

NUTRIENT INPUT EFFECTS FROM FIRE
RETARDANT ON EXOTIC SPECIES, SPECIES
RICHNESS, AND SPECIES DIVERSITY IN A
COASTAL CALIFORNIA GRASSLAND.

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Abstract

California grasslands have undergone an extensive transformation in floristic composition over the past 250 years. Introduced species have spread widely, largely replacing native annuals and perennials. Nutrient inputs, such as fertilizers and atmospheric deposition, have been found to facilitate invasion of grasslands by introduced species, as well as cause declines in species richness and species diversity. It has been hypothesized that an ammonium-phosphate-based fire retardant, Phos-Chek, commonly used to combat wildfires in backcountry areas, may be a substantial source of nutrient inputs when applied to grasslands. This hypothesis is based on the fire retardant's composition as well as field observations following an application to a coastal California grassland. Exotic thistle species were found to respond vigorously and species richness and diversity appeared to decline. Based on the assumption that the Phos-Chek fire retardant acts as a nutrient input, the purpose of this study was to determine how the fire retardant impacts exotic species (specifically exotic thistle and exotic annual grasses), species richness, and species diversity in a coastal grassland in central California. While phosphate levels were not analyzed, this study found that the fire retardant significantly increased ammonium and nitrate levels in the soil, therefore providing essential nutrients for plants. The nutrient inputs resulted in increased growth of exotic annual grasses, but had no effect on exotic thistles. The increased exotic grass growth led to declines in short statured forbs, as well as declines in species richness and species diversity.

Introduction

Invasion and alteration of native plant communities by exotic plants is a growing conservation problem (Maron and Connors 1996). Invasive exotic species have had short-term effects on native grasslands, such as drastically altering fire cycles (D'Antonio and Vitousek 1992), nutrient cycling (Vitousek 1990), and wildlife forage quality (Trammell and Butler 1995). Invasive species are causing a decline in native plant species as well as ecosystem diversity (Stohlgren et al. 1999). Today's coastal California grasslands are a prime example of a native plant community that has been altered by the invasion of exotic species.

California grasslands have undergone extensive transformations in floristic composition with the addition of many invasive species over the past 250 years (Hatch et al. 1999). Prior to the 1770's the original grasslands are thought to have been dominated by perennial bunchgrasses, such as *Nassella* (Stromberg and Griffin 1996), *Danthonia*, and *Deschampsia* (Bartolome et al. 1986). Many European plants arrived in California during the 1770's and have since spread widely, largely replacing native annuals and perennials with introduced species (Hatch et al. 1999). These plants were either intentionally introduced as cereal or forage crops, or inadvertently introduced through impurities in crop seed and in packing material (Carlsen et al. 2000). Currently California grasslands are dominated by introduced Mediterranean annuals, such as *Erodium*, *Bromus*, *Hordeum*, *Hypochaeris*, and *Avena* (Stromberg and Griffin 1996). The success of introduced species in California grasslands has been attributed to a variety of mechanisms: 1) being superior competitors for water and light (Carlsen et al. 2000), 2) being superior colonizers of both artificial and natural disturbances (Parker et al. 1993), 3) effectively reducing the fecundity and seedling establishment of competing native species (Carlsen et al. 2000, Stromberg and Griffin 1996), 4) responding better to overgrazing by livestock than native species (Hatch et al 1999), and 5) responding more vigorously to nutrient inputs (Maron and Connors 1996).

Nutrient inputs into low nutrient native grasslands, whether in the form of fertilizer applications or atmospheric nitrogen deposition, have demonstrated negative effects that threaten conservation of native grasslands. Nutrient inputs have been shown to facilitate invasion of coastal grassland communities by exotic grasses and forbs (Maron and Connors 1996) by favoring fast-growing weedy species, which in effect reduce species richness (Kitajima and Tilman 1996) and species diversity (Vinton and Burke 1995).

Nutrient inputs can facilitate shifts in dominance toward weedier non-native species. This shift in species composition with nutrient addition can be mediated by a shift in the limiting resource. With the addition of nitrogen to low-nutrient environments, competition shifts from primarily root competition to primarily shoot competition, with fast-growing species that are better competitors for light dominating and slower-growing species that are better competitors for nutrients being suppressed (Wilson and Tilman 1995). In a 12-year study of nitrogen deposition in Minnesota grasslands, it was found that with the addition of nitrogen there were major shifts in plant composition, with slower growing species, such as native bunchgrasses, declining and fast-growing species, such as weedy annual Eurasian grasses, becoming dominant (Wedin and Tilman 1996). Nitrogen inputs from legumes, such as the nitrogen-fixing shrub, bush lupine, have been demonstrated to mediate a shift in vegetation in California coastal prairie from native species to weedy introduced grasses and forbs (Maron and Connors 1996). It was found that the total above ground live plant biomass was more than twice as great in dead lupine patches as in adjacent lupine free grassland, but that dead lupine patches contained 57% fewer native species. Maron and Connors suggest that bush lupines facilitated the invasion of the coastal prairie plant community by creating open patches with high levels of nitrate and ammonia once the lupines die. Introduced annuals, which they found to be superior colonizers in the open patches, are able to rapidly grow

with nutrient enrichment and become superior competitors for light (Maron and Connors 1996).

The shift toward fast growing weedy species caused by nutrient additions can result in a decline in species richness. Maron and Connors (1996) found that the species composition inside high nitrogen dead lupine patches contained 47% fewer plant species than in adjacent lupine free grassland. Thurston (1968) found that the addition of nitrogen to grassland fields stimulated the growth of all grasses but resulted in the suppression of all legumes, therefore decreasing species richness. Legume elimination in response to nitrogen has been found in many nutrient input studies (Huenneke et al. 1990, Mamolos et al. 1995, Thurston 1968, Woodmansee & Duncan 1980).

Species diversity, determined by a combination of species richness and abundance, has been shown to decrease with nutrient inputs due to shifts in dominance toward higher biomass accumulating species along with declines in species richness. Bobbink (1991) found that when nitrogen was added to chalk grasslands there was a strong increase in *Brachypodium*, which under low-nutrient conditions is usually limited by nutrient availability as well as by other components of the vegetation. The increased growth of *Brachypodium* led to the overtopping of most other species and therefore a decrease in lower forbs and graminoids. Over time Bobbink et al. (1988) found that there was a decrease in species diversity with increasing dominance of *Brachypodium*.

To explore the impact of nutrient inputs on exotic species, species richness, and species diversity, I studied the effects of nutrient addition from a fire retardant application in a California coastal grassland. Coastal grasslands experience the threat of wildfires and the control of these grassland fires is a primary focus for land managers. Application of fire retardant applied by aircraft is a common practice. One such fire retardant, Phos-Chek G-75F, consists of ammonium phosphate and ammonium sulfate; salts that provide nitrogen, phosphorus, and sulfur to plants (L. Vandersall, personal communication). Following a fire in October of 1999 at Landels-Hill Big Creek Reserve, a

grassland that received a fire retardant application but had not burned, produced dense populations of two exotic thistles, *Silybum murianum* (milk thistle) and *Carduus pycnocephalus* (Italian thistle), the following spring. The increase in thistle densities appeared to suppress the growth of other grass and forb populations (J. Smiley, *personal communication*, and Bio 169L at UCSC, *unpublished data*). Prior to the fire, *Silybum* and *Carduus* populations existed at low densities within the grassland (J. Smiley, *personal communication*). The population increase of *Silybum* and *Carduus* after the fire appeared to be in response to the fire retardant application.

