Project Title: Ten years of vegetation development following the 2002 Hayman Fire, Colorado

Joint Fire Science Project Number: 11-1-1-5

Principal Investigator:

Dr. Paula J. Fornwalt, USDA Forest Service, Rocky Mountain Research Station, Fort Collins, Colorado

Co-authors:

Dr. Scott R. Abella, National Park Service, Fort Collins, Colorado (currently with Natural Resource Conservation LLC, Boulder City, Nevada)

Mr. Byron J. Collins, USDA Forest Service, Rocky Mountain Research Station, Fort Collins, Colorado (currently with Stantec Inc., Denver, Colorado)

Final Report

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I. Abstract

Dry coniferous forests of the western United States provide a dramatic example of a biome being transformed by wildfires, yet patterns of post-fire vegetation recovery are largely unclear. We leveraged a unique set of pre-fire and post-fire vegetation data, as well as a set of vegetation data collected in unburned areas, to examine changes in understory plant (*i.e.*, graminoid, forb, and shrub) communities and tree regeneration (*i.e.*, trees <1.4 m tall) in the decade following the 2002 Hayman Fire, the largest wildfire in Colorado's recorded history. Temporal patterns of understory plant composition and tree regeneration varied widely with fire severity. Understory plant composition immediately after low severity fire showed appreciable resistance to change from pre-fire conditions, and demonstrated a continued return toward pre-fire conditions in subsequent years. Meanwhile, understory plant composition following severe fire showed an increasing deviance from pre-fire conditions with passing time. Moderate severity plots had intermediate resemblance to the pre-fire community in all post-fire years. These compositional changes appear to be driven primarily by newly colonizing species, and by changes in the relative abundance of species present in the plots before the fire, rather than by localized extinctions of pre-fire species. Burning tended to increase exotic richness and cover relative to pre-fire and unburned areas, but native species always comprised >89% of total richness and cover, even following severe fire. By ten years post-fire, ample regeneration of *Pseudotsuga menziesii* and/or *Pinus ponderosa* was observed in low and moderate severity plots, as well as in unburned control plots. However, in severely burned plots, *P. menziesii* and *P. ponderosa* regeneration was scarce. Our results inform the ongoing debate in the literature about whether these recent large, and often severe, wildfires are 'ecological catastrophes.'

II. Background and purpose

Dry coniferous forests of the western United States provide a dramatic example of a biome being transformed by wildfires. Annual area burned since the 1980s has increased more than 6-fold over previous decades (Westerling *et al.* 2006), and the largest fires in recorded history have occurred in the 2000s in several western states. These largest fires, and numerous similar fires, are so expansive that they are often termed 'mega-fires' (*e.g.*, Adams 2013). Given that the prognosis is for wildfire, including mega-fires, to continue to increase in occurrence in coming decades (Litschert *et al*. 2012; Adams 2013), it is important for us to gain an understanding of wildfire's impacts on ecological properties and processes.

Considerable debate exists regarding whether mega-fires and other recent wildfires are 'ecological catastrophes' (Keane *et al.* 2008). With regard to vegetation, the effect of a fire will be influenced by the interactions between fire severity patterns and the fire-adaptedness of the species growing within and surrounding the burn (Schimmel & Granström 1996; Turner *et al.* 1997; Wang & Kemball 2005). If many native tree and understory species are not capable of surviving or regenerating following the fire, or if exotic species become well-established post-fire, then effects may indeed be catastrophic (Crawford *et al.* 2001; Savage & Mast 2005; Collins & Roller 2013). Conversely, the fire may provide an ecological benefit if many native tree and understory species survive or regenerate in the burn (Turner *et al*. 1997; Fornwalt & Kaufmann in press).

At 55,800 ha, the 2002 Hayman Fire is the largest fire known to burn in Colorado. This fire was ignited on the afternoon of June 8, 2002. Low fuel moistures, heavy, continuous fuel loadings, and strong, gusty winds enabled the Hayman Fire to burn over 24,000 ha on June 9, mostly as a high severity fire with complete overstory mortality (Finney *et al.* 2003). Less extreme weather conditions followed the next day and persisted for the following three weeks, causing the fire to burn with a finer, more heterogeneous mosaic of low, moderate, and high severities. The fire was declared contained on July 2.

The goal of our Joint Fire Science Program project (11-1-1-5) was to provide new insight into longer-term post-fire vegetation recovery patterns by conducting post-fire year ten understory plant (*i.e.*, graminoid, forb, and shrub) composition and tree regeneration (*i.e.*, trees <1.4 m tall) measurements for a network of existing plots within and surrounding the 2002 Hayman Fire. Understory plant surveys for the plots within the fire had previously been conducted five to six years pre-fire (1996/7), and annually during post-fire years one through five (2003 – 2007); tree regeneration surveys had been conducted during post-fire years two, three, and four (2004 – 2006). Additionally, unburned plots surrounding the fire had been surveyed for both understory plant composition and tree regeneration in post-fire years two, three, and four (2004 – 2006). Specifically, our objectives were to:

1. Identify trends in understory plant composition with fire severity ten years following the Hayman Fire, and relate these trends to pre-fire and to initial post-fire patterns.
2. Assess the potential for exotic understory plants to continue to invade and persist in the Hayman Fire.
3. Investigate patterns of tree regeneration relative to fire severity and time since fire.

