the response of plant invasions (Borden and Black 2011).

The application of composted organic material has been proposed as a means to increase plant production and sequester C in rangelands (Cabrera et al. 2009, Ippolito et al. 2010, Powlson et al. 2012, Ryals and Silver 2013), and reduce greenhouse gas emissions by diverting organic waste from landfills (DeLonge et al. 2013). Compost amendments release N gradually over several years (Ryals and Silver 2013), which has the potential to increase mineral N availability for both current annual grass communities and invasive species. Compost amendments also provide phosphorus and other nutrients, increase soil water holding capacity, and increase the fraction of recalcitrant soil organic matter content. In restoration studies, recalcitrant C amendments (commonly sawdust) have been used to immobilize N, thereby increasing competitiveness of native grass species (DiTomaso 2000, Corbin and D'Antonio 2004b, Perry et al. 2010, Mitchell and Bakker 2011).

The impact of compost amendments on grassland plant diversity, forage production, and forage nutritional quality are not well known, but critical for understanding trade-offs between rangeland C sequestration and economic sustainability of grasslands managed for grazing. The objective of our research was to determine the impacts on plant dynamics in two grassland ecosystems that were managed for C sequestration. We investigated the effects of compost amendment on plant production and N content. We hypothesized that grasslands would be resistant to shifts in community composition and increases in the abundances of secondary invaders, *C. lanatus* and *E. caput-medusae* following compost amendment.

MATERIALS AND METHODS

Study sites

The study was conducted on valley grasslands at the University of California Sierra Foothill

Research and Extension Center (Browns Valley, California, USA; 39.2° N, 121.3° W) and on privately owned coastal prairies (Nicasio, California, USA; 38.1° N, 122.7° W). Annual rainfall amounts at the valley grassland during experimental years were 380, 641, 843, and 549 mm/yr, compared to a 22 yr mean of 720 mm/yr. At the coastal prairie, annual rainfall was 771, 1050, 1163, and 778 mm/yr, compared to a 38 yr mean of 950 mm/yr. Mean air temperatures range from 2 °C in January to 35 °C in July at the valley grassland and from 6 °C in January to 20 °C in July at the coastal prairie. Valley grassland soils are xeric inceptisols and alfisols in the Auburn-Sobrante complex. Coastal prairie soils are mollisols in the Tocaloma-Saurin-Bonnydoon series. Soil texture was similar at both sites with mean percentages of clay, silt, and sand of 16%, 41%, and 43% (Ryals et al. 2014).

Experimental design

Field experiments at each site were established in October 2008 and continued for four growing seasons to September 2012. Treatments consisted of untreated controls and one-time additions of composted organic matter. Plots were 25 × 60 m buffered by a ≥5-m strip arranged in three randomized complete blocks at each site. The compost amendment treatment consisted of a single application of commercially available composted organic green waste (Feather River Organics, Marysville, California, USA) with a N concentration of 1.87% and a C:N ratio of 11. Compost was applied as a thin surface dressing approximately 1.3 cm thick, equivalent to 1.42 kg·C·m⁻², 129 g total N·m⁻², and 7.0 kg-dry matter·m⁻², in December 2008. Compost was free of contamination by weeds, seeds, and pathogens, according to U.S. Composting Council Seal of Testing Assurance program.

Grazing management

Both sites were grazed by cattle at a medium intensity using rotational grazing to achieve site-recommended residual dry matter (RDM) levels. Cattle grazed during the spring for up to 4 weeks, depending on the amount of standing forage. Valley grassland plots were grazed February through March, while coastal prairie

plots were grazed later in the growing season, ranging from mid-April through mid-June. A minimum of 84 g/m² of standing biomass was left after grazing. Fields were grazed again in September prior to the fall rains to achieve RDM levels of 130 g/m² at the valley grassland and 170 g/m² at the coastal grassland. Treatment plots were situated in grazing paddocks approximately 15 ha in size. During grazing, cattle were not isolated within plots, but instead allowed to graze the entire paddock. Herd sizes ranged from 60 to 100 head of mature cows during each grazing event.

Measurements of aboveground biomass and nitrogen content

Aboveground plant biomass was measured within 24 h prior to grazing events and within 24 h following grazing. These measurements served as an indication of standing biomass (before grazing), biomass consumed (before grazing—after grazing), and grazing intensity (after grazing). Aboveground biomass was determined by clipping vegetation to the soil surface from a 200 cm² area ($n = 9$ per plot). Biomass samples were then dried at 65 °C and weighed. We estimated the amount of plant biomass consumed by cows as the difference between pre-grazed and post-grazed biomass using plot averages. We used error propagation to determine standard errors of the means of biomass consumed. The amount of RDM was determined as the amount of standing dead biomass after fall grazing.