The purpose of this study was to determine how ammonium-phosphate-based fire retardant impacts exotic species (specifically exotic thistle and exotic annual grass species), species richness, and species diversity in a coastal grassland in central California. I test the assumption that fire retardant addition increases soil levels of ammonium and nitrate, in addition to two related hypotheses. First, I hypothesize that if a fire retardant addition causes an increase in ammonium and nitrate in the soil and exotic weedy species respond more vigorously to these inputs (Maron and Connors 1996, Wedin and Tilman 1996), then both exotic thistle and grass populations will increase with the addition of fire retardant. Second, I hypothesize that if an increase in exotic thistle and grass populations, resulting from the fire retardant addition, suppress the growth of short statured forb species, then a decrease in species richness and species diversity will occur.

Materials and Methods

Study Site

Landels-Hill Big Creek Reserve is part of the UCSC reserves system and is situated on the central California Big Sur coastline, within the Santa Lucia Mountains. The reserve encompasses 4200 acres within Monterey County, and is approximately 45 miles south of Carmel and 55 miles north of Cambria on Ca.Hwy.1 (N36°04.205' W121°35.939'). The reserve includes extensive coastal

grasslands that are dominated by exotic annual grasses and forbs, with patches of native perennial grasses and forbs. I conducted the study beginning in December 2000 and ending in May 2001.

Field Experiment

The study plots were located within the coastal fog belt on south-facing slopes (ranging from facing 158°SE - 238°SW; elevation approximately 1200 feet) near Highlands Peak. Six grassland hillsides were chosen, based on the criterion that they had not recently burned nor received a fire retardant application. To study the impacts of fire retardant on exotic thistle species, I chose three hillsides that had high thistle densities (approximately 51,000 seedlings per hectare) and three hillsides with low thistle densities (approximately 3,000 seedlings per hectare with no seedlings within the plots). Within each of the six hillsides three pairs of study plots (each pair consisting of 2 1-m² plots with a 2 meter buffer zone in between, n = 18 paired plots), were randomly selected at approximately the same elevation on the slope to avoid nutrient leaching between the paired plots. For each paired study plot, the eastward plot was the control and the westward plot was the experimental plot.

I applied the fire retardant treatment (Phos-Chek G-75F) to experimental plots on January 21, 2001. This was the same fire retardant applied by aircraft in the Big Creek fire of 1999. The fire retardant is manufactured by ASTARIS LLC, out of St. Louis, MO (formerly Monsanto Co.) and was donated by ASTARIS LLC for the purpose of this study. The retardant was received in powder form and was mixed with water at a rate of 1.12 pounds per gallon. I applied the retardant in a continuous even coat with a hand-pumped 2-gallon fertilizer sprayer, at a rate of one quart per 2.25 square meters as recommended by the Phos-Chek Application Guide (Monsanto Co. 1993) for shortgrass fuel types. The vegetation was dry at the time of fire retardant application, due to a lack

of rain since 10 days prior to application and the first rain occurred 2 days after application.

Data Collection

To characterize each plot, I collected soil samples and analyzed them for ammonium and nitrate, collected data on plant composition and abundance, final plant biomass, and grass height. In order to assess changes in both soil nutrients and plant community characteristics caused by the application of fire retardant, I characterized each plot before treatment on January 13 & 14, 2001, one week after treatment on January 27, 2001 (plot characterization consisted only of collecting soil samples), eight weeks after treatment on March 17 & 18, 2001, and sixteen weeks after treatment at the end of the growing season on May 12 & 13, 2001.

Soil samples were collected from all 36 plots with a soil corer (depth 20 cm, volume 98.17 cubic cm). During each soil collection three soil samples were collected from each plot and homogenized together in an effort to create an accurate plot profile. Soil samples were kept cool until analyzed for inorganic nitrogen, within the first week of collection. I analyzed all soil samples in the soils lab at the Center for Agroecology and Sustainable Food Systems (CASFS), UC-Santa Cruz. Inorganic nitrogen, in the form of ammonium and nitrate, was extracted from wet soil with 2M KCl (Keeney and Nelson 1982). The extractant was analyzed with a Lachat autoanalyzer. The moisture content of all soil samples was determined by subtracting the soil dry-weight, after 24 hours of drying at 100°C, from the soil wet-weight. Using the moisture content of the soil samples, the resulting values of ammonium and nitrate found in soils were converted to reflect that which would be found per gram of dry soil.

The plant composition of each plot was determined by estimating the percent cover of each plant species within the plot. A 1-m² quadrat with a 100-square grid was placed over each plot and

the cover of each square occupied by a species was estimated, totaled for the whole grid, and converted into a percentage of the whole plot. Forbs were identified to species. Grasses were identified as either exotic annuals or native perennials, due to the difficulty of grass species identification in non-flowering seasons. Exotic annual grasses largely consisted of *Bromus diandrus* and *Avena barbata*, while the native perennial grasses largely consisted of *Nassella pulchra* and *Danthonia californica*. The exotic annual grasses were so abundant within the plots that their percent cover was determined by subtracting the sum of bare ground, forb, and native grass percent cover from the plot, thus making total cover equal to 100%. At the time of data analysis, with the exception of calculations of species richness and diversity (see below), all plant species were placed into three functional groups: exotic grass, exotic thistle, and non-thistle forbs. Due to their rarity and inconsistency within the plots, native grasses were dropped from analyses, except in estimations of exotic grass cover and calculations of species richness and diversity.

Species richness and Shannon-Wiener Diversity Indices were determined for each plot based on the data collected on plant composition and abundance. For these calculations I treated exotic annual grasses as a single group and native perennial grasses as a single group, while forbs were split into all component species. Species richness was determined by counting the number of grass groups and forb species present within each plot. The Shannon-Wiener Diversity Index (H') for each plot was determined by multiplying the percent cover of each grass group and forb species by its natural log and taking the negative sum of these factors for all species present:

Where $H' = - \sum [(\% \text{ cover species A}) * \ln (\% \text{ cover species A})], \dots, [(\% \text{ cover species X}) * \ln (\% \text{ cover species X})]$.

Because exotic grasses and native grasses were both treated as single groups, while forbs were split into their component species in calculations of richness and diversity, these calculations are biased to favor plots with a higher number of forb species.

Final aboveground plant biomass was determined for each plot at the end of the growing season, in May. Plants were clipped at the soil surface, separated into exotic annual grasses, *Carduus* and *Silybum* thistle species together, and all remaining forbs, and dried at 70°C for 48 hours. Average thistle stem biomass was used in data analysis to determine the effects of retardant on thistle density at the individual level. Average thistle stem biomass was calculated by dividing the total thistle biomass for each plot by the total number of thistle stems harvested from the plot.

Average grass height was determined for each plot using a 2m pole and a straw plate with a hole in its center (G. Hayes, *personal communication*). The plate was placed over the pole and allowed to slide down until it was stopped by the bulk of grasses within the plot. The stopping height of the plate was recorded. This was conducted at three points within each plot and the three values were averaged together for data analyses.

Data Analyses

All data were analyzed using Stat View 5.0.1. (SAS Institute Inc. 1999) and effects were called significant if $P < 0.05$. To determine if there was a significant interaction between the factors of fire retardant treatment (control or experimental), thistle density (high or low), and Date (response variables repeatedly measured at March and May, as well as January (post-treatment) for soil nutrient levels), I performed a repeated measures (Date) three-way analysis of variance. I also examined all two-way interactions as well as main effects, using the Bonferroni / Dunn test to determine significant differences within main effects. I performed pair-wise comparisons for control

vs. experimental plots for each response variable at each given date and thistle density. Similar pair-wise comparisons were made for high vs. low-density thistles, as well as comparison among measurement dates. The level of significance measured by the ANOVA is conservative due to the inability of Stat View to perform ANOVA on repeated and nested designs, thereby increasing the variability in the means of the measurements. Due to the large amount of natural variability inherent in this study and for the sake of extrapolating any possible patterns, I frequently relied on the less conservative but more accurate pair-wise comparisons to determine significance.