Our results provide new insight into fire effects and recovery patterns from wildfires increasingly shaping landscapes across the western United States.

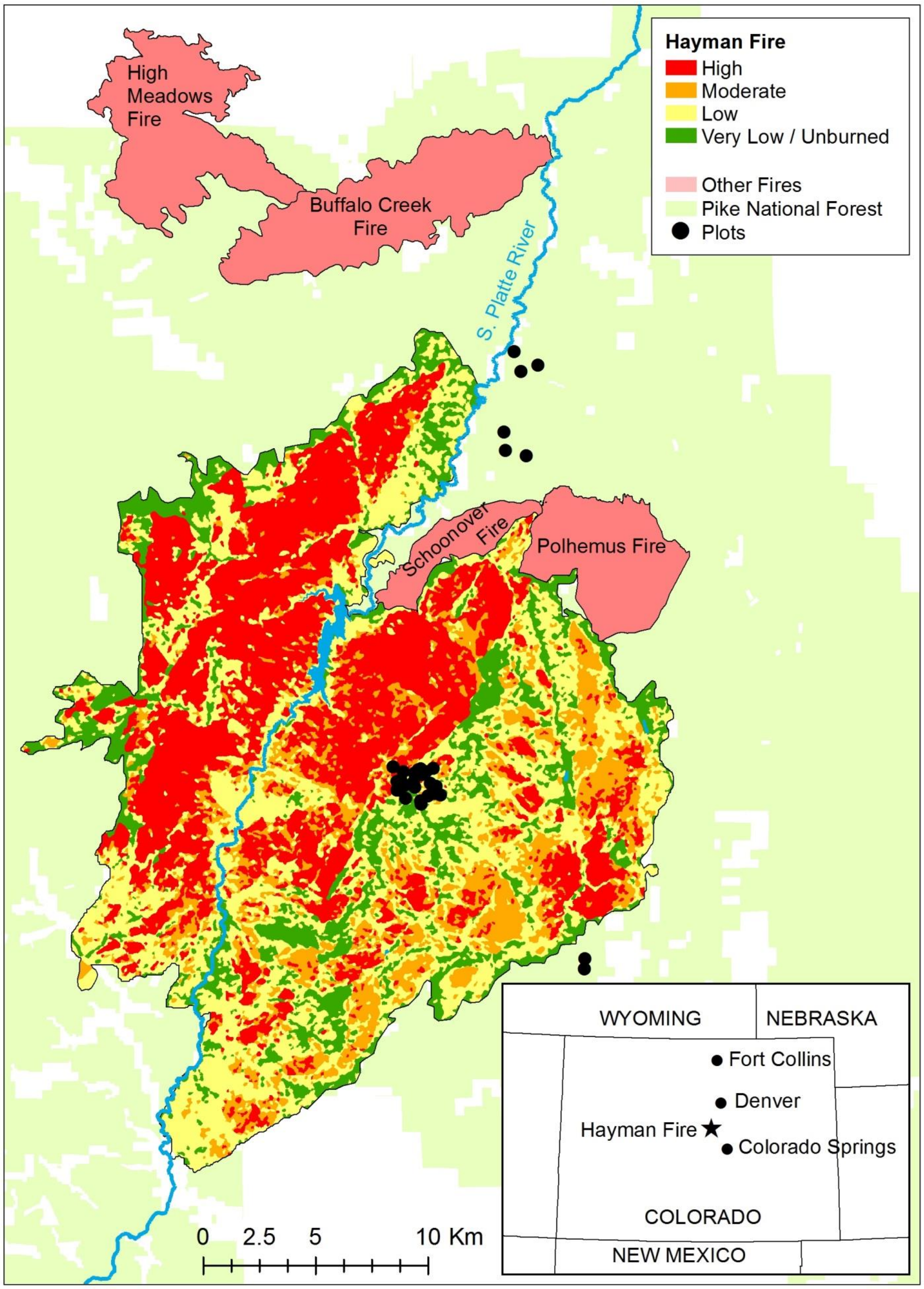
III. Study description and location

Study area

Our study area is 60 km southwest of Denver, Colorado, USA, on Pike National Forest lands within and surrounding the Hayman Fire (Figure 1). Started via human ignition on June 8, 2002, the Hayman Fire ultimately burned 55,800 ha to become the largest wildfire in Colorado's recorded history (Graham *et al.* 2003). According to burn severity maps developed by the USDA Forest Service, ~ 35% of area within the fire perimeter experienced high severity fire, 16% moderate severity, and 49% was either unburned or experienced low severity fire (Robichaud *et al.* 2003).