Total plant N concentration and content was measured as an indices of N inputs in these annual grasslands; they also served as indicators of forage nutritional quality because crude protein, a commonly used index, is directly proportional to plant N (Stokes and Prostko 1998). Nitrogen concentrations were measured on biomass samples collected <24 h prior to grazing events. Biomass samples were ground finely using a ball mill and analyzed for N concentration with an elemental analyzer (Carlo Erba Elantech, Lakewood, New Jersey, USA). Nitrogen content of aboveground biomass was determined by multiplying N concentration of each biomass sample by its mass and expressed in units of mass per area. We recognize that plants harvested at early growth stages generally have higher plant N

content than mature plants harvested at flowering stages (Stokes and Prostko 1998). Due to differences in the timing of grazing, we compared treatment effects on N concentrations within sites and did not compare between sites.

Measurements of plant diversity and abundance

Plant diversity indices were estimated from annual vegetation surveys at the end of each growing season from 2009 to 2012. Vegetation surveys were conducted using both point intercept and cover class methods, as the effectiveness of each is often dependent on vegetation structure (McCune and Grace 2002, Kercher et al. 2003). Two 40-m transects were set diagonally in each plot. For the point intercept method, a pin was placed every 0.5 m along each transect. All individuals touching the pin were identified to the species level. Each individual was only recorded once per pin. Relative cover of each species was calculated as the number of times a species was recorded divided by the number of points. Species richness was determined as the number of unique species identified from all pin points. Cover classes were determined according to the Daubenmire subplot method (Daubenmire 1959). A 1 × 1 m quadrat was placed at every 8 m along each transect, for a total of 10 Daubenmire subplots per treatment plot. Within each Daubenmire subplot, percent cover per square meter was visually estimated into one of seven categories: 0%, <1%, 1–5%, 5–25%, 26–50%, 51–75%, 76–100%. Relative percent cover was averaged across subplots using the midpoint value for each category. Cover estimates were then used to calculate evenness values for each treatment plot based on the Shannon Index (McCune and Grace 2002). Species richness was determined as the number of unique species per 1 m² averaged across subplots for each treatment plot (Hurlbert 1971).

In addition to the community survey, we examined treatment effects on two invasive weed species that pose risks to the productivity and ecological status of rangelands in the western USA. At valley grasslands, the grass species *E. caput-medusae* is an aggressive competitor. *E. caput-medusae* was already present and in relatively high abundance (~30–40%) at our field site prior to the establishment of the experiment, like

many similar ecosystems throughout California. At the coastal prairie, the noxious forb, *C. lanatus*, was also present prior to and during the time of the experiment. Neither site contained both species. We monitored the changes to the relative abundance of *E. caput-medusae* and *C. lanatus* using cover class data for 4 yr following the single compost addition.

Statistical analysis

Analysis of variance (ANOVA) was used to assess the effects of compost amendment on these diversity indices as well as aboveground biomass, biomass consumption by cows, and aboveground plant N content and concentration. Treatment was used as a fixed-effect and block as a random factor. Sites were analyzed separately because grazing at each site occurred at different stages of plant growth. Biomass and plant N variables were log-transformed to achieve normality and homoscedasticity. We tested the effects of treatment, year, and the interaction between treatment and year on these variables using repeated-measures ANOVA (MANOVA).

To evaluate treatment effects on the relative abundance of individual plant species, we calculated the log response ratio (Hedges et al. 1999, Stein et al. 2010) for each plant species as

$$\ln \text{RR}(i) = \ln \frac{C_{\text{treatment}}(i)}{C_{\text{control}}(i)}$$

where $\text{RR}(i)$ is the response ratio of cover of each species (i). The terms $C_{\text{treatment}}$ and C_{control} are the average species' cover in the treatment and control plots, respectively. Log response ratios were calculated separately for each block and reported as block mean \pm 1 SE. Sites were analyzed separately. Species that occurred in $\geq 8\%$ of plots within each site were included in this analysis (e.g., 13 species at the valley grassland and 19 species at the coastal prairie). This assessment included species that accounted for $99\% \pm 1\%$ and $88\% \pm 1\%$ of the relative abundances at the valley grassland and coastal prairie, respectively. Greater cover of a species in compost plots relative to control plots is represented by positive $\ln\text{RR}$ values, whereas negative $\ln\text{RR}$ values indicate less cover in compost plots relative to controls. For this analysis, we present data only from

cover class vegetation surveys because results did not depend on sampling method.

Analyses were performed using either 11.0.0 JMP software (SAS, Cary, North Carolina, USA) or R version 2.15.1 (The R Foundation for Statistical Computing, Vienna, Austria). Statistical significance was determined as $P < 0.05$ unless otherwise noted. Data are reported as mean \pm 1 SE and plotted separately for each site.

