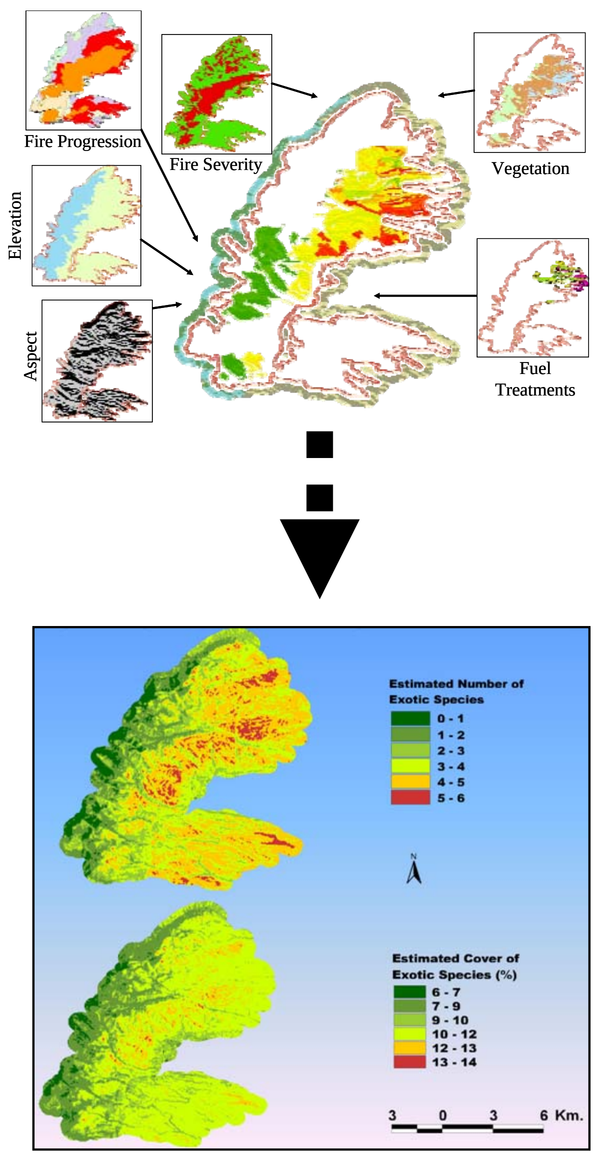
SPATIAL INTERACTIONS AMONG FUELS, WILDFIRE, AND NON-NATIVE PLANTS



Final Report

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Executive Summary

This project investigated the relationships among fuels, wildfire severity, and non-native plants in three mixed conifer forests in the Rocky Mountains of Colorado and New Mexico. Our research addressed the following questions:

- *To what extent is fire severity related to stand conditions?*

The relationship between fuel variables and fire severity varied substantially among our three study sites, but fuel treatment by prescribed fire consistently appeared as an informative and significant mitigating variable. Stand conditions that can be managed by mechanical thinning, such as tree density and mean tree diameter, also significantly influenced the severity of all three fires: fire severity decreased with increases in mean tree diameter and/or decreases in stand density. Our models explained a significant portion of the variability in fire severity, but explanatory power varied among sites. Historic fire regime may influence the degree to which fire behavior and severity can be explained by fuel variables versus weather variables and suggests caution in applying fuel treatments outside of short fire return interval systems.

- *Is fire severity a predictor of non-native abundance?*

Fire severity was a consistent predictor of higher non-native species cover at all three fires and was a more important predictor of non-native species establishment than other abiotic variables. Our results suggest that wildfires may be one of the more important mechanisms for continued spread of non-native species in the western US.

- *Do disturbances created by pre-fire treatments provide a source for post-fire invasion by non-native species?*

The influence of fuel treatments is less than that of wildfire on the establishment of non-native species, but there is a potential for higher establishment of non-native species in thinned areas. We found a slightly higher incidence of non-native species in the thinned areas of one of our study sites. However, we found no difference in non-native species cover between treated and untreated areas at the other two sites.