The study area has a semi-arid climate with an average January temperature of -3°C and average July temperature of 19°C. Over the past 60 years, precipitation has averaged 38 cm yr^{-1}, with most falling during summer (USDA Forest Service, Manitou Experimental Forest, Woodland Park, CO, USA). Precipitation was near or above this long-term average for the 1996/7 pre-fire sampling years and sharply below average in the fire year of 2002; precipitation was also below average for all years in the decade following the fire. Soils are derived from Pike's Peak granite and are generally gravelly and poorly developed (USDA Forest Service 1992). Unburned forests are characteristic of the montane zone of the Colorado Front Range (Kaufmann *et al.* 2000), with *Pinus ponderosa* (ponderosa pine) generally dominating overstories on south- and west-facing slopes and ridgetops, and intermixing with *Pseudotsuga menziesii* (Douglas-fir) on northern and eastern slopes. Elevations range from 2000 m to 2600 m.

Figure 1. Location of study area and study plots within and surrounding the 2002 Hayman Fire. Other recent large (>1000 ha) fires are also shown.



Study sites

Data collection within the Hayman Fire occurred at a 400-ha site in which 20 randomly-located 1000-m^2 (20 m × 50 m) plots were originally established in 1996 or 1997 (Kaufmann *et al*. 2000; Fornwalt *et al*. 2003, 2009). Immediately following the Hayman Fire, we re-established each plot and classified it as burning with high, moderate, or low severity based on the fire's direct effects on the overstory and forest floor. Plots with < 50% overstory mortality were categorized as burning with low severity, while moderate severity plots had ≥ 50% overstory mortality but only modest levels of crown and forest floor consumption (Fornwalt *et al.* 2010; Fornwalt & Kaufmann in press). High severity plots were those with 100% overstory tree mortality and nearly complete forest floor consumption.

In 2004, three unburned sites were established to provide a comparison with the Hayman Fire site. The unburned sites were ~300 ha in size, and were selected to match the environmental conditions, land-use history, and pre-fire overstory conditions of the burned study site as closely as possible. The unburned sites were just outside the Hayman Fire perimeter, 10 to 18 km from the burned site. Each unburned site originally contained three randomly-located 1000-m^2 plots, but one plot was partially logged in 2011 and was dropped from the data set, leaving eight plots.

Data collection and data classification

Understory plant composition (graminoid, forb, and shrub species) and cover were recorded using the modified-Whittaker sampling design (Stohlgren *et al.* 1995). Burned plots were surveyed seven times, in 1996 or 1997 (five or six years pre-fire), annually from 2003 to 2007 (one to five years post-fire), and in 2012 (ten years post-fire). Unburned plots were surveyed four times, in 2004, 2005, 2006, and 2012 (two, three, four, and ten years post-fire). Areal cover of each species was estimated in ten 1-m^2 subplots per plot. Species presence was noted in two 10-m^2 subplots, one 100-m^2 subplot, and the 1000-m^2 plot. Most plants were identified to species, but some were only identified to genus (*e.g.*, *Carex* or *Chenopodium* spp.). Nomenclature follows The PLANTS Database (Natural Resources Conservation Service 2013).

To aid in analysis, understory species were classified in three ways. First, species in burned plots were classified as either 'legacy' (present in plots during the pre-fire survey) or 'new' species (not present in the pre-fire survey). A species could be a legacy species in one plot but a new species in another, depending on whether it was recorded before fire. Second, species were classified into one of four groups reflective of their life history and growth form: short-lived forbs (annual, biennial, or annual-perennial life spans), long-lived forbs (perennial life spans), graminoids, and shrubs. Short- and long-lived graminoids were not separated into their own groups because short-lived graminoids were scarce. Third, species were classified as either native or exotic to the continental United States. These latter two classifications were made using The PLANTS Database (Natural Resources Conservation Service 2013) and local botanical keys (Harrington 1964; Weber & Wittmann 2001).

To quantify tree regeneration, we documented the height and species of all live trees <1.4 m tall within four 15-m^2 circular subplots per plot. Measurements were conducted in all burned and unburned plots in 2004, 2005, 2006, and 2012 (two, three, four, and ten years post-fire).

Data analysis

We analyzed our dataset using both multivariate and univariate techniques. Multivariate analyses were conducted in PC-ORD 6.0 by ordinating understory species composition (relative cover) of burned plots using non-metric multi-dimensional scaling (NMS; Sørensen distance, 'slow and thorough' setting). From these ordinations, we further calculated successional vectors, depicting species compositional change between pre- and post-fire years. As a measure of amount of change, we calculated lengths of vectors from vectors standardized to the origin as the Euclidean distance between ordination scores of pre- and post-fire years on each plot. We examined univariate changes in understory community similarity, understory plant richness, understory plant cover, and tree regeneration with respect to burn severity, year, and burn severity × year using repeated measures analysis of variance in SAS 9.4. Plot-level Sørensen similarity indices between pre- and post-fire years were calculated in PC-ORD using matrices of relative understory cover (cover species/∑ all species on a plot). Understory richness (species 1000 m^{-2}) and cover were examined in total and by the three groups described above (legacy and new species; short-lived forb, long-lived forb, graminoid, and shrub; and native and exotic). Cover was square-root transformed to improve distribution and homogeneity of residuals. Models used the spatial power covariance matrix, accommodating greater correlation between two repeated observations closer in time than between two distant observations. For models with terms significant at $P < 0.05$, we examined pairwise differences between levels of each term using least squares means and Tukey-Kramer adjustment.