RESULTS

Effects of compost addition on aboveground biomass production, nitrogen, and residual dry matter

Significant treatment differences in grazed aboveground biomass were detected at both grassland sites within the first year following the compost application (Fig. 1). The positive response of biomass production in plots receiving compost amendments persisted throughout the 4-yr study. Plots that received compost amendments had $76\% \pm 21\%$ and $41\% \pm 21\%$ (block mean \pm 1 SE) more aboveground biomass prior to grazing than control plots at the valley grassland and coastal prairie, respectively ($P < 0.05$ at each site). Treatment effects did not appear to be dependent on rainfall (no year \times treatment interaction), and rainfall conditions ranged widely throughout the years of the experiment. At the time of grazing, composted plots contained an average of 100 ± 16 and $128 \pm 6 \text{ g}\cdot\text{m}^{-2}\cdot\text{y}^{-1}$ more aboveground biomass in the valley grassland and coastal prairie, respectively.

Aboveground biomass measured immediately after grazing events provided an indication of grazing intensity. For most years, the amount of aboveground biomass left standing immediately after grazing events did not differ between treatments (Fig. 1). At the valley grassland, cows consumed an average of $136 \pm 6 \text{ g}\cdot\text{m}^{-2}\cdot\text{y}^{-1}$ more forage from compost relative to control plots (Fig. 2; $P < 0.0001$) for both treatments and all years. During the last 2 yr of the study, control plots had approximately 40% more standing biomass compared with composted plots. At the coastal prairie, biomass consumed by cows did not differ significantly between treatments (Fig. 1), nor were there significant differences in the amount of standing biomass left after spring grazing. At both sites, there was no treatment difference in

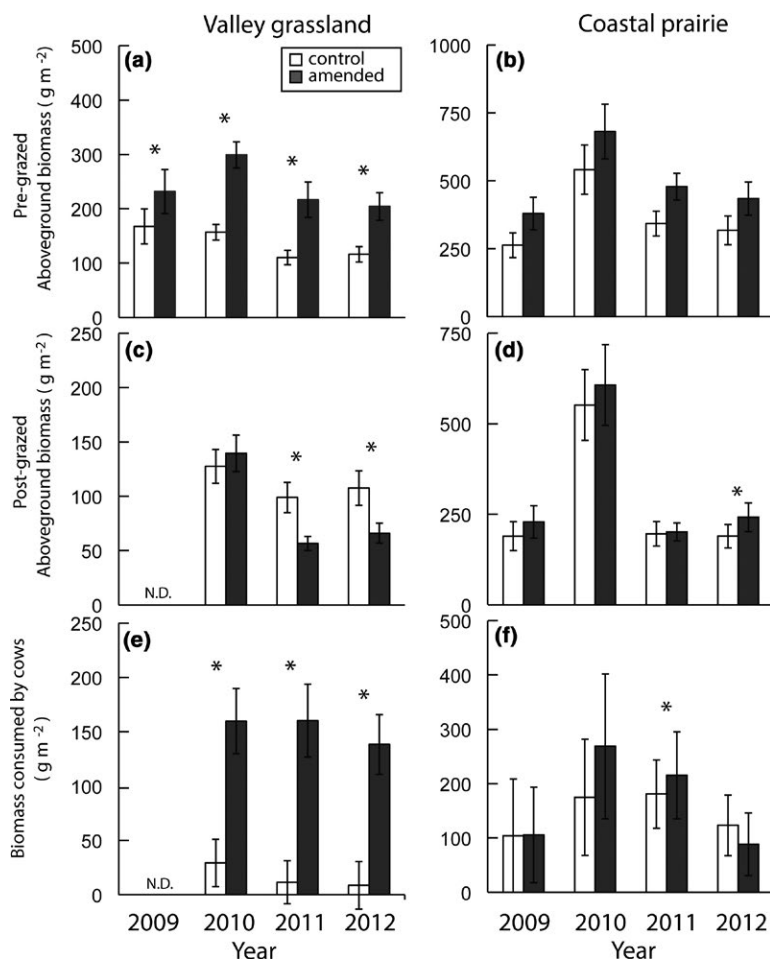


Fig. 1. Dry weight of standing biomass prior to grazing event (a, valley grassland; b, coastal prairie) and <24 h after grazing event (c, valley grassland; d, coastal prairie) from compost-amended and control treatment plots. The amount of forage consumed by cows (e, valley grassland; f, coastal prairie) was calculated as the difference between pregrazed and postgrazed biomass. Bars are block mean \pm 1 SE. Asterisks indicate significant differences at $P < 0.05$. N.D. indicates no data collected.

the amount of standing biomass after fall grazing. The average fall RDM levels were 130 g/m^2 at the valley grassland and 170 g/m^2 at the coastal prairie. There was not a significant treatment differences at either site.