Response variables consisted of soil nitrate and ammonium levels, exotic grass cover, exotic grass height, exotic grass biomass, exotic thistle cover, exotic thistle biomass, exotic thistle stem biomass, forb cover, forb biomass, species richness, and species diversity. The response variable measurements preceding fire retardant treatment in January (pre-treatment) were not included in ANOVAs, although pair-wise comparisons with pre-treatment measurements were conducted to check for initial similarity as well as overall changes throughout the study. Change indices were created for each response variable, such that January index = 0 (the beginning), March index = March minus January, and May index = May minus March. The purpose of performing ANOVA models on the change indices was to find significant effects by factors and their interactions while accounting for initial variation between control and experimental plots. I relied on the change index when analyzing response variables that differed initially for control and experimental plots (e.g. forb cover).

Results

Soil Nutrients

Soil ammonium was significantly higher in fire retardant treated plots than in controls (Figure 1; treatment effect, ANOVA, $F = 8.5$, $df = 1, 34$, $P = 0.006$). Soil ammonium in fire

retardant treated plots was significantly greater than controls in January (post-treatment; paired t test, $t = - 2.31$, $df = 17$, $P = 0.03$), March (paired t test, $t = - 2.93$, $df = 17$, $P = 0.009$), and May (paired t test, $t = - 2.28$, $df = 17$, $P = 0.04$). In both fire retardant treated and control plots soil ammonium decreased from January (pre-treatment) to May, showing a significant effect of season on soil ammonium (Figure 1; date effect, ANOVA, $F = 5.32$, $df = 2, 68$, $P = 0.0071$).

Soil nitrate levels were consistently lower than ammonium levels across all dates and treatments (Table 1). Soil nitrate was not different between fire retardant treated and control plots at any point during the study. However, fire retardant treated plots showed a significant increase in soil nitrate levels immediately following fire retardant addition (Pre-treatment vs. Post-treatment; Figure 2; paired t test, $t = - 2.34$, $df = 17$, $P = 0.032$); whereas control plots showed no change throughout the study.

Composition of Exotic Species and Forbs

Exotic Grasses

There was no effect of treatment or thistle density on exotic grass cover. However, exotic grass cover increased significantly from March to May, demonstrating a seasonal effect on grass cover (Table 2; date effect, ANOVA, $F = 7.54$, $df = 1, 32$, $P = 0.009$).

Exotic grass biomass in fire retardant treated plots was significantly greater than in controls (Table 3; treatment effect, ANOVA, $F = 5.98$, $df = 1, 32$, $P = 0.02$). However, thistle density had an effect on how the fire retardant treatment affected grass biomass. In plots with high-density thistle there was no difference between control and fire retardant treated grass biomass; whereas in plots with low-density thistle the fire retardant treated grass biomass was significantly greater than the control grass biomass (Figure 3; paired t test, $t = - 2.68$, $df = 8$, $P = 0.028$). High-density thistle

appears to have suppressed the response of exotic grass biomass to the fire retardant treatment.

Exotic grass height in both March and May was significantly taller in fire retardant treated plots than in controls (Figure 4; treatment effect, ANOVA, $F = 9.32$, $df = 1, 30$, $P = 0.005$). There was also a significant effect of date on grass height (Figure 4; date effect, ANOVA, $F = 52.7$, $df = 2, 60$, $P < 0.0001$), with grass height significantly decreasing from January to March (Bonferroni/Dunn for date, $P = 0.0064$) and significantly increasing from March to May (Bonferroni/Dunn for date, $P < 0.0001$). There was a significant interaction between date and treatment in their effect on grass height (date by treatment effect, ANOVA, $F = 3.97$, $df = 1, 30$, $P = 0.05$), so that in March the grass in fire retardant treated plots was 22% taller than control plots; whereas in May the grass in the fire retardant treated plots was 33% taller than control plots. Thistle density had an effect on how grass height responded to fire retardant addition. In high-density thistle there was no difference in height between control and fire retardant treated plots; whereas in low-density thistle the fire retardant treated plots had significantly taller grasses in both March (paired t test, $t = -2.38$, $df = 7$, $P = 0.05$) and May (paired t test, $t = -7.21$, $df = 7$, $P = 0.0002$).

Exotic Thistle

There was no difference in thistle cover between control and fire retardant treated plots. It was not possible to determine if thistle density (high or low) affected the thistle cover response to treatment (thistle by treatment effect) because plots with low-density thistle maintained almost zero thistle throughout the study, therefore showing no change in response to treatment and providing no comparison for high-density thistle plots.

There was no effect of fire retardant addition on thistle biomass. There was a strong effect of thistle density on thistle biomass, as expected, with high-density thistle plots having significantly

higher thistle biomass than low-density thistle plots, which had virtually zero thistle biomass (Table 3; thistle effect, ANOVA, $F = 20.5$, $df = 1, 32$, $P = 0.0001$). There was no effect of fire retardant addition on thistle stem biomass. There was an effect of thistle density on thistle stem biomass, with low-density thistle plots having significantly lower stem biomass than high-density thistle plots (Table 3; thistle effect, ANOVA, $F = 24.07$, $df = 1, 32$, $P < 0.0001$).

Non-Thistle Forbs

Unexpectedly, the forb cover in fire retardant treated plots was significantly higher than control plots in January (pre-treatment; Figure 5, Table 2; paired t test, $t = -2.09$, $df = 17$, $P = 0.05$). Because the two treatments were initially dissimilar, an Analysis of Variance found no effect of treatment on forb cover. However, an ANOVA for change indices found a significant effect of treatment on change in forb cover (treatment effect, ANOVA, $F = 10.1$, $df = 1, 64$, $P = 0.003$); with fire retardant treated plots showing greater declines in forb cover than controls. From January to March the forb cover in fire retardant treated plots had significantly decreased by 37% (Figure 5; paired t test, $t = 2.9$, $df = 17$, $P = 0.01$); whereas control plots had increased by 12.4%, making the two treatments statistically similar. From March to May both treatments had significantly decreased in forb cover, control plots by 62% (Figure 5; paired t test, $t = 3.7$, $d.f. = 17$, $P = 0.0015$) and fire retardant treated plots by 83% (Figure 5; paired t test, $t = 2.85$, $df = 17$, $P = 0.011$); making forb cover in fire retardant treated plots significantly lower than control plots (Figure 5; paired t test, $t = 2.2$, $df = 17$, $P = 0.04$). The significant decline in control plots from March to May demonstrates a significant effect by season on forb cover (date effect, ANOVA, $F = 28.85$, $df = 2, 64$, $P < 0.0001$). The difference in how forb cover in the two treatments responded to changes in the season was reflected in a significant interaction between treatment and date on forb cover change indices (date by treatment effect, ANOVA, $F = 4.9$, $df = 2, 64$, $P = 0.01$).

