The Effects of Thinning and Burning on Understory Vegetation in North America: A Meta-Analysis

We conducted a meta-analysis to determine the effects of fire and fire-surrogates on understory vegetation in dry forests in North America. Means and standard errors were extracted from papers containing data on the response of understory functional groups to thinning and burning treatments to calculate effect sizes. For each response variable, we compared three treatment pairs: burn versus control, thin vs control and thin vs burn. We calculated standardized mean differences (Hedges’ d) for each pair and tested if this differed from zero using a random effects model fit with restricted maximum likelihood [@Hedges+Olkin-1985]. Exotic species richness was higher in thin treatments than in control treatments (p=0.000543) and shrub cover was lower in burn treatments than in control treatments (p=0.034437). East-West coefficient p values were also calculated to account for geographic variation. After the East-West correction, total understory species richness was found to be higher in burn treatments than control treatments (p=0.002047) and total understory percent cover was found to be significantly lower in thin treatments than in control treatments (p=0.021671).

# Introduction

North American forests have been shaped by fire over evolutionary and ecological time scales. However, for much of the 20th century, land managers concentrated on minimizing the amount of land that burned. Compared to presettlement fire regimes in many contemporary forests, fire intervals have lengthened [@Cyr+Gauthier+etal-2009; @Spetich+Perry+etal-2011; @Aldrich+Lafon+etal-2010], although there is evidence for significant variability in historical fire return intervals [@Odion+Hanson+etal-2014]. Increased recognition of the central role of fire in maintaining forest structure and function has contributed to a shift from fire exclusion to the reintroduction of fire in fire-dependent forests, most often with the aim of reducing fuels and restoring historic stand structure [@Agee+Skinner-2005]. This recognition has prompted federal initiatives such as the National Fire Plan and Healthy Forest Restoration Act (2003) that mandate federal land managers to restore forest structure and function and reduce risk of wildfire on federal lands. Use of widespread fuel treatments has led to increasing discussion of the effectiveness, suitability and ecological impacts of thinning and prescribed fire [@Schoennagel+Veblen+etal-2004; @Schoennagel+Nelson-2010; @Schwilk+Keeley+etal-2009].

Although prescribed fire is often the preferred fuel reduction practice, forest managers often face social and economic constraints on burning. Additionally, in forests thought to have departed significantly from historical fire return intervals, there is concern that introducing fire may result in unnaturally high intensity fire that may be difficult to manage or may have negative ecological effects. Therefore, mechanical fuel reduction methods have increasingly been used to reduce fuels or restore historic stand structure through thinning [@Crow+Perera-2004]. Uncertainty regarding the relative ecological effects of prescribed fire vs mechanical treatments has led to increasing attention to the ecological effects of fire and so-called “fire surrogates” such as the National Fire and Fire Surrogate study [@Schwilk+Keeley+etal-2009; @McIver+Stephens+etal-2012].

Early forest management emphasized recruiting trees for commercial harvest. However, in the last half of the 20th century, forest management practices have shifted focus to include managing for ecosystem services, including biodiversity. In most forests, the majority of plant biodiversity is found in the understory herbaceous layer. In addition to harboring high diversity, understory herbaceous communities have profound effects on forest nutrient cycling [reviewed by @Gilliam-2007]. Most attention has been paid to the effects of fire and mechanical treatments on forest structure and fuels; the extent to which mechanical treatments or thinning approximate effects of prescribed fire on forest understory vegetation is not as well understood. Results from the National Fire and Fire Surrogate study demonstrated that fire and mechanical treatments differed most in their effects on understory vegetation [@Schwilk+Keeley+etal-2009]. This is not entirely surprising: although both fire and thinning remove overstory trees and allow increased light to reach understory plants, fire restructures habitat and soils that many plants depend on for germination and growth [@Bond+vanWilgen-1996; @Gundale+DeLuca+etal-2005; @DeLuca+MacKenzie+etal-2006; @Gundale+Metlen+etal-2006]. Thinning, on the other hand, removes rather than consumes vegetation and may alter nutrient dynamics [eg @Boerner+Waldrop+etal-2006]. Many mechanical thinning methods also result in soil disturbance and compaction that fire does not cause [@Schwilk+Keeley+etal-2009]. The growing body of work comparing fire and thinning effects on vegetation offers an opportunity to increase the generality of conclusions through meta-analysis.