Compost amendments significantly affected plant N content. For compost treatments, plant N content of pregrazed biomass was significantly greater at both sites for all 4 yr of the study (Fig. 2). At the valley grassland, aboveground biomass N in compost-amended plots increased by $8.0 \pm 1.2 \text{ g-N}\cdot\text{m}^{-2}$ over 4 yr, equivalent to an increase of $89\% \pm 6\%$ each year ($P < 0.001$). At the coastal prairie, aboveground plant N con-

centration increased by $5.7 \pm 1.1 \text{ g-N}\cdot\text{m}^{-2}$ over 4 yr or by $44\% \pm 10\%$ each year ($P < 0.05$). The effect of compost amendments on aboveground plant N concentration was not consistent. At the valley grassland site, vegetation from composted plots had higher N concentration than control plots during year 1 ($P < 0.0001$) and 4 ($P < 0.10$). At the coastal prairie site, plant N concentrations were greater in composted relative to control plots in year 2 ($P < 0.05$) and slightly lower in year 3 ($P < 0.10$). The interaction between treatment and year was significant at $P < 0.10$ for N concentrations at both grassland sites. However, the response of plant N content did not depend on

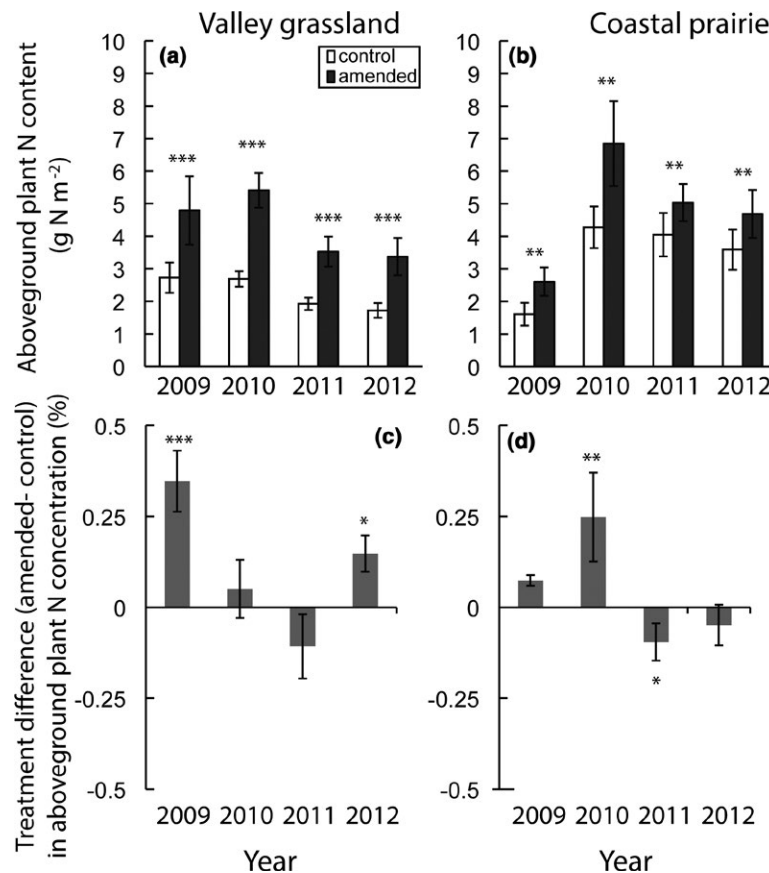


Fig. 2. Plant N content (a, valley grassland; b, coastal prairie) and treatment difference in plant N concentration (c, valley grassland; d, coastal prairie) immediately prior to grazing events from control and amended plots. Error bars are ± 1 SE. Asterisks indicate significance. * $P < 0.10$; ** $P < 0.05$; *** $P < 0.0001$.

time and showed consistent increases across all 4 yr of the study, suggesting a strong effect of biomass gain on these trends.

Effects of compost addition on plant diversity and species composition

Species richness at the coastal prairie was slightly greater than that of valley grassland by 1.82 ± 0.28 species m^{-2} , averaged across all treatments and years ($P < 0.05$). Overall, species richness and evenness of vegetation communities at both grassland sites were relatively resistant to compost additions (Fig. 3). Species richness or evenness did not differ by treatment at the valley grassland. At the coastal prairie, species richness and evenness during year 1 were significantly greater in the composted plots ($P < 0.05$). There was a significant effect of

year and a year by treatment interaction for evenness ($P < 0.0001$) and a significant effect of time for species richness ($P < 0.0001$) at both sites.