- *Does post-fire seeding mitigate invasion risk?*

Establishment and spread of non-native species following wildfire may be deterred through appropriate post-fire management actions. However seed mixes are often contaminated with non-native species and their application on landscape scales may introduce a large number of non-native weed seeds. Seed mixes were extensively applied by air at two of our sites where we found a positive association between the cover of non-native species and seeded grasses. However, at our other site, seed mixes were intensively applied by hand or seed drill on a more limited scale. Here post-fire seeding successfully deterred non-native species establishment, similar to the effect of abundant native cover. Post-fire treatments that encourage high vegetative cover, without introducing new non-native species in contaminated seed mixes, would best prevent further spread of non-native species.

- *Do invaded areas represent greater post-fire fuel hazard?*

The influence of non-native plant species on post-fire flammability was not consistent across our three study sites. Non-native species significantly increased post-fire flammability at one site, decreased flammability at another site, but had no effect at the third site. The suite of non-native species found at each site varied and different species will uniquely influence the fuel bed parameters that determine flammability, such as surface-area-to-volume ratio and relative packing. However, differential species influences on flammability may become more pronounced as total vegetation cover increases over time.

Our findings highlight some of the ecological risks and benefits associated with pre- and post-fire management activities and our multi-scale sampling method provided an excellent data source and input for spatial models. Integration of remotely sensed data, geographic information systems, and field data can be used to produce spatial statistical prediction maps; a cost-effective means to identify areas vulnerable to non-native plant species invasion and increased potential for wildfire.

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1. **Project Background**

1.1 ***Rationale***

Synergistic interactions and positive feedbacks among fuels, extreme wildfire behavior, and non-native plant species are widely recognized as major threats to the structure and function of natural ecosystems (Mack and D'Antonio 1998). Twentieth century land use and management practices may have unwittingly increased the vertical and horizontal continuity of fuels and the incidence of large catastrophic wildfires in forest types that previously experienced more frequent, less-severe fires (Allen et al. 2002). Disturbances such as fire may promote non-native plant species invasions by increasing available light and nutrients, as well as by decreasing competition from native plants for these resources (Fox 1979, Melgoza et al. 1990). Once established, non-native species may further alter fuel bed characteristics that increase the likelihood of future catastrophic wildfires (Whisenant 1990a). Despite the recognition of interactions between fire and non-native invasive plant species, these interactions have not been well studied; particularly in western montane coniferous forests (Harrod and Reichard 2001). This project sought to elucidate some of the spatial relationships among fuel characteristics, burn severity, non-native plant species, and fuel flammability after three large wildfires in montane coniferous forests of the Rocky Mountains in New Mexico and Colorado.

Burn severity is the post-fire manifestation of fire behavior (Rothermel and Deeming 1980) resulting from complex interactions among fuels, topography, and weather (Rothermel 1972). A relationship between fuel conditions and burn severity is therefore expected. However, the predictive models commonly used to derive this relationship are limited under the extreme environmental conditions that generally accompany large wildfire events (Andrews 1986; Rothermel 1991). Empirical evidence relating fuel modification to fire severity is surprisingly sparse (Martinson and Omi 2003).

Non-native plant invasion into wildfire burn areas is commonly expected based on disturbance theory (Fox 1979). Non-native plants have been found to invade Hawaiian woodland (Hughes et al. 1991) and Great Basin steppe (Billings 1994) after wildfire, as well as California chaparral after prescribed fire (Zedler and Scheid 1988; D'Antonio et al. 1993). But other investigators have found prescribed fire to have either no effect one growing season post-fire (in Rocky Mountain ponderosa pine *op. cit.* Petterson 1999) or to inhibit non-native plant invasions (in Great Plains grasslands *op. cit* Smith and Knapp, 1999; Whisenant 1990b). The Fire Effects Information System (Fischer et al. 1996) includes more than 80 non-native species, but data on the post-fire response of most of these are limited and the relationship to fire severity is rarely investigated. The effect of post-fire seeding and mulching on mitigating non-native plant invasion is also uncertain (Robichaud et al. 2000). Non-native invasions may be facilitated by seeding in some cases, particularly via seed contamination (Beyers 2004).