## Objectives

Our objective was to conduct a meta-analysis of the literature that investigated effects of thin and burn treatments on understory herbaceous and shrub species in dry forests in North America. Specifically, we were interested in the degree to which thin treatments mimic prescribed burn treatments and to what extent burning or thinning differ from control or no treatment patches.

We ask the following questions:

1. Do thin treatments have similar percent cover of native species, exotic species, herbaceous species, and shrubs compared to prescribed burn and control treatments?
2. Do thin treatments have similar species richness of native species, exotic species, herbaceous species, and shrubs compared to prescribed burn and control treatments?

We hypothesize thin and burn treatments have higher total percent cover and species richness of understory plants compared to controls.

We also hypothesize that thin treatments will have increased cover and richness of non-native species compared to prescribed burn treatments.

We hypothesize that total species richness of understory plants will increase in thin and burn treatments compared to controls [@Metlen+Fiedler-2006, @Wienk+Sieg+etal-2004, @Fornwalt+Kaufmann+etal-2014], total percent cover of understory species will increase in thin treatments and decrease in burn treatments compared to controls [@Collins+Moghaddas+etal-2007], exotic understory species richness and percent cover will increase in both thin and burn treatments compared to controls [@Collins+Moghaddas+etal-2007, @Dodson-2004], shrub species richness and percent cover will decrease in burn treatments compared to controls [@Zhang+Webster+etal-2008], shrub species richness and percent cover will increase in thin treatments compared to controls [@Nelson+Halpern+etal-2008], and that herbaceous species richness and percent cover will increase in thin treatments and decrease in burn treatments compared to controls [@Metlen+Fiedler-2006, @Collins+Moghaddas+etal-2007].

# Methods

## Literature Search and Vetting

In May 2014 we performed a search of the scientific literature investigating effects of prescribed fire and thinning treatments on understory vegetation. We used multiple databases: ISI Web of Science (http://www.webofknowledge.com) and AGRICOLA (http://agricola.nal.usda.gov/) both of which searched literature published since 1970 and Forest Science [Ann and Pat: citation or url?] which searched literature published since 1939. We also supplemented these with a search using Google Scholar (http://scholar.google.com/) which, despite limitations in coverage, includes gray literature publications as well as proceedings which sometimes led to published articles. In addition to these search engines, we included additional references gleaned from publications found in the literature search and from a recent U.S. Department of Agriculture / U.S. Department of Interior Joint Fire Sciences Rainbow Series document on the effects of fire on invasive plant species [@Zouhar+Smith+etal-2008]. We searched for the following terms in which ’\*’ indicate wild card searches uses to include plural forms, etc. :

* Understory AND native\*
* Percent Cover AND native\*
* Fire AND Understory\*
* Understory AND exotic\*
* Percent Cover AND exotic\*
* Fire AND Percent Cover\*
* Understory AND forb\*
* Percent Cover AND forb\*
* Burn\* AND Understory
* Understory AND graminoid\*
* Percent Cover AND graminoid\*
* Burn\* AND Percent Cover
* Understory AND shrub\*
* Percent Cover AND shrub\*
* Thin\* AND Understory
* Thin\* AND Percent Cover

The literature search from the databases yielded approximately 3,500 references which were then vetted for appropriate material. Documents were eliminated that dealt with medical issues (i.e. new treatments for burn victims), investigations of ecological processes related to fire but not relevant to the scope of this document (i.e. nutrient cycling, insect infestation, etc.), or modeling studies with little empirical data. Papers from geographical locations outside of North America were also excluded. We were specifically interested in studies that were experimental in nature and that collected quantitative data on the response of understory plants to a prescribed fire or thinning treatment. We further narrowed our search to papers that specifically compared thinning (understory or overstory) and prescribed fire. We excluded papers that dealt exclusively with thinning, prescribed fire or wildfire. This vetting process yielded the 57 references included in this document.

Because statistical reporting was not uniform across references, we performed a second round of vetting to exclude papers that could not be placed in a quantitative meta analysis. Papers that reported chi square tests or failed to include standard errors were excluded.

[DWS: Josh, why, shouldn’t those work for calculating d?

JOW: The answer to this is not simple, sorry! Here is my reasoning: One can mathematically calculate d from those, but I still don’t think they should be included: “Once a metric is chosen, it must be applied to all included studies; one cannot mix and match different measures of effect in a single meta-analysis (Koricheva 2013, page 71). That one quote is somewhat insufficient for explaining why I don’t want to include them. I have a digital copy of Koricheva 2013 if you would like to take a look.