Thistle density significantly affected how forb cover change indices responded to the fire retardant treatment (Figure 6; thistle by treatment effect, $F = 5.44$, $df = 1, 32$, $P = 0.026$). In plots with high-density thistle there was no difference in the change indices between the control and fire retardant treated plots during the study, with both treatments showing a significant decline in forb cover from January (pre-treatment) to May (Figure 6, Table 2; control paired t test, $t = 2.74$, $df = 8$, $P = 0.026$ and experimental paired t test, $t = 2.72$, $df = 8$, $P = 0.026$). In plots with low-density thistle the fire retardant treated plots showed a significant decline in forb cover from early January (pre-treatment) to March (Figure 6, Table 2; paired t test, $t = 3.13$, $df = 8$, $P = 0.01$) followed by another significant decline from March to May (Figure 6, Table 2; paired t test, $t = 3.23$, $df = 8$, $P = 0.012$). In contrast, the control plots showed no change from early January (pre-treatment) to March, followed by a significant decline from March to May (Figure 6, Table 2; paired t test, $t = 4.42$, $df = 8$, $P = 0.002$). By May, low-density thistle fire retardant treated plots had significantly lower forb cover than their controls (Figure 6, Table 2; paired t test, $t = 2.29$, $df = 8$, $P = 0.05$). This appears to demonstrate that high-density thistle suppressed the response of forb cover to fire retardant treatment. Thistle density was also found to affect forb cover in general. Forb cover in high-density thistle plots was significantly lower than forb cover in low-density thistle plots (Figure 6; thistle effect, ANOVA, $F = 25.95$, $df = 1, 32$, $P < 0.0001$).

Forb biomass was significantly lower in fire retardant treated plots than in control plots (Figure 7, Table 3; paired t test, $t = 2.04$, $df = 17$, $P = 0.05$). Thistle density also had a significant effect on forb biomass (Figure 7; thistle effect, ANOVA, $F = 8.06$, $df = 1, 32$, $P = 0.008$) with plots in low-density thistle having greater biomass than plots in high-density thistle (Table 3).

Species Richness

There was no difference in species richness between control and fire retardant treated plots. However, there was a difference in the change indices for species richness between the two treatments, with fire retardant treated plots showing greater decreases than controls. In control plots species richness minimally increased by 1.6% from January (pre-treatment) to March, and then significantly declined by 22% from March to May (Figure 8; paired t test, $t = 2.92$, $df = 17$, $P = 0.01$). In fire retardant treated plots species richness significantly declined by 16% from January (pre-treatment) to March (Figure 8; paired t test, $t = 2.76$, $df = 17$, $P = 0.014$), followed by another significant decline by 38% from March to May (Figure 8; paired t test, $t = 3.08$, $df = 17$, $P = 0.007$). This demonstrates a negative effect on species richness due to fire retardant addition, as well as seasonal effects from March to May (date effect, ANOVA, $F = 16.65$, $df = 1, 32$, $P = 0.0003$). There was no effect of thistle density on species richness.

Species Diversity

There was no difference in species diversity between control and fire retardant treated plots. However, as with species richness, there was a significant difference in the change indices for species diversity in the two treatments (Figure 9; treatment effect, ANOVA, $F = 5.3$, $df = 1, 32$, $P = 0.028$); with fire retardant treated plots showing significantly greater decreases than controls. In control plots the species diversity increased by 11% from January (pre-treatment) to March and then significantly declined by 48% from March to May (Figure 9; paired t test, $t = -4.64$, $df = 17$, $P = 0.0002$). In fire retardant treated plots species diversity declined by 13% from January (pre-treatment) to March, and then significantly declined by 57% from March to May (Figure 9; paired t test, $t = -3.75$, $df = 17$, $P = 0.0016$). This demonstrates a negative effect on species diversity due to fire retardant, as well as by seasonal effects from March to May (date effect, ANOVA, $F = 35.22$, df

= 1, 32, $P < 0.0001$).

Although thistle density showed no effect on how species diversity responded to treatment in an ANOVA, pair-wise comparisons showed that thistle density had an effect on how species diversity responded to treatment. Plots with high-density thistle showed no difference in species diversity between control and fire retardant treated plots; whereas plots with low-density thistle had significantly higher species diversity in control plots than in fire retardant treated plots in both March (Figure 10; paired t test, $t = 2.45$, $df = 8$, $P = 0.04$) and May (Figure 10; paired t test, $t = 2.59$, $df = 8$, $P = 0.03$). This demonstrates that high-density thistle suppressed the impacts of fire retardant addition on species diversity.

Discussion

Many studies have found that nutrient inputs into grassland communities cause an increase in exotic plant populations, which overall results in the suppression of short statured forbs (Huenneke et al. 1990, Kitajima and Tilman 1996), as well as declines in both species richness and species diversity (Huenneke et al. 1990, Kitajima and Tilman 1996, Maron and Connors 1996, Vinton and Burke 1995). Based on these studies and the assumption that fire retardant (Phos-Chek G-75F) increases available nitrogen levels in soil, I tested two hypotheses. I first hypothesized that nutrient inputs from fire retardant into a California coastal grassland would increase populations of exotic thistle and exotic grass. This study found that the fire retardant significantly increased ammonium and nitrate levels in the soil and that this resulted in increased growth of exotic grasses, but not of exotic thistles. Secondly, I hypothesized that the increase in exotic populations would result in the

suppression of short statured forbs, which would in effect cause declines in species richness and diversity. This study found that in plots where exotic grass growth increased due to fire retardant application, forb populations declined along with species richness and diversity.

Soil Nutrients and Fire Retardant

The fire retardant addition (Phos-Chek G-75F) increased the available nitrogen in the soil, primarily that of ammonium and to a lesser degree that of nitrate. The increase in soil ammonium is likely a direct result of the treatment, as ammonium is a major constituent of the retardant; whereas the increase in nitrate is likely an indirect result of the ammonium increase, due to nitrification of the ammonium into nitrate by chemoautotrophic and heterotrophic bacteria (Paul and Clark 1996). In most soils, if ammonium is not immediately utilized by organisms, it is converted to nitrate by nitrification (Paul and Clark 1996). The seasonal decline in ammonium from January to May could be due to a combination of nitrification, uptake by new plant growth in the spring, uptake for microbial growth, absorption by clays and organic matter, and high rates of volatilization as it becomes available from plant decomposition (Jackson et al. 1988).

Fire Retardant Effects on Exotic Species

The fire retardant addition increased the biomass and height of the exotic grasses. Similarly, Maron and Connor (1996) found that an exotic grass, *Bromus diandrus*, increased in shoot biomass resulting from nitrogen inputs via nitrogen-fixing *Lupinus arboreus* in a greenhouse study. Bobbink

(1991) found that when nitrogen was added to chalk grasslands there was a strong increase in the invasive grass *Brachypodium*, which under low-nutrient conditions was limited by nutrient availability as well as other components of the vegetation. In contrast, I found no effect of fire retardant on exotic grass cover, demonstrating that the increased grass biomass due to fire retardant addition was from an increase in grass height rather than an increase in thickening or branching grass growth.

Thistle density affected how exotic grass height and biomass responded to the fire retardant addition. In low-density thistle the fire retardant addition increased grass height and biomass; whereas in high-density thistle the fire retardant addition had no effect on grass height or biomass when compared to controls. High-density thistle appears to have suppressed the response of exotic grass to the fire retardant addition. This is a curious result considering that the high-density thistle doesn't appear to be out-competing the exotic grass for nutrient inputs (based on the lack of response by thistle to nutrient inputs) and high-density thistle doesn't appear to be hindering the growth of the grasses and therefore suppressing a response to nutrient inputs (there was no difference in grass height or biomass between the control plots from high and low-density thistle). One explanation for this curious response is that higher phosphate levels in association with high-density thistle may be confounding the results. Supporting this, upon analyses of surface soils from thistle-infested and adjacent thistle-free areas, Michael (1968) found that *Carduus pycnocephalus* was associated with soils of higher phosphate and *Silybum marianum* was associated with soils of higher nutrient concentration generally. While phosphate levels during this study were unknown, it is possible that

plots in high-density thistle were higher in phosphate than plots in low-density thistle, which would affect the response of plant composition to nutrient inputs. Wilson and Tilman (1995) found that when nitrogen along with small amounts of phosphate were added to chalk grasslands, *Brachypodium*, an annual grass, was greatly stimulated and became the dominant species. However, when nitrogen was added along with large amounts of phosphate there was a general increase in grassland productivity, without any one species showing a dominant response. If the high-density thistle plots have higher phosphate concentrations, then Wilson and Tilman's (1995) findings may explain why there was no domination by the exotic grasses with nutrient addition in these plots. Further studies are needed to determine how high phosphate levels, associated with some thistle species, affect community responses to nutrient inputs.