Both grassland types were dominated by non-native annual grasses and forbs, which is typical of most rangelands in California (Bartolome et al. 2007a). The relative abundance of two noxious species of concern did not vary with compost addition (Fig. 4). At the valley grassland, the exotic annual grass, *E. caput-medusae*, was the second most abundant grass species after *A. barbata*. The average relative abundance of *E. caput-medusae* was approximately 30% and did not differ between treatments, except for the third year when the relative abundance of *E. caput-medusae* was 13% greater in the control plots than composted plots ($P < 0.05$). At the coastal prairie, the

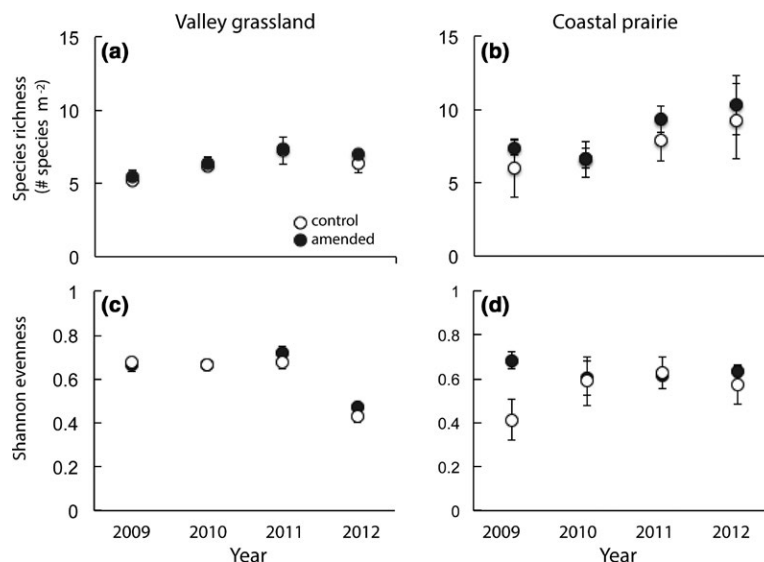


Fig. 3. Plant species richness (a, valley grassland; b, coastal prairie) and Shannon evenness index (c, valley grassland; d, coastal prairie) in control and amended plots. Symbols are block mean \pm 1 SE. Asterisks indicate significance at $P < 0.05$.

relative abundance of invasive thistle, *C. lanatus*, was <4% and no treatment effect was detected (Fig. 4). Analysis of log response ratios (lnRR) of *E. caput-medusae* and *C. lanatus* showed similar patterns.

We analyzed the compost treatment effect (lnRR) of the 13 and 19 most common species at the valley grassland and coastal prairie, respectively (Fig. 5). Increases, decreases, and no changes to individual species abundance were observed at both sites. At the coastal prairie, there were no major shifts in the plant communities regarding taxonomic placement or life-history strategy. Compost amendments significantly increased four grasses (*Festuca perennis*, *Vulpia bromoides*, *Bromus diandrus*, and *Bromus carinatus*), one forb (*Geranium dissectum*), and one legume (*Medicago polymorpha*) species and decreased one grass (*Avena barbata*) and one forb (*Hypochaeris glabra*) species. Additionally, compost increased the number of rarely occurring species at the coastal prairie (Fig. 6). There were 16 additional forb and grass species that occurred in less than 5% of the observations of composted plots that were never observed in control plots over the 4-yr study period. In contrast, we observed a shift in the abundance of forbs and grasses at the valley grassland. Here,

compost amendments significantly increased three grass species (*F. perennis*, *B. diandrus*, and *Hordeum murinum*) and decreased the abundance of two common forbs (*Erodium botrys* and *Sanicula bipinnatifida*) and one bulb (*Dichelostemma capitatum*). At both grassland types, the largest treatment responses were observed from species of low to mid abundance.

DISCUSSION

Effects of compost addition on biomass production

Aboveground biomass measured just before the first grazing event (3–5 months after compost applications) was $52\% \pm 41\%$ (coastal) and $38\% \pm 21\%$ (valley) greater in plots receiving a compost amendment. Most rangelands are N-limited or colimited by N and water (Harpole et al. 2007). Compost is a source of N and generally increases soil water holding capacity (Gagnon et al. 1998, Ryals and Silver 2013), both of which likely drove the responses observed in this study. Notably, increased biomass production was sustained throughout 4 yr with no apparent signs of diminishing, despite a wide range in annual rainfall (380–843 mm/yr at the valley grassland and 771–1163 mm/yr at the coastal prairie). This result indicates

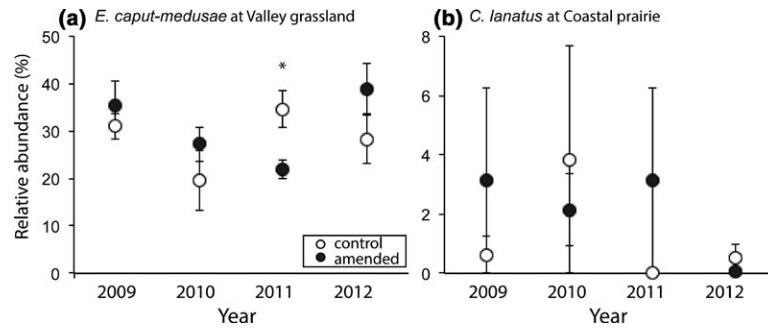


Fig. 4. Relative abundances of (a) *E. caput-medusae* at the valley grassland and (b) *C. lanatus* at the coastal prairie for 4 yr in amended and control plots. Symbols are treatment means and error bars are ± 1 SE. Asterisks indicate significance at $P < 0.05$.