IV. Key findings and management implications

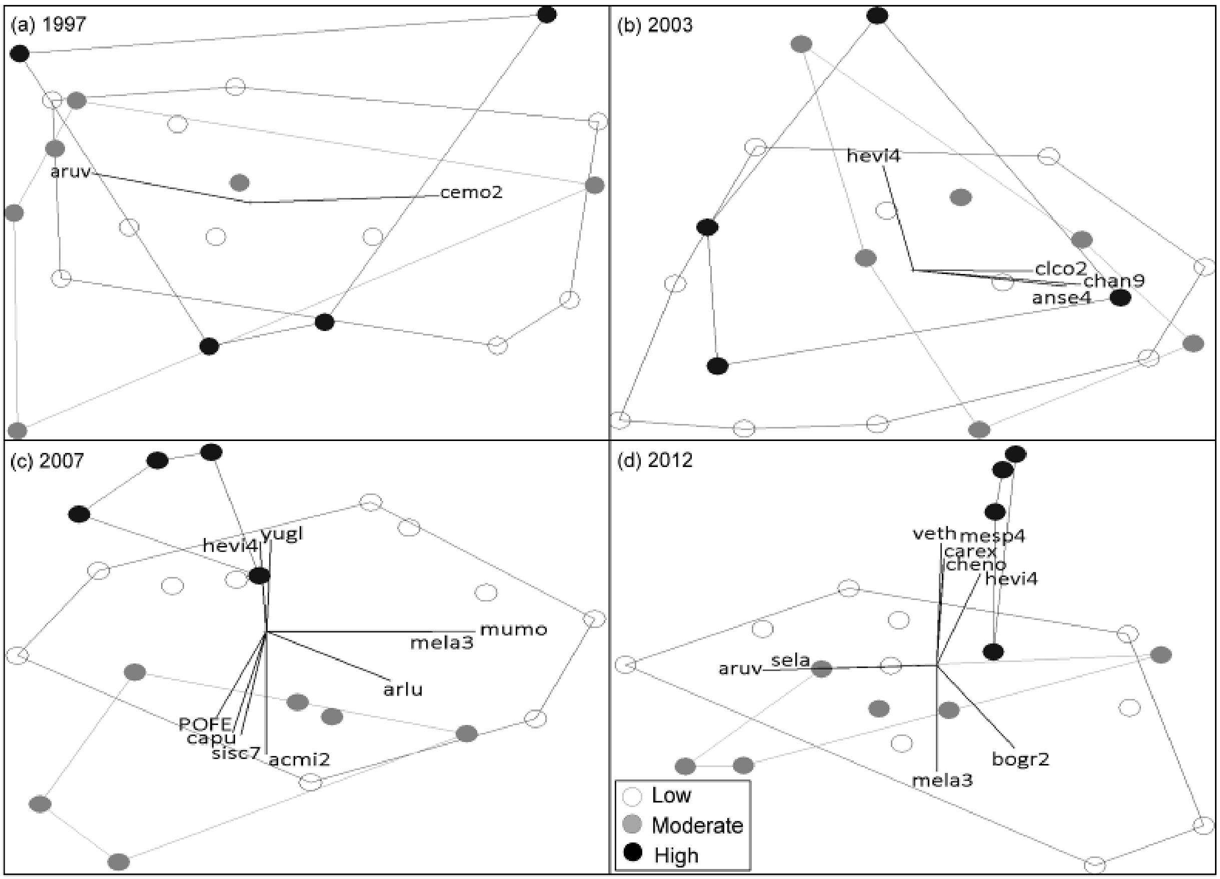
Key findings, and their management implications, are described below in relation to the three project objectives.

Identify trends in understory plant composition with fire severity ten years following the Hayman Fire, and relate these trends to pre-fire and to initial post-fire patterns.

NMS ordinations revealed that fire severity and time since fire impacted understory community composition in burned plots (Figure 2). There was little to no grouping of plots by fire severity before fire, but differentiation among the fire severity classes increased as time since fire passed. At five years post-fire in 2007, plots assembled into a compositional gradient in multivariate space from low, moderate, to high severity, a pattern maintained at ten years post-fire. Furthermore, ten years post-fire, low severity plots exhibited less deviance from the pre-fire community than they did at one or five years post-fire, suggesting a return to pre-fire conditions (data not shown). Meanwhile, deviance of high severity plots continued to increase, suggesting further divergence from the pre-fire community. Moderate severity plots were variable through time and had intermediate resemblance to the pre-fire community by ten years post-fire.