Although I found fire retardant additions increased exotic species growth, I found no such pattern for exotic thistles. The response of exotic thistles found in this study differed from the one found at the Big Creek Reserve in 1999, in the spring after fire retardant was applied for fire breaks. At that time the Big Creek Reserve experienced noticeable increases in the size of thistle populations. The lack of response found in this study may be due to a combination of differences in fire retardant concentration and timing of application. When the fire retardant was applied to the reserve during the fire of 1999 the Phos-Chek powder was mixed into the consistency of slurry, which dropped into the grasslands in large solid patches that held together (John Smiley, *personal communication*). In my study the fire retardant was applied at the concentration recommended by the Phos-Chek Application Guide (Monsanto Co. 1993), which had the consistency of a liquid and

could be applied in a fine even mist. Therefore, based on observations of fire retardant consistency, the concentration of nutrient inputs during the fire of 1999 may have been much greater than the inputs during this study, which may in part account for the difference in thistle response. Supporting this, Austen et al. (1985) found that the yields of both *Carduus pycnocephalus* and *Silybum marianum* increased with increasing nutrient concentrations.

The timing of the fire retardant addition may also account for some differences. Both *Carduus* and *Silybum*, being winter annuals, tend to utilize available nitrogen only during germination in the fall following the first rains, and during rapid growth in the spring (Jackson et al. 1988). The fire retardant application in 1999 was applied in October, at a critical time when thistles were actively taking in nitrogen for storage and germination. Groves and Kaye (1989) found that additions of nitrate actually increase germination rates of both *Carduus* and *Silybum*. The fire retardant application in 1999 may have increased the germination rate of the thistles, leading to increased populations in the following spring. In contrast, the fire retardant application during this study was applied in January, at a time when most thistles were in a state of arrested growth (Evans et al. 1979), and not resuming nitrogen utilization until growth in spring. Therefore, because of application time in this study, thistles were not able to utilize nutrients for germination and nutrients that potentially could have been used for resumed growth in spring may have been largely lost to other soil processes such as volatilization, leeching, and denitrification (Paul and Clark 1996).

Fire Retardant Effects on Non-Thistle Forbs

The fire retardant addition resulted in a significant decline in cover and biomass of non-thistle forbs. Their decline from January to March appears to be a result of nutrient burning by the fire retardant treatment. This is based on observations of brown and withered non-thistle forb foliage (indication of tissue burn), one week after treatment. In contrast, the decline from March to May appears to be in response to competition from exotic annual grass species. While increasing competition from grasses appears to be a seasonal trend from March to May (as the grasses get taller), nutrient inputs appear to further intensify this competition, causing even greater declines in forb cover and biomass. This agrees with Wilson and Tilman's (1995) findings that with the addition of nutrients to low-nutrient environments, competition shifts from primarily root competition to primarily shoot competition, with fast-growing species that are better competitors for light (i.e. exotic grasses) dominating, and slower-growing species that are better competitors for nutrients (i.e. forbs) being suppressed. A decline in forbs, in response to increases in weedy grasses, with nutrient inputs into grasslands has been found in many competition studies (Wilson and Tilman 1995, Bobbink et al. 1988, Thurston 1968, Huenneke et al. 1990).

Thistle density affected how non-thistle forb cover responded to fire retardant additions. In low-density thistle plots the fire retardant addition caused declines in non-thistle forb cover as compared to controls; whereas in high-density thistle plots there was no effect of fire retardant on non-thistle forb cover. In high-density thistle plots, the lack of effect by fire retardant on non-thistle forb cover may have been due to the similar lack of effect by fire retardant on exotic grasses

discussed previously. During this study, declines in forb cover following fire retardant addition appear to result from increased competition from exotic grasses, due to stimulated exotic grass growth from fire retardant. In high-density thistle the lack of effect of fire retardant on exotic grass height or biomass may have resulted in a lack of effect on grass competition with non-thistle forbs, and therefore a lack of change in non-thistle forb cover.

Thistle density had an effect on non-thistle forb cover and biomass. In high-density thistle, the non-thistle forb cover and biomass were greatly decreased when compared to low-density thistle. The suppression of non-thistle forb growth in high-density thistle plots may have been due to the basal rosette growth form of thistle. In this study it appeared that the thistles left few inter-spaces between individual basal rosettes where a short statured forb could grow. Similarly, Parsons (1973) found that the blanketing effect of overwintering thistle rosettes could severely reduce the establishment of short statured plants.

Fire Retardant Effects on Species Richness and Species Diversity

The decline in forb species number along with declines in forb cover, in response to the fire retardant addition, led to a significant decline in species richness and species diversity. The forbs most commonly lost were *Eschscholzia*, *Lupinus*, *Hypochaeris*, and *Gnaphalium*. Likewise, Huenneke et al. (1990) found that nitrogen and phosphorus additions in a California serpentine grassland for two years resulted in a substantial decline in species richness and diversity, primarily from the loss of native forbs and legumes. Similar to this study, Huenneke et al. proposed that, given the low stature of the native forb and legume species, they were most likely out competed for

light.

The implications of this study are that the application of ammonium-phosphate based fire retardant to California coastal grassland results in declines in species richness and species diversity by increasing populations of exotic annual grasses that suppress populations of short statured forbs. Until a non-toxic non-nutrient based fire retardant is created, land managers will have to be prepared to manage the community level responses following fire retardant applications. Management practices may include manually removing exotic annual grass height in the growing season following fire retardant application, to avoid declines in short statured forbs. Another possibility is for those agencies who are mixing and applying fire retardant, to reduce the concentration of the fire retardant to minimal amounts (appropriate concentrations published in the Phos-Chek Application Guide (Monsanto Co. 1993)), while still maintaining an effective fire retardant. Further studies are needed to determine how coastal grasslands receiving different nutrient input concentrations differ in their response. This especially applies to the response of exotic thistle species, whose response appears to depend in part on the nutrient input concentration, in addition to season of application. Another area that deserves future study is the effect of high phosphate levels on community responses to nutrient inputs. During this study high phosphate levels associated with some thistle species may have been responsible for preventing domination by exotic species following fire retardant application. Likewise, perhaps high phosphate levels in a future fire retardant would prevent weedy exotic species from becoming dominant in response to future applications, therefore maintaining species richness and diversity.

Tables and Charts

Table 1. Average soil nutrients (ppm NH₄ and NO₃; n = 18), for control and fire retardant treatments across all soil sampling dates.

Table 2. The average percent cover of exotic grass, exotic thistle, and non-thistle forbs for control and fire retardant treatments in total (n = 18), high (n = 9), and low (n = 9) density thistle plots.