Basically, different assumptions go into the different methodologies for reporting results. If we allow for multiple reporting methods, we mix and match the assumptions going into our overall calculations. This mixing of assumptions either weakens or invalidates our results when we put everything together. The number of papers that reported using chi square tests, for example, was low, so even if we ‘softened’ up our parameters to allow their inclusion, it would hurt our results more than help. What we are using was by far the most common method of reporting data, so I think it makes sense to keep things as pure as possible.

More detail from Koricheva Chapter 7: “However, in many other cases it is of interest to combine various types of noncomparative metrics (i.e., simple measurements of responses) of effect size across studies. The need to combine such ecological or evolutionary responses or parameters is characteristic of observational data, but may also be useful for experimental data. Such effects include parameters like heritability, diversity indices, rate of population increase, time to an event such as metamorphosis or death […]. In these cases, the response itself is combined across studies, rather than combining the comparison of the experimental and control groups’ responses (as in Hedges’ d or the log response ratio) across studies. (Koricheva 2013, page 72)”

Basically, the way we have done it, we kept things simple and pure by only allowing one method for data reporting. Am I missing something? –].

In addition, studies which reported data that was collected 10 or more years after the thinning or burning event were excluded. After the final vetting, a total of 35 references remained.

## Data Extraction and Analysis

We investigate the effect of burning and thinning treatments on two response variables describing effects on understory vegetation: species richness and plant cover. Each of these was recorded separately for each of five species groups: total species, non-natives, graminoids, forbs, and shrubs. Graminoids and forbs data was combined into a “herbaceous” species group due to the low availability of data for graminoids and forbs. This results in 8 possible variables, although not all were available in each study included.

For each selected article, we extracted means and either standard deviations or standard errors of the mean for each response variable across each treatment. We calculated pairwise treatment effect sizes for each response variable for three different pairwise comparisons: Thin vs Burn, Thin vs Control, and Burn vs Control. For each comparison, we calculated the unbiased standardized mean difference (Hedge’s d) between mean values with the following equation:

where is the mean value of the response variable in the “experimental treatment” (Burn or Thin depending on contrast), is the mean value of the response variables in the “experimental control” (Control or Burn depending on the contrast), is the pooled standard deviation of both groups, and is a term that corrects for bias due to small sample size [@Gurevitch+Hedges-2001]. The effect size, d, can be interpreted as the difference between the cover or species richness of plants in treatments relative to controls, measured in units of standard deviations.

We conducted all analyses in R [@R\_Development\_Core\_Team-2013] using the metafor package [@Viechtbauer-2010]. We assumed effect sizes varied randomly among comparisons and therefore we used random-effects models [@Gurevitch+Hedges-2001]. We fit models using restricted maximum-likelihood. To test whether mean effect sizes for a comparison differed significantly from zero, we assumed a normal distribution of effect sizes and their confidence intervals [z statistics, @Viechtbauer-2010].

All hypotheses were a priori. We utilized one-tailed comparisons and halved p values (alpha = 0.05). We utilized a Holm p value adjustment (Bonferroni correction) to control for familywise error rate.

For each article, we extracted treatment mean values, standard errors or standard deviations, and sample sizes from the results text, tables or figures as required. A handful of compromises and assumptions were necessary to reconcile each reference into a single, comparable format. When papers reported mean species richness or percent cover values and standard errors for multiple years per treatment, the mean of these means and standard errors was taken to generate a single representative value. This methodology was used when extracting data from @Metlen+Fiedler-2006, @Phillips+Waldrop-2008, @Laughlin+Fule-2008, @Mason+Baker+etal-2009, and @Waldrop+Yaussy+etal-2008. All other sources reported data for a single year. [JOW My methods on a few of these changed–I need to double check which ones really used means vs specific years]

[DWS: Josh, Your references table in the repo does not have the full references. Please solve this and make sure the schwilk.bib file has all references we used.only Zald etal 2008 ref I could find was for overstory only ??. Could not find correct Fule ref, but he has others which should have data. See https://github.com/schwilklab/understory-ma/issues/11]. [JOW: The references table is complete. I don’t see an issue with Zald, it contained understory data in Table 2.]

Because native species represented over 99% of species richness and percent cover for papers in which both parameters were reported, ‘native’ was utilized as a representative value for ‘total’ species in cases where only ‘native’ was reported [@Dodson+Metlen+etal-2007, @Collins+Moghaddas+etal-2007, and @Huffman+Stoddard-2013].