A current paradigm suggests that post-fire invasion by non-native plants increases fuel flammability and initiates a positive feedback cycle that maintains ecosystems in a perpetually altered state of non-native dominance (D'Antonio and Vitousek 1992). Fire frequency has reportedly increased since the introduction of non-native grasses in Idaho shrublands (Whisenant, 1990a) and Hawaiian woodland (Hughes et al., 1991). Knapp (1998) found that large fires in the Intermountain West are clustered in areas dominated by non-native annual grasses. Increased fire frequency in areas invaded by non-native plants (especially grasses) is presumed to result from physical alterations to fuel bed complexes that increase their flammability. Altered fuel characteristics such as increased surface area-to-volume ratio and horizontal continuity and decreased fuel moisture content might explain increases in fire intensity, size, and length of seasons (D'Antonio and Vitousek 1992). However, we are unaware of a study that has actually measured and calculated fuel bed characteristics to relate predicted post-fire flammability (after Burgan and Rothermel 1984) to non-native species presence or abundance.

1.2 *Objectives*

The goal of this research was to determine the factors that contribute to post-fire invasion by non-native plants and to identify effective mitigation options for land managers. We sampled three large wildfires in montane coniferous forests in the Rocky Mountains of New Mexico and Colorado to meet the following objectives in support of our research goal:

- Relate wildfire severity to manageable pre-fire fuel characteristics (e.g., stand density, basal area, canopy base height).
- Relate plant species (native and non-native) composition to wildfire severity.
- Relate post-fire fuel flammability to non-native plant species abundance.
- Extrapolate plot-level information to landscape scales with generalized predictive spatial models derived from remotely sensed imagery to allow broader examination and conclusions regarding the interactions among fuels, wildfire, and non-native plant invasions.

1.3 *Hypotheses*

We tested four null hypotheses based on our stated objectives:

H_{o1}: There is no correlation between wildfire severity and manageable pre-fire fuel characteristics, rather any observable trends in wildfire severity will be explained by other variables (e.g., slope, aspect, burn date (as a proxy for weather conditions)).

H_{o2}: There is no correlation between the abundance of non-native plants and wildfire severity, rather any observable trends in non-native plant cover will be explained by other variables (e.g., elevation, soil type, proximity to roads and streams).

H_{o3}: There is no correlation between fuel flammability and the abundance of non-native plants, rather any observable trends in fuel flammability will be explained by other variables (e.g., fuel load, topographic influences on curing rates).

H_{o4}: Spatial models cannot be developed to accurately predict field conditions from remotely sensed information, restricting the above hypothesis tests to traditional site-specific analyses.

Rejection of the above null hypotheses would allow us to infer that non-native plant species contribute to the perpetual alteration of some ecosystems by increasing their flammability, but that proactive and strategic fuels management can mitigate post-fire non-native invasions by reducing wildfire severity. Further, successful development of predictive spatial models (Chong et al. 2001) would allow us to determine the landscape conditions at greatest risk to non-native plant invasions after fire.

1.4 ***Deliverables***

The funded proposal for this project included eight deliverables. Table 1 lists the proposed deliverables and the method of product delivery.

Table 1. Products proposed and delivered by this project.

Proposed Deliverable	Product Delivery
3 Databases of plant species location and abundance.	Metadata described in Appendix C.2 and submitted for inclusion in the JFSP-funded FRAMES online catalog (http://frames.nbii.gov/portal/server.pt).
3 Progress reports.	Oral presentations delivered at JFSP Principal Investigator meetings in 2002, 2003, and 2004 (see Appendix A).
3 Arcview shapefiles that map predicted post-fire invasion by non-native plant species.	Metadata described in Appendix C.4 and submitted for inclusion in the JFSP-funded FRAMES online catalog (http://frames.nbii.gov/portal/server.pt).
Models of post-fire invasion risk and flammability.	Described in Section 3 of this report.
Outline for potential workshop.	Presented in Appendix D.
Final report.	Submitted May 31, 2005.
Publishable manuscript(s).	See Appendix A for citations and URLs: 2 papers in published proceedings. 2 chapters in a US Forest Service General Technical Report. 2 papers submitted to peer-reviewed journals. 1 doctoral dissertation. 1 master's thesis.
Project web site.	http://www.cnr.colostate.edu/frws/research/weeds/

2. **Methods**

2.1 ***Study Areas***

We sampled three wildfires in the course of this study: the 2000 Cerro Grande fire, the 2000 Hi Meadow fire, and the 2002 Hayman fire (Figure 1). Each fire occurred in low-elevation forests of the Rocky Mountains, burned at least 4,000 ha (10,000 acres) with variable severity, and included both pre- and post-fire management activities.