Figure 2. NMS ordinations of the (a) pre-fire, (b) one-year post-fire, (c) five-year post-fire, and (d) 10-year post-fire understory plant communities before/following the 2002 Hayman Fire, Colorado, USA. Plots, grouped by burn severity connected via convex hulls, exhibit differentiation through time, especially for the high-severity class. Vectors display species correlated ($r2 \geq 0.40$) with plant community gradients. Species abbreviations follow The PLANTS database (Natural Resources Conservation Service 2013): acmi2 = *Achillea millefolium*, anse4 = *Androsace septentrionalis*, arlu = *Artemisia ludoviciana*, aruv = *Arctostaphylos uva-ursi*, bogr2 = *Bouteloua gracilis*, capu = *Calamagrostis purpurascens*, carex = *Carex* spp., cemo2 = *Cercocarpus montanus*, chan9 = *Chamerion angustifolium*,

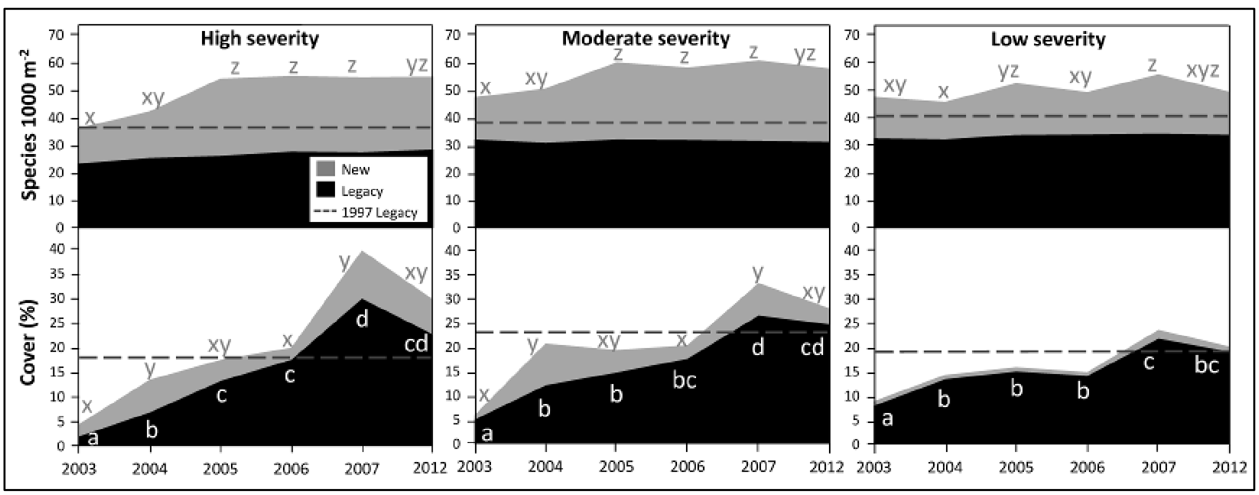
cheno = *Chenopodium* spp., clco2 = *Clematis columbiana*, hevi4 = *Heterotheca villosa*, mela3 = *Mertensia lanceolata*, mesp4 = *Mentzelia speciosa*, mumo = *Muhlenbergia montana*, POFE = *Poa fendleriana*, sela = *Sedum lanceolatum*, sisc7 = *Silene scouleri*, yugl = *Yucca glauca*, and veth = *Verbascum thapsus*.



The compositional changes revealed by the multivariate analyses appear to be driven more by newly colonizing species, and by changes in the relative abundance of legacy species, than by localized legacy species extinctions (Figure 3). Even severely burned plots contained >60% of the pre-fire species (24 of the 38 pre-fire species) in the first post-fire year, >70% of the pre-fire species (29 of the 38 pre-fire species) in the tenth year. Furthermore, an average of 15 new species per 1000-m^2 plot were documented in the first post-fire year across all severities; the number of new species per plot was subsequently sustained or increased for the duration of the study, with the greatest accrual of new species occurring in moderate and high severity plots. New species colonizing our plots were primarily short-lived and long-lived forbs, with short-lived forbs tending to establish in the first or second post-fire year, and long-lived forbs tending to establish later.

Our findings on understory plant compositional changes in the decade following the Hayman Fire have several implications for management. First and foremost, our results demonstrate that the Hayman Fire was not an ‘ecological catastrophe’ from the perspective of understory plants. Rather, burning promoted rich and productive understories despite the entire 10-year post-fire period receiving below-average precipitation. These understories contained both pre-fire species, which largely demonstrated an ability to recover even following severe fire, and newly-established species. Our results also provide insight into the need for post-fire rehabilitation treatments such as seeding. Seeding has become a somewhat controversial practice, as it can introduce novel genotypes, promote exotic plants (either by being directly seeded or by being present as seed contaminants), and retard natural recovery processes (Peppin *et al.*, 2010). Given that we largely found equal or higher values of understory plant richness and cover after burning, as well as relatively low values of post-fire exotic richness and cover (see below), seeding seems unnecessary for promoting native plants.

Figure 3. Dynamics of legacy and new understory plant species following the 2002 Hayman Fire. Letters compare means (P < 0.05) separately for legacy species (a, b, c, d) and new species (x, y, z) among years within a burn severity class. Broken lines signify levels in the pre-fire community.