Functional Group	Treatment	Thistle Density	Average % Cover in January (pre-treatment)	Average % Cover in March	Average % Cover in May
Exotic Grass	Control	Total	86.05	82.6	89.4
		High	87.8	84.4	91.1
		Low	84.3	80.8	87.7
	Fire Retardant Treated	Total	81.6	80	85.35
		High	84.6	78.8	84.9
		Low	78.6	81.2	85.8
Exotic Thistle	Control	Total	3.05	3.75	1.76
		High	6.1	7.2	3.5
		Low	0	0.03	0.02
	Fire Retardant Treated	Total	3.85	6.05	2.62
		High	7.7	11.9	5.2
		Low	0	0.2	0.03
Non-Thistle Forbs	Control	Total	6.05	6.8	2.55
		High	1.3	1.9	0.7
		Low	10.8	11.7	4.4
	Fire Retardant Treated	Total	8.9	5.55	.95
		High	2.0	1.2	0.5
		Low	15.8	9.9	1.4

Table 3. The average final biomass (g) of exotic grass, exotic thistle, exotic thistle stems, and non-thistle forbs for control and fire retardant treated plots in total (n = 18), high (n = 9), and low (n = 9) density thistle plots.

Functional Group	Thistle Density	Average Final Biomass (g) in Control	Average Final Biomass (g) in Fire Retardant Treated
Exotic Grass	Total	325.34	443.71
	High	364.31	409.61
	Low	286.37	477.80
Exotic Thistle	Total	28.82	23.23
	High	57.60	46.16
	Low	0.03	0.27
Exotic Thistle Stem	Total	1.83	1.52
	High	3.63	2.86
	Low	0.03	0.18
Non-Thistle Forb	Total	11.53	6.66
	High	4.81	1.83
	Low	18.25	11.49

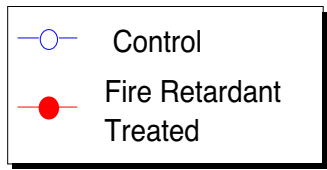


Figure 1. Average ammonium (ppm NH₄; n = 18; mean +/- S.E.), in control and fire retardant treated soils collected before treatment in January (PreJan), after treatment in January (PostJan), March, and May.

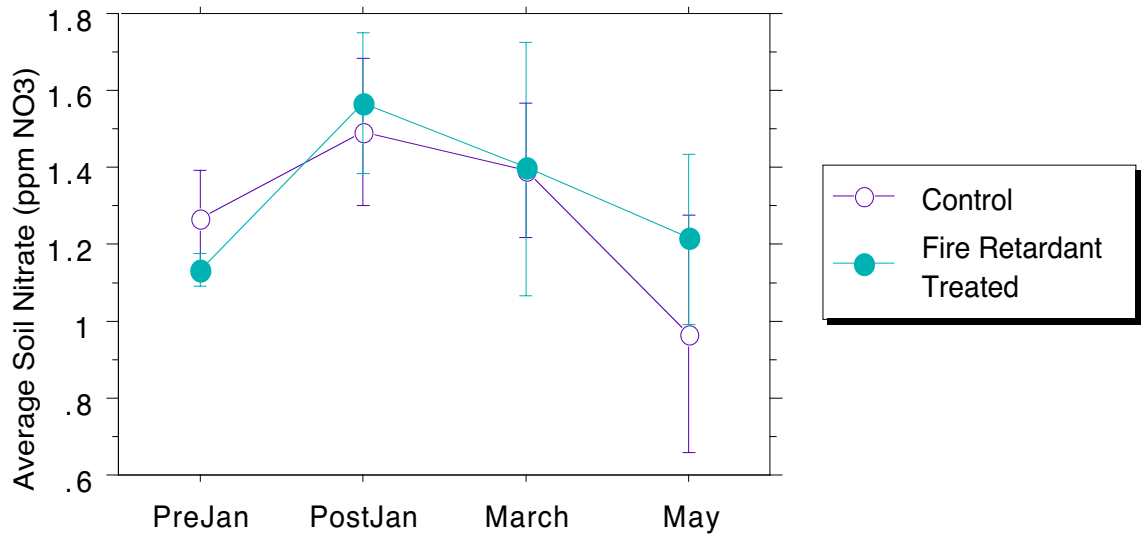


Figure 2. Average nitrate (ppm NO₃; n = 18; mean +/- S.E.), in control and fire retardant treated soils collected before treatment in January (PreJan), after treatment in January (PostJan), March, and May.

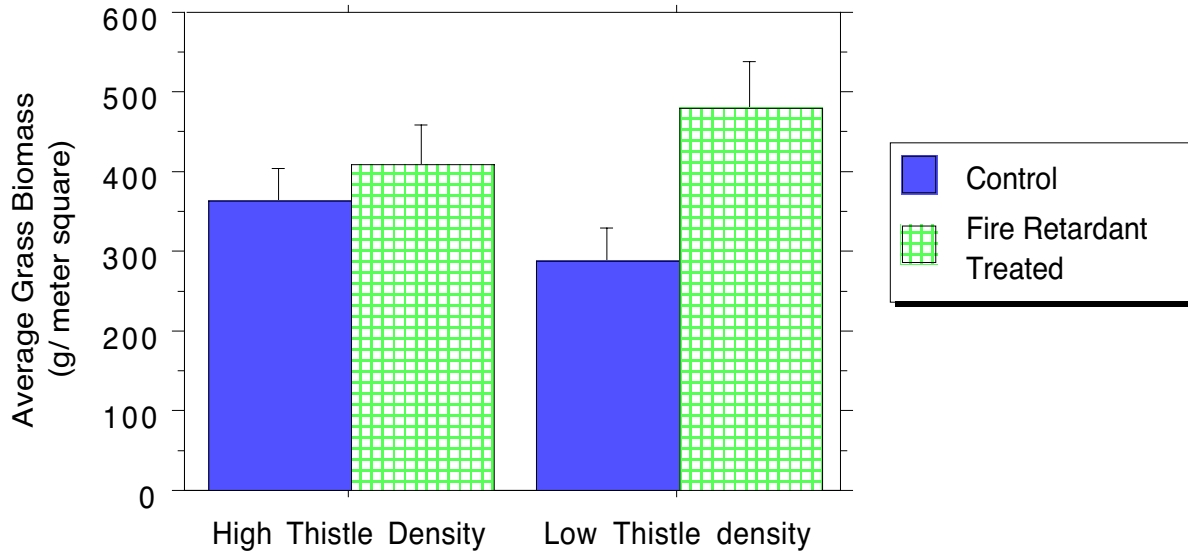


Figure 3. The average grass biomass (g / m^2 ; $n = 9$; mean \pm S.E.) from control and fire retardant treated plots in high and low density thistle.

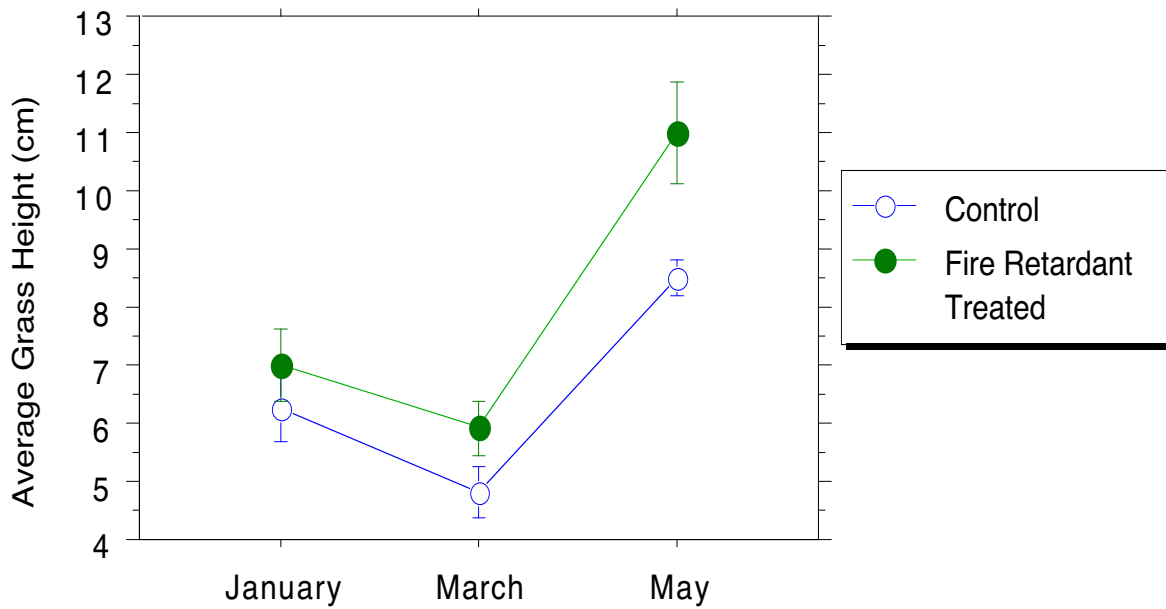


Figure 4. The average exotic grass height (cm; n = 18; mean +/- S.E.) in control and fire retardant treated plots in January (pre-treatment), March, and May.