Papers with a wide degree of sampling methodologies and time-lines were included. Length of time from treatment to sampling ranged from 1 to 8 years (mean = 2.8 years, median = 2 years). Only one paper reported data that was collected more than 5 years after treatment [@Nelson+Halpern+etal-2008]. Varying levels of prescribed burn severity were inherent due to differences in species composition, terrain, weather, and season. For studies which reported data for multiple levels of burning severity, the moderate level of burning was selected for inclusion in this analysis. Varying forms of thinning and mastication were used in thinning treatments. These included chainsaw, dragging a chain between tractors, hand-thinning, thin-and-pile, thin-and-scatter, thin-only, thin-and-chip, partial-cut, and clear-cut. For each paper, data were selected that were as close to a thin-only treatment as possible.

[DWS: something on other per-study variables recorded, use of those? Did we simply not have the replication?][JOW: Can you clarify?]

# Results

Table 1. Data sources

Table 2. Standardized mean differences (z-values) and lower and upper confidence intervals at . pvals-table

Figure 1. Geographic distribution of data sources. Each triangle represents a study site.

Figure 2. Thinning treatments caused an increase in exotic species richness when compared with control treatments (p=0.000543).

Figure 3. Burning treatments caused a decrease in shrub cover when compared with control treatments (p=0.034437).

Figure 4. Burning treatments caused an increase in total species richness when compared with control treatments when modified East/West (p=0.002047).

Figure 5. Thinning treatments caused a decrease in total cover when compared with control treatments when modified East/West (p=0.021671).

Table 3. Complete list of a papers

## Species Richness

Exotic species richness was higher in thin treatments than in control treatments (p=0.000543). There was no significant difference in exotic species richness between burn and control treatments, or between thin and burn treatments. After the East-West correction, total understory species richness was found to be higher in burn treatments than control treatments (p=0.002047). Before East-West correction, there was no significant difference in total understory species richness between any of the treatment groups.

There was no significant difference in herbaceous species richness or shrub species richness between any of the treatment groups. However, only 5 papers reported species richness data for thinning and burning in shrubs.

## Percent Cover

Burning decreased percent cover of shrubs compared to controls (p=0.034437). There was no significant difference in shrub percent cover between thin and control treatments, or between thin and burn treatments. After East-West correction, total understory percent cover was found to be significantly lower in thin treatments than in control treatments (p=0.021671). Before East-West correction, there was no significant difference in total understory percent cover between any of the treatment groups.

There was no significant difference in exotic percent cover or herbaceous percent cover between any of the treatment groups. However, only 4 papers reported percent cover data for thinning in non-natives, and only 6 papers reported percent cover data for burning in non-natives.

# Discussion

Understory communities response to fire and thinning was highly variable across the included studies and few comparisons had mean differences significantly different from zero [Table 2]. In general, understory plant species did not respond as predicted to fire surrogate treatments.

All thinning treatments resulted in positive z-values (increased species richness and percent cover). All burning treatments resulted in negative z-values (decreased species richness and percent cover), except for burning in non-native richness, in which case burning had a significantly positive effect compared with controls (Table 2). Non-native understory species tended to thrive after disturbances, but especially after thinning.

We were extremely conservative when reporting our results and when vetting papers for inclusion in our study. It is likely that as the body of data concerning understory species continues to grow, additional trends will emerge. In particular, exotic richness may increase in burning compared to controls (we found this to be true with p=0.00447, but p=0.05809567 after Bonferroni), and total cover may increase in thinning treatments compared to controls (p=0.02463, but p=0.2955996567 after Bonferroni). In future studies it may be appropriate to utilize less stringent requirements for paper-inclusion.

Disturbance treatments were different from controls, as predicted, but thinning and burning were not surrogates. Thinning has the negative consequence of enhancing richness and cover of non-native species, which is not a desirable outcome in most management scenarios. Burning reduced shrub cover as compared to the other two treatments and this may or may not be a negative consequence depending on the management objective.

[DWS: TODO, more]

Increase of non-native species due to disturbance is well established as is the intensity of disturbance and amount of increase [@Bartuszevige+Kennedy-2009; @Schwilk+Keeley+etal-2009]. One concern of manipulating systems for conservation outcomes (e.g. fire surrogate treatments) is the risk of increasing the amount of exotic species. This is especially true when large-scale manipulations are applied such as in national forests for which follow-up treatment may be unfeasible. Although increases in these studies were not large, they could be biologically significant if they were allowed to increase in forest understory or if they were introduced after the treatment application. However, some forest stands may be at greater risk for establishment of exotic species. For example, exotic species are less likely to establish in the interior of forests, and more likely to establish in areas near other large invasions and human establishments [OTHER CITATIONS, @Bartuszevige+Gorchov+etal-2006]. Thus, an important consideration for treatment application is proximity to the wildland urban interface (WUI).