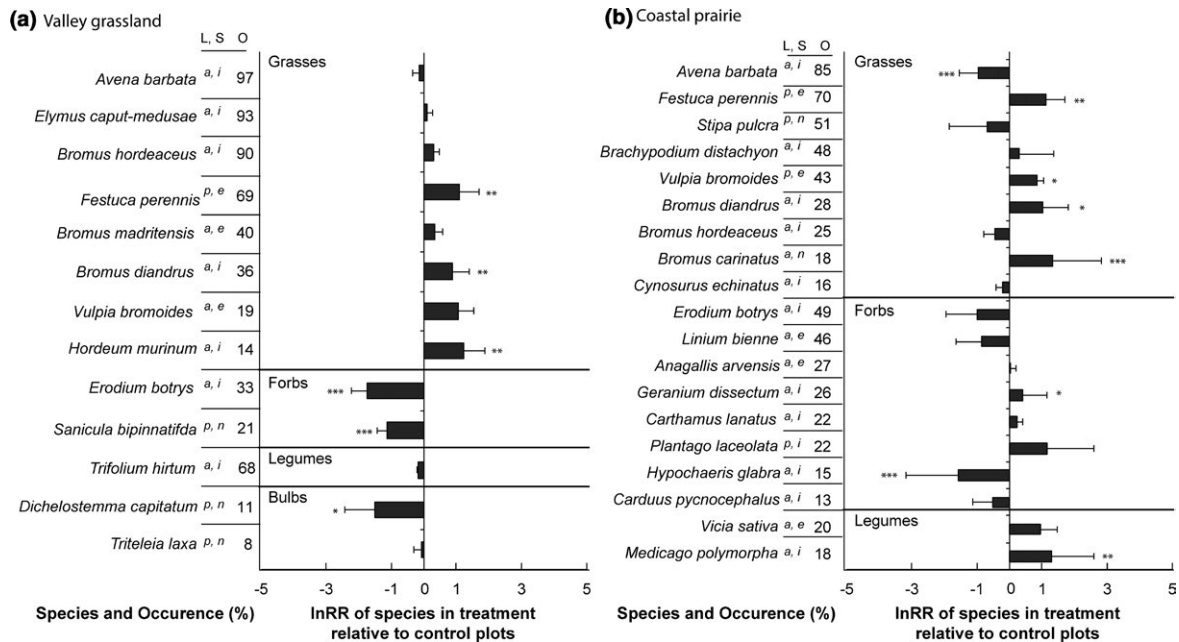


Fig. 5. The influence of compost amendment on the percent cover of plant species with $>10\%$ occurrence (O) across all site observations at the (a) valley grassland and (b) coastal prairie. Species are grouped by functional type (grasses, forbs, legumes, and forbs). Lifecycle (L) indicates annual (a) or perennial (p). Status (S) indicates ecological impact as designates by CalFlora, as native (n), invasive (i), or exotic (e). Bars are paired plot treatment means of the log response ratios (lnRR) averaged over 4 yr. Positive values indicate that the relative cover of a plant species increased due to treatment. Negative values indicated a reduction of species cover. Error bars are ± 1 SE. Asterisks indicate significant difference from 0, where $*P < 0.05$, $**P < 0.01$, and $***P < 0.0001$.

that treatment effects did not depend strongly on rainfall or other environmental conditions of a given year. This carryover effect can likely be attributed to the nature of compost acting as a slow release fertilizer (Claassen and Cary 2007) that elevated plant-available nutrients

and soil water holding capacity for several years following application (Gerzabek et al. 1997, Blair et al. 2006, Ryals and Silver 2013).

We did not observe a treatment effect on the amount of RDM left standing after fall grazing, even though grazing animals were managed at