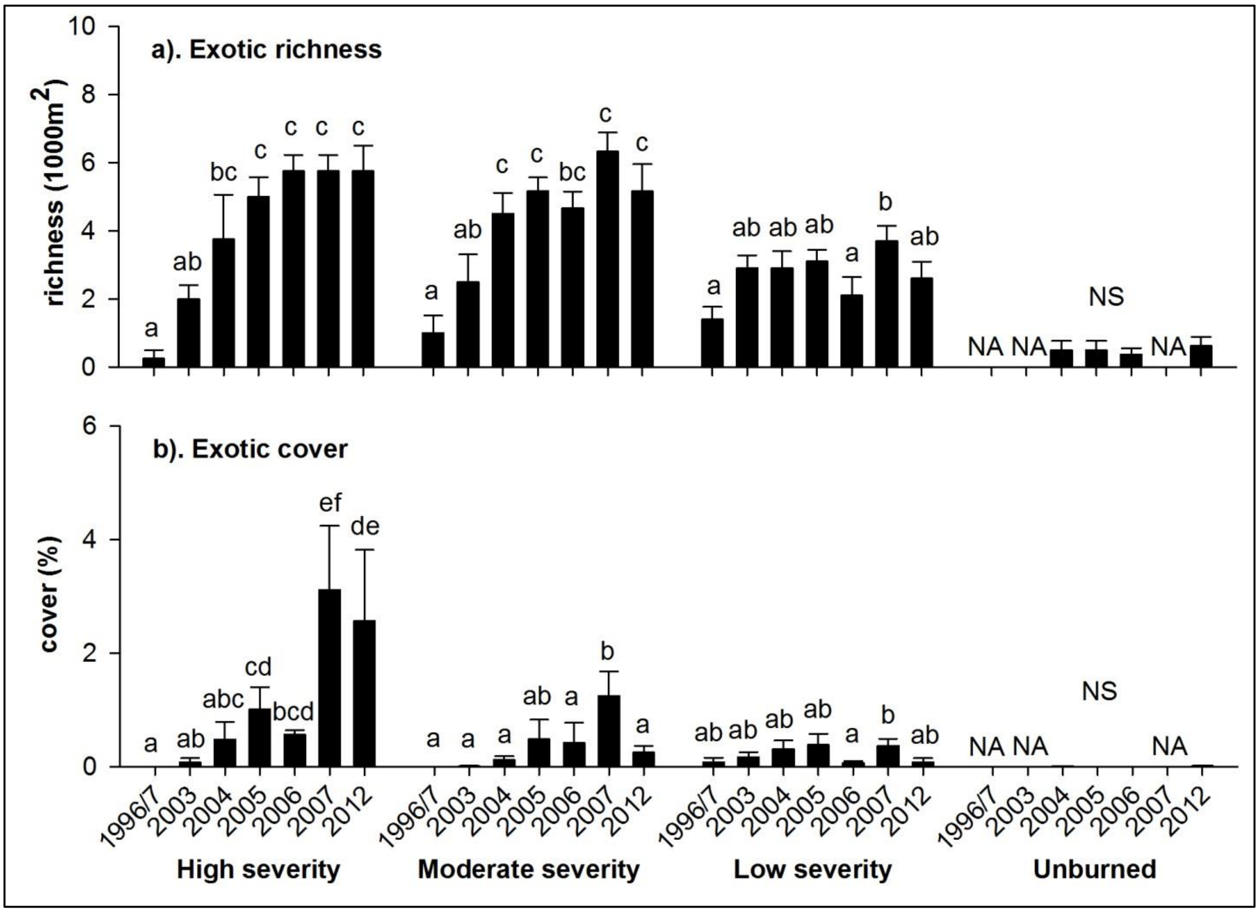


Assess the potential for exotic understory plants to continue to invade and persist in the Hayman Fire.

Burning tended to increase exotic plant richness and cover relative to pre-fire and unburned conditions (Figure 4). By the second post-fire year, exotic richness in moderately and severely burned plots was significantly greater than pre-fire richness, and remained so for the duration of the study; post-fire exotic cover was also significantly greater than pre-fire cover for four of the six post-fire years in high severity plots and for one of the six post-fire years in moderate severity plots. Following low severity burning, post-fire exotic richness was elevated over pre-fire levels in one post-fire year, and exotic cover was never elevated. On unburned plots, in contrast, exotic plants were sparse and showed no variance through time. However, despite the trend for elevated exotic richness and cover after fire, particularly in severely burned areas, exotic richness and cover values were relatively low, and native species always comprised >89% of total richness and cover.

Invasion by exotic plants was driven both by new colonizers, where 10 of the 17 total exotic species recorded during the study were absent from the pre-fire community, and by expansion of five of the seven species already present before the fire. For example, *Lactuca serriola* (prickly lettuce) was absent from the pre-fire community but occupied 55% of burned plots in post-fire year one and 85% of burned plots in post-fire year five; by post-fire year ten, *L. serriola* was found in 35% of burned plots. *Bromus tectorum* (cheatgrass) was also absent pre-fire but was found in 20% of plots in post-fire years five and ten. *Bromus inermis* (smooth brome), *Linaria vulgaris* (butter-and-eggs), *Taraxacum officinale* (common dandelion), *Tragopogon dubius* (yellow salsify), and *Verbascum thapsus* (common mullein) all were present in the pre-fire community, and in post-fire year ten, they were found in 2 – 12 times more plots than before the fire.