To prevent the spread of exotic plants into forest ecosystems after thinning, managers should consider several management options including: no treatment, pre-treatment of exotic plants to reduce their abundance prior to treatment, seeding with native plants [@Korb+Johnson+etal-2004], reducing grazing by domestic livestock prior to and immediately after treatment [@Keeley-2006b], or conducting a low impact disturbance (e.g. burning only); [@Dodson+Fiedler-2006; @Laughlin+Bakker+etal-2008]. Thinning treatments in particular can be modified to reduce soil disturbance (which facilitates invasion of exotic plants). Also, thinning in winter months when equipment will drive over snow will also minimize soil disturbance and thus, the probability of invasion [@Gundale+DeLuca+etal-2005].

We had insufficient data on hebaceous species to generate significant results, even after lumping together forbs and graminoids. Further studies directed at the effects of fire and fire surrogates on the richness and cover of herbaceous species, forbs, and graminoids are needed for analysis to take place.

Many of the studies included in this review concluded that multiple entries into a forest are needed to properly restore the understory to the historical range of variation [Harrington+Edwards-1999; @Metlen+Fiedler-2006; @Laughlin+Bakker+etal-2008; @Waldrop+Yaussy+etal-2008]. Few studies have followed systems over multiple entries; however, Laughlin et al. [-@Laughlin+Bakker+etal-2008] followed a restoration for over a decade after multiple entries. In this system, there was an immediate positive response to herbaceous production. However, differences in species richness took much longer to occur; species richness was higher in treated areas compared to controls after 11 years. The results from this long-term study indicate that restoration of the understory to historical variability is a long-term process involving repeated prescribed burns. The @Laughlin+Bakker+etal-2008 data also provide another important lesson: active fire suppression has occurred for most of the last century and restoration management of the forests is a relatively new occurrence, therefore, it may take multiple treatments to restore a forest. In addition, it may take many years before the effects of the treatments are fully realized.

While it may take many years for the effects of restoration treatments to become fully realized, the results also depend on the pretreatment condition of the area [@Dodson+Peterson+etal-2008]. @Dodson+Peterson+etal-2008 found that treatments did affect understory plant response but the degree of the response was dependent on the pre-treatment condition of the forest such that greater responses were observed in treatment plots with lower initial values. One reason @Dodson+Peterson+etal-2008 were able to document this affect was the Before-After-Control-Impact design of the FFS study. Instead of only collecting data in an unmanipulated “control” plot, pretreatment data were also collected. This is a powerful experimental design that should be encouraged in future investigations of forest restoration.

@Dodson+Peterson-2010 investigated potential differences in treatment effect at multiple spatial scales. They found that treatment did not significantly affect species richness at the smaller quadrat scale (alpha diversity) but diversity at the unit scale (beta diversity) was significantly increased. Thus, effects of forest treatments may not be evident at the scale at which most monitoring is conducted (1 m) but overall impacts may be evident at the forest level. The studies included in this review typically measured results at smaller spatial scales (1–400 m) and evaluated alpha diversity. However, additional analysis to investigate beta diversity may reveal more consistent patterns and may shed light on large-scale impacts of fire and fire surrogate treatments on understory plant communities.

Finally human socio-economic factors are often considered when determining application of treatments. Exotic plants are also associated with the wildland urban interface (WUI) because many exotics are used in landscape and horticultural plantings. Although the Healthy Forest Restoration Act (2003) mandates that most of the forest restoration occurs at the WUI, it is important to recognize that these areas serve as foci for exotic spread into the forest matrix [@Bartuszevige+Gorchov+etal-2006]. Invasion of the forest by exotic plants works against the prescribed goals of forest management to reduce wildfire risk and increase native biodiversity. Some exotic plants can change the fire interval or intensity through a variety of mechanisms such as increasing fuel loads or moisture content of the fuel [@Brooks+DAntonio+etal-2004]. In addition, exotic plants can reduce biodiversity by becoming the dominant species in the forest understory.

Non-native plants were recorded in most studies we presented, but were often at a low density or cover, even post-treatment. Regardless, it is important to understand the potential threat of these species to native understory species in forested landscapes. In general, prescribed fire and thinning treatments can be used successfully to restore understory community composition, but managers would be wise to take into consideration the presence and potential impacts of exotic plants.

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# References