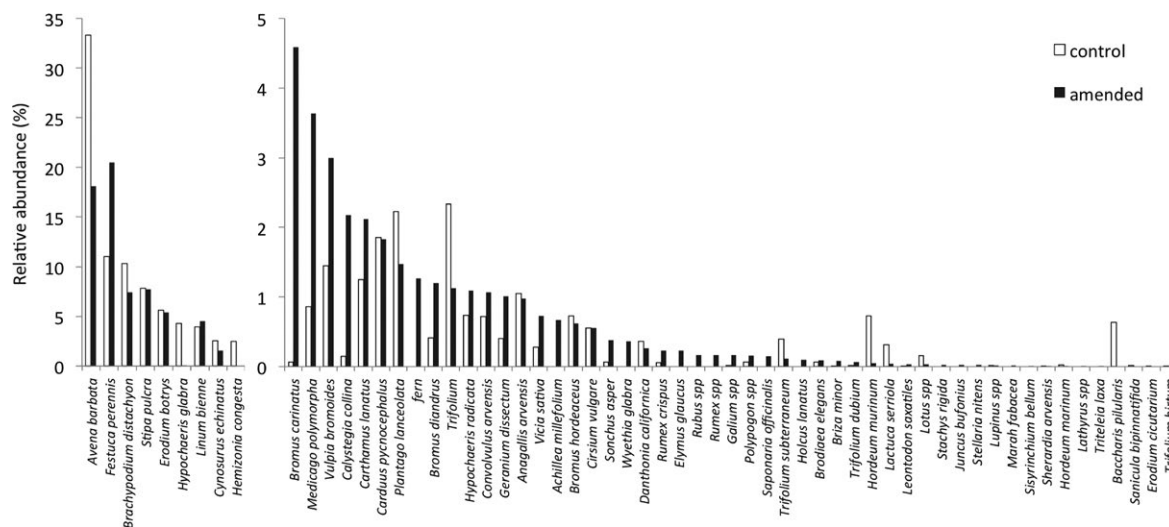


Fig. 6. Relative abundances of all species occurring at the coastal prairie. Bars are mean values of all 4 yr of individual species from control (white bars) and compost-amended (black bars) plots.

the larger paddock scale. The manipulation of RDM is a widely used management tool used in grasslands in Mediterranean climates (George et al. 1996). The mulching effect from RDM has been shown to influence plant production and species composition in the subsequent year (Bartolome et al. 2007b). The addition of compost to grasslands can have similar effects as RDM management with the exception that compost provides a more concentrated source of nutrients than RDM and more recalcitrant organic matter. The amount of RDM at the valley grassland was slightly higher than the recommended minimum for annual grasslands with slopes <40% and no woody cover of 56–78.5 g/m² (Bartolome et al. 2006) but on target for the site-specific grazing management plan (D. Flavell, *personal communication*). The RDM levels at the coastal prairie were within the recommended minimum range for coastal prairies with slopes <40% and no woody cover of 134–202 g/m² (Bartolome et al. 2006). In the absence of grazing, the increase in plant production would have led to higher RDM levels with the compost amendment.

Effects of compost addition on plant nitrogen

The N content of plants increased following a single compost application, and the effect persisted for all 4 yr of the study. Plant N content increased compared to control plots by 44% and 89% at coastal prairie and valley

grassland, respectively. A similar result was reported following the application of composted biosolids to disturbed perennial grasslands (McFarland et al. 2010). Aboveground plant N concentration responded positively in most years at the valley grassland and showed variable responses at the coastal prairie. The interaction between treatment and year for N concentrations at both grassland types suggests that treatment responses depend somewhat on conditions within a given year. Thus, the large positive response of plant N content availability is largely driven by large and sustained increases in aboveground biomass, rather than changes in plant N concentration. These long-lasting increases in plant production and N content have positive implications for improving rangeland sustainability by decreasing dependency on forage supplements (DeLonge et al. 2013) and by buffering the impacts of high interannual variability in plant production during drier years. Increases in plant N content correspond directly to increases in crude protein, a common index used by specialists to assess nutritional quality of forage (Stokes and Prostko 1998, McFarland et al. 2010). During unfenced rotational grazing events at the valley grassland, cows consumed an average of 136 g·m⁻²·y⁻¹, or 450%, more forage from composted compared to control plots. However, the amount of standing biomass left after grazing

was similar or slightly less on composted plots. Similar, albeit more variable, trends were observed at the coastal prairie where grazing events occurred toward the end of the growing season.

Effects of compost amendment on plant diversity and secondary invaders

External nutrient inputs can be important drivers of changes to species diversity and community composition in most grassland ecosystems (Faust et al. 2012). The Mediterranean and Eurasian annual grasses that dominate California's rangelands are aggressive competitors of native perennial grasses and thrive in the resource-pulse-driven semiarid conditions (Norton et al. 2007). The impacts of grassland management practices that alter nutrient cycling on vegetation communities in these heavily invaded grasslands are not well known.

Extensive research has explored the role of inorganic N inputs on species loss in terrestrial ecosystems worldwide (Foster and Gross 1998, Samuel and Hart 1998, Stevens et al. 2004, Clark and Tilman 2008, Cole et al. 2008, Bobbink et al. 2010). Most of these studies used natural N deposition gradients or experimental inorganic N additions. Observed increases in biomass production with inorganic N additions are generally accompanied by declines in species richness (Tilman 1993) and increases in fast-growing weedy invasive species (Davis et al. 2000), although results of empirical studies have varied (Clark et al. 2007). In contrast, our results and results from composted biosolid amendments (Borden and Black 2011) show that organic N inputs do not drive plant invasions or reduce diversity.

We hypothesized that the grasslands in our study, which are dominated by exotic annual species, would be relatively resistant to shifts in community composition with a one-time compost amendment. Compost slowly releases N and increases storage of C and N in physically stable soil organic matter pools (Ryals et al. 2014). Species richness varied significantly over the 4-yr study, but showed little effect of compost amendments. The abundance of native species did not change, and the overall species composition remained similar at each site over time.