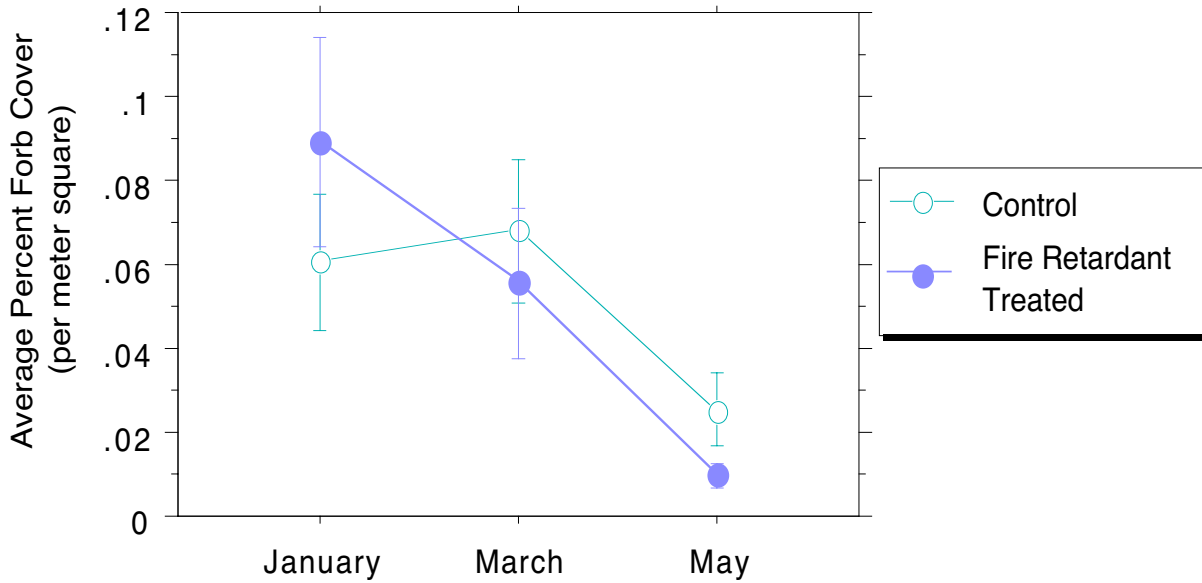


Figure 5. The average percent cover by non-thistle forbs (n = 18; mean +/- S.E.) in 1-m² control and fire retardant treated plots in January (pre-treatment), March, and May.

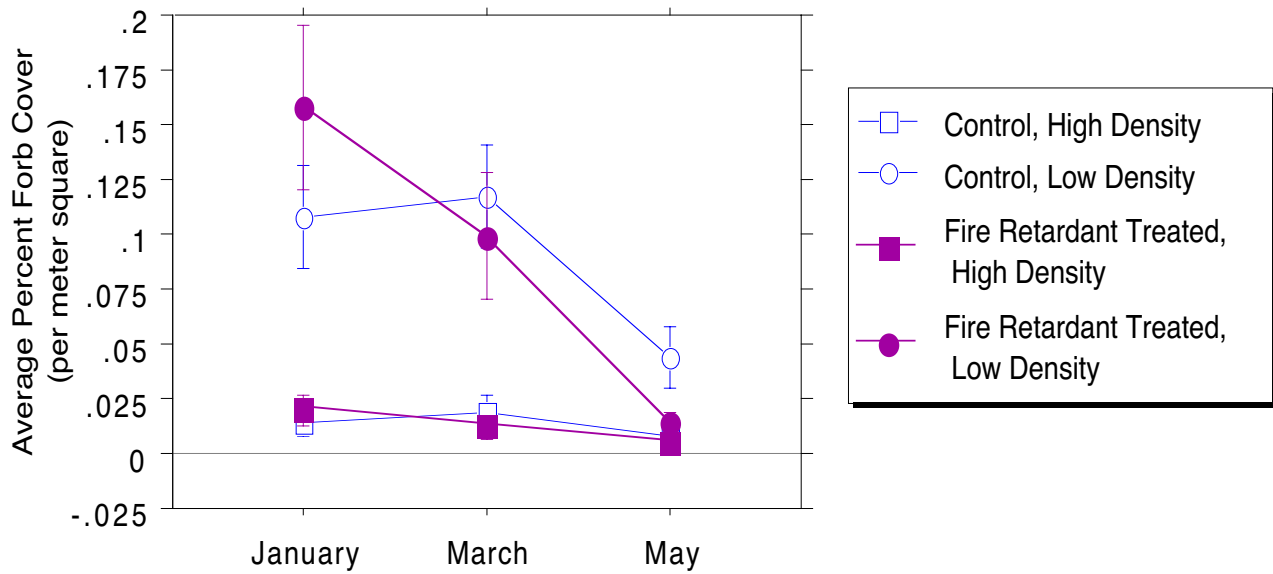


Figure 6. The average percent cover by forbs ($n = 9$; mean \pm S.E.) in 1-m² control and fire retardant treated plots, for high and low density thistle in January (pre-treatment), March, and May.

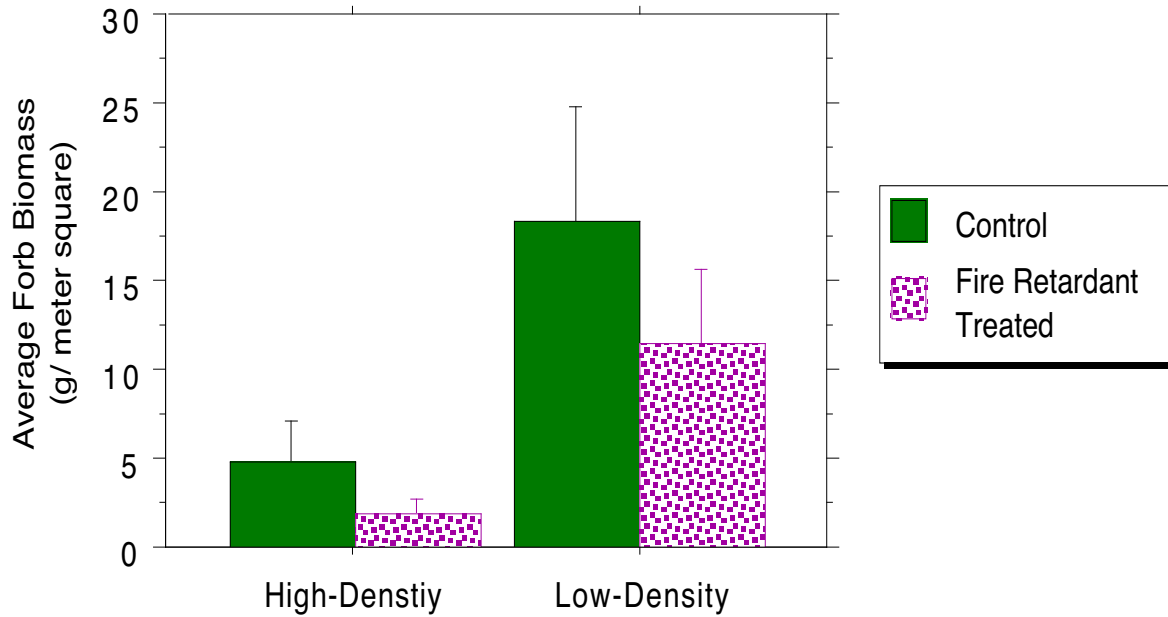


Figure 7. The average forb biomass (g / m^2 ; $n = 18$; mean \pm S.E.) from control and fire retardant treated plots in high and low density thistle.