Figure 4. Exotic plant richness and cover before (1996/7) and after (2003 – 2012) the 2002 Hayman Fire. Bars are means and error bars are standard errors of means. Letters separate means through time within a burn severity class (NS = not significant at P < 0.05). NA for unburned plots notes data not available.



Many researchers have found that exotic plants increased shortly after wildfire in western dry coniferous forests, and that exotics were most abundant in severely burned areas (Crawford *et al*. 2001; Griffis *et al*. 2001; Freeman *et al*. 2007; Kuenzi *et al*. 2008; Fornwalt *et al*. 2010). Our results reinforced these findings and further showed that in severely burned areas, elevated levels of exotic richness and cover persisted even ten years following fire. However, our study also reported relatively low values of exotic richness and cover, even in severely burned areas, and burned communities remained dominated by natives. Thus, we suggest that exotics in the Hayman Fire should not be a major management concern at present. Nonetheless, the trend for exotic plants to remain elevated through time is cause for some concern, especially since some of the species include aggressive invaders like *Linaria vulgaris* and *Bromus tectorum*.

Investigate patterns of tree regeneration relative to fire severity and time since fire.

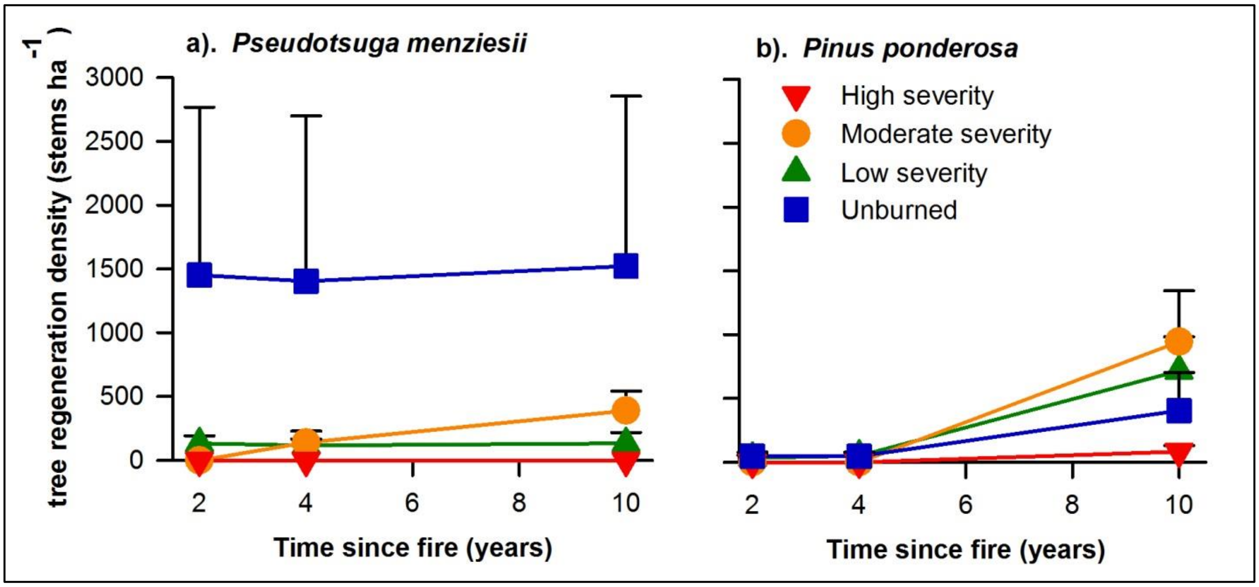
Tree regeneration was dominated by *P. menziesii* (50% of total tree regeneration), *Populus tremuloides* (quaking aspen; 33%), and *P. ponderosa* (13%) across all burned and unburned plots and years. Trace amounts of *Picea pungens* (blue spruce; 3%) and *Pinus flexilis* (limber pine; <1%) were also found. Because >80% of regenerating *P. tremuloides* stems were concentrated in one unburned and two burned plots, this species was not analyzed further. *P. pungens* and *P. flexilis* were also not analyzed further due to their low abundances in our plots.

P. menziesii regeneration varied with both fire severity and time since fire (Figure 5a). In post-fire year two, *P. menziesii* regeneration in unburned plots was abundant, albeit highly variable; lightly burned plots also contained some regenerating *P. menziesii*. Height measurements (averaging 0.3 m in unburned and 0.5 m in burned plots) and observations of numerous whorls on these regenerating stems indicated that most established prior to the year of the fire. Regeneration densities in unburned and lightly burned areas ten years following fire were little changed from initial densities. In contrast, moderate and high severity plots contained no *P. menziesii* regeneration in post-fire year two, indicating that any pre-fire regeneration was killed. Some regeneration was observed, however, in moderate severity plots in post-fire years four and ten. *P. menziesii* regeneration was not subsequently documented in high severity plots.

P. ponderosa regeneration also varied with fire severity and time since fire (Figure 5b), although patterns were quite different than those for *P. menziesii*. Regeneration was scarce in unburned and lightly burned plots and absent in moderately and severely burned plots two years following fire. By post-fire year ten, ample *P. ponderosa* regeneration was documented in unburned, lightly burned, and moderately burned plots, but not in severely burned plots.