We found that the abundances of a few individual grass and forbs species responded either positively (e.g., *F. perennis* and *B. diandrus* at both sites) or negatively (e.g., *D. capitatum* at the valley grassland and *H. glabra* at the coastal prairie) to compost amendments, but compost application did not lead to major shifts in dominant plant functional types at either grassland site. Intermediate levels of RDM management (within the range of our study) slightly increased grass cover and slightly decreased forb cover in similar Mediterranean grasslands (Bartolome et al. 2007b). It is important to note that our study included grazing animals that reduced the amount of RDM. Higher levels of RDM common in ungrazed valley grasslands have the potential to significantly increase grass cover at the expense of forbs and overall plant diversity (Bartolome et al. 2007b). Therefore, compost can be a powerful management tool to increase plant biomass production without adversely affecting plant communities especially if combined with RDM management via grazing or other approaches.

Plant communities at our sites were strongly dominated by just a few species. At the valley grassland, two exotic annual grass species (*A. barbata* and *B. hordeaceus*) and one noxious annual grass species (*E. caput-medusae*) comprised three-quarters of the total plant cover. The dominance of these grasses was unaffected by compost addition. At the coastal prairie, the three dominant species comprised half of the total plant cover and included an invasive annual grass (*A. barbata*); an exotic, perennial grass (*F. perennis*); and a native, perennial grass (*S. pulchra*). While these three species remained dominant in both compost and control plots, there was a significant decline in the abundance of the annual *A. barbata* and a reciprocal increase in the abundance of the perennial *F. perennis*. It is also interesting to note that a greater number of rarely occurring forb and grass species were observed in compost-amended plots at the coastal prairie. The implication of these subtle shifts in annual grassland communities on ecosystem structure and function is not well known. Our results are contrary to studies of composted biosolid application to a semiarid shortgrass steppe grassland, which demonstrated increases in perennial grass cover (Sullivan et al. 2006, Ippolito et al. 2010), but in agreement with findings that composted

biosolid application did not change vegetation communities in a rangeland dominated by invasive species (McFarland et al. 2010).

Aboveground biomass in composted plots increased without reducing species diversity over 4 yr. Compost amendments did not considerably alter the abundance of the secondary invaders that threaten the resiliency of these grassland communities (Dahl and Tisdale 1975, DiTomaso 2000). At the coastal prairie, no treatment differences in *C. lanatus* abundance were detected over the 4 yr, but long-term effects are unknown. *C. lanatus* has large seedbanks that can persist in the soil for up to 10 yr (Sindel 1997, Grace et al. 2002), and some studies report a lag in shifts in grassland communities up to 9 yr (Faust et al. 2012). Seeds of *E. caput-medusae* are highly adapted for germination in the litter layer. At the valley grassland, the prevalent noxious annual grass, *E. caput-medusae*, was widespread but was not affected by the compost addition. There is evidence that *E. caput-medusae* invasion increases with N enrichment (Dahl and Tisdale 1975, Blank and Sforza 2007) and decreases with labile C additions (Young et al. 1998).

We did not observe the introduction of plant species that were previously undocumented at the sites. Thus, we infer that the plant seeds and weeds were destroyed during the composting process. There remains a risk of new plant introductions from compost additions if seeds persistent in finished compost. In the case of commercially processed compost, as the type used in this study, this risk is minimized due to controlled composting conditions, testing, and independent certification from agencies such as the U.S. Composting Council. Uncertified or on-farm composting facilities should maintain high temperature during composting to ensure weed seed mortality.

Management implications

Our results have important implications for the management of multiple ecosystem services and diversity in annual grasslands. It is often assumed that conventional rangeland management practices have minimal importance in regulating ecosystem processes compared to abiotic constraints (Jackson and Bartolome 2007). Amending rangelands with compost is a relative new approach, and the impact of

its use on grassland communities is not well known. Contrary to the general assumption from conventional practices, our data from two rangeland types suggests that a single compost addition can enhance several ecosystem services consistently through time. These results suggest that compost amendment to rangelands may provide ecosystem services, including C storage and enhanced forage production, without adversely altering plant communities.

Monitoring changes in aboveground biomass, plant N, and vegetation community structure associated with management are necessary to determine the magnitude of these key trade-offs or cobenefits of rangeland C sequestration strategies. We found that a one-time compost amendment greatly increased aboveground biomass and N content at both grassland types for 4 yr. Secondary invasive plant species of concern in the region did not increase with the addition of compost. The lack of major shifts in vegetation or prolonged responses of noxious species suggests that there are few trade-offs between C sequestration and plant diversity in these grasslands. Compost amendment, combined with site-specific RDM management practices, can be a powerful management tool for increasing forage production and sequestering carbon without directly impacting the plant communities of valley grasslands or coastal prairies.

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