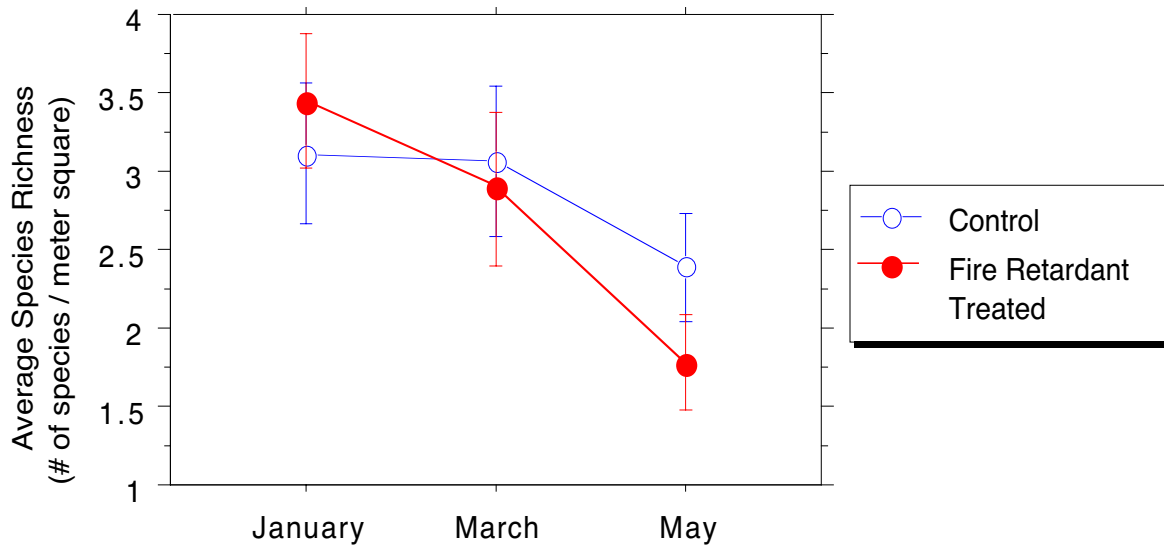


Figure 8. The average species richness (# of species / per m²; n = 18; mean +/- S.E.) in control and fire retardant treated plots in January (pre-treatment), March, and May.

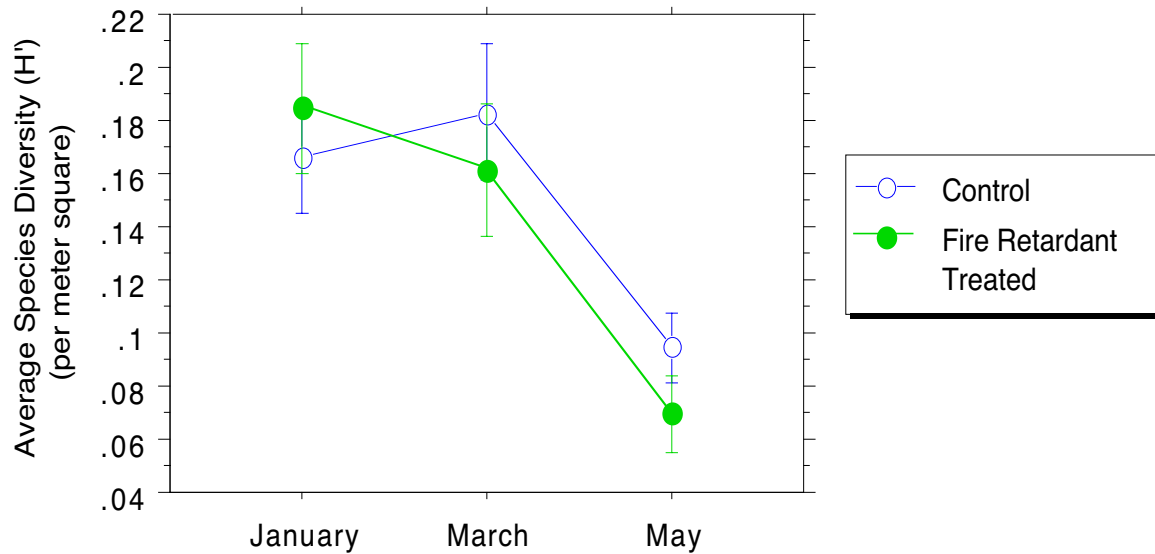


Figure 9. Average Shannon-Wiener Diversity Indices (H') (n = 18; mean +/- S.E.) in 1-m² control and fire retardant treated plots in January (pre-treatment), March, and May.

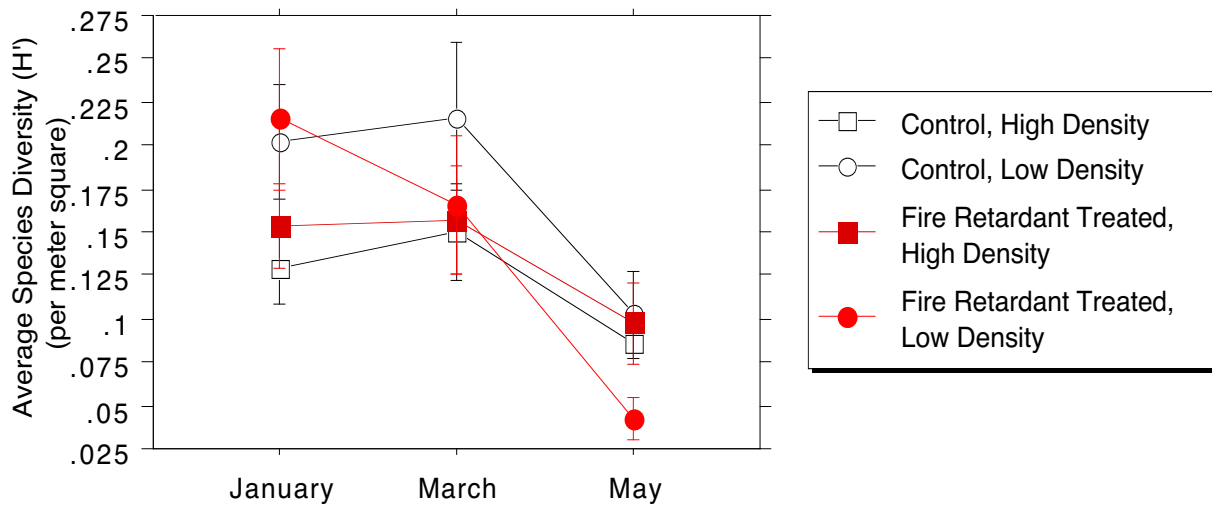


Figure 10. Average Shannon-Wiener Diversity indices (H') (n = 9; mean +/- S.E.) in 1-m² control and fire retardant treated plots within high and low density thistle, in January (pre-treatment), March,

and May.

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