With ~80 regenerating conifers ha^{-1} on average, and no surviving pre-fire overstory, our severely burned plots remain well below the level at which they would be considered fully stocked (370 stems ha^{-1}). In areas such as those that we studied, where surviving trees (and thus a seed source) are 100s or even 1000s of meters away, planting *P. ponderosa* and/or *P. menziesii* is likely necessary if managers wish to return them to a coniferous forest cover type in the foreseeable future. However, other areas, such as those adjacent to a seed source, may have adequate levels of regeneration to meet stocking guidelines (Bonnet *et al.* 2005).

Figure 5. ***Pseudotsuga menziesii*** **and** ***Pinus ponderosa*** **regeneration (trees <1.4 m tall) in burned and unburned plots 2, 4, and 10 years following the 2002 Hayman Fire.**



V. Relationship to other recent findings and ongoing work on this topic

This project directly relates to two other projects that we are currently conducting. The first project is utilizing this same network of plots to examine overstory tree and surface fuel dynamics during the decade following the Hayman Fire. The second project is more thoroughly examining tree regeneration in severely burned portions of six Front Range wildfires, including the Hayman Fire; the aim of this project, being conducted by a M.S. student at Colorado State University, is to characterize tree regeneration patterns in severely burned areas in relation to distance from seed source and other hypothesized driving factors.

VI. Future work needed

While results of this project advanced our understanding of longer-term vegetation recovery patterns following wildfire, additional research that expands our project's spatial and temporal scope is needed. We do not know of any other longer-term examinations of understory plant composition and exotic plant invasions following wildfires in the western United States, and longer-term examinations of tree regeneration are limited; thus, work on these topics is necessary to evaluate the generality of our findings to broader landscapes. Additionally, future vegetation measurements in our unique network of plots (*e.g.*, during post-fire years 15 and 20) are necessary to examine post-Hayman recovery patterns over even longer time frames.

VII. Deliverables crosswalk table

Findings have been or will be communicated to multiple audiences using a variety of formats, including refereed publications, presentations, and field tours.

Deliverable	Status
Field tours	We have presented portions of this work on two field trips to date: • Fornwalt PJ. Post-fire plant dynamics in Front Range ponderosa pine – Douglas-fir forests. Denver Chapter of the Colorado Native Plant Society, Deckers, CO, 12 July 2013. • Fornwalt PJ. Post-fire understory plant development and tree regeneration following the Hayman Fire. Colorado State University Restoration Ecology Class (NR479), Deckers, CO, 19 August 2013. We also anticipate that additional field trips will occur in 2014 and beyond.
Oral/poster presentations	Portions of this work have been presented orally five times to date: • Fornwalt PJ and Collins BJ. Ten years of ecosystem recovery following the Hayman Fire. Colorado Native Plant Society Denver Chapter Monthly Meeting, Denver, CO, 23 October 2012. • Fornwalt PJ and Collins BJ. Ten years of overstory stand structure, surface fuel, and tree regeneration dynamics following the 2002 Hayman Fire. 5th International Fire Ecology and Management Congress, Portland, OR, 3-7 December 2012. • Fornwalt PJ. Ten years of ecosystem change following the 2002 Hayman Fire. Colorado Native Plant Society Northern Chapter Monthly Meeting, Denver, CO, 4 April 2013. • Fornwalt PJ and Abella SR. The 2002 Hayman Fire – ecological benefit or catastrophe? Colorado Weed Management Association Annual Meeting, Colorado Springs, CO, 4-5 December 2013. • Fornwalt PJ. Ecological effects of the 2002 Hayman Fire, Colorado. Western State Colorado University, Natural and Environmental Sciences Departmental Seminar, Gunnison, CO, 21 February 2014. Furthermore, we plan to present some of our findings at the upcoming Large Wildland Fires Conference: • Fornwalt PJ and Abella SR. Ten years of understory vegetation assembly after Colorado's largest mega-fire. Large Wildland Fires: Social, Political & Ecological Effects, Missoula, MT, 19-23 May 2014.

Deliverable	Status
Refereed publication	We expect to publish our results as two refereed manuscripts. One manuscript, recently submitted to *Global Change Biology*, focuses on understory plant community dynamics. The tree regeneration data collected in support of this project will be combined with overstory tree and surface fuel data to form the second paper (see Section V), which is currently in preparation. • Abella SR and Fornwalt PJ. In review. Ten years of understory vegetation assembly after a North American mega-fire. Submitted to *Global Change Biology* on 24 February 2014. • Fornwalt PJ and Collins BJ. In preparation. Tree and fuel load dynamics in the decade following a Colorado mixed severity wildfire. To be submitted to *Fire Ecology* in spring 2014. Additionally, portions of this work were highlighted in the Colorado Weed Management Association newsletter: • Fornwalt PJ. 2013. The 2002 Hayman Fire – ecological benefit or catastrophe? Perspectives from the understory plant community. *Weed Watch* 29(3): 14-15.

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