Figure 1. Study site locations. Three wildfires were sampled in the eastern Rockies for information on pre-fire stand conditions, fire severity, post-fire plant species composition, and post-fire fuel characteristics. Distribution of sample plots follow a stratified random sampling design (Figure 2).

Study Site:	Cerro Grande, NM	Hi Meadow, CO	Hayman, CO
Fire Date:	May 2000	June 2000	June 2002
Sample Date:	Summer 2001	Summer 2002	Summer 2003
Fire Size (km^2):	193	44	554
Sample Size :	79	94	122

The Cerro Grande fire was management ignited on May 4, 2000 in Bandelier National Monument near Los Alamos, New Mexico. The objective of the prescribed fire was to reduce fuels and restore pre-settlement forest structure. The fire went out of prescription on May 5 and high winds on subsequent days forestalled control until June 8. The fire reached a final size of 193 km^2. The most active burning days were on May 10 and 11 when the fire burned into the Garcia Canyon watershed where the Santa Fe National Forest had done extensive fuel-reduction treatments since 1994. The treatments included mechanical thinning and prescribed burning, both in isolation and in combination. Grass seed was aerially applied to areas that were classified as high and moderate fire severity (80 km^2) to reduce the potential for increased runoff and erosion. Elevation ranges from 2,000 m to 3,140 m. White fir (*Abies concolor*) is abundant at higher elevations and ponderosa pine (*Pinus ponderosa*) is dominant at mid-elevations with pinyon pine (*Pinus edulis*) and juniper (*Juniperus* spp.) abundant at lower elevations. We sampled this area in the summer of 2001.

The Hi Meadow fire started on June 12, 2000 from an undetermined ignition source on private land in Park County, Colorado. Before containment on June 20 the fire grew to a size of 44 km^2. Approximately half the burn area was on the Pike National Forest, which had accomplished treatments since 1990 involving both prescribed fire and mechanical thinning on about 12.5 km^2. Post-fire seeding occurred on about 12.5 km^2, as well. Elevation ranges from 2,150 m to 2,500 m. Ponderosa pine is dominant in the canopy with lodgepole pine (*Pinus contorta*) and Douglas-fir (*Psuedotsuga menziesii*) also present. We sampled this area in the summer of 2002.

The Hayman fire ignited on June 8, 2002, from an illegal camp fire on the Pike National Forest in Park County, Colorado, approximately 48 km south of the Hi Meadow burn area. The fire remained active until June 28, by which time it had burned 554 km^2. Approximately one-third of this area burned on a single day (June 9). Management activities had occurred on approximately 81 km^2 within the burn area, though we focused on the prescribed fire and mechanical thinning activities conducted since 1990. Post-fire seeding occurred on about 130 km^2. Elevation ranges from 2,150 m to 2,500 m. Ponderosa pine and Douglas-fir are dominant in the canopy with lodgepole pine also present. We sampled this area in the summer of 2003.

2.2 ***Landscape Stratification***

Sample points within each study area were selected randomly within several strata. Landscape stratification was accomplished with Arcview GIS software (ESRI 1999) and existing spatial data layers (Figure 2). Strata included vegetation type (including pre-fire fuel treatment status), aspect, burn severity (including unburned reference areas within 300 m of the fire perimeter), and post-fire mitigation activities (with a focus on seeding). Fire progression maps were used to restrict sampling to those burn periods that affected the majority of the fuel treatment areas (May 10-11, 2000 in the Cerro Grande fire, June 13-15, 2000 in the High Meadow fire, and June 9, 2003 in the Hayman fire). Areas that had been subject to management activity prior to 1990 were avoided, as were areas that were subject to post-fire activities other than seeding (e.g., herbicides or felling). At least three plots were sampled within each stratum.

2.3 ***Data Collection***

We established a Modified-Whittaker plot at each sampling point (Stohlgren et al. 1995, 1998). The Modified-Whittaker plot is multi-scale and has nested within it one 100-m^2 plot, two 10-m^2 plots and ten 1-m^2 quadrats (Figure 3). Our sampling objectives focused on re-construction of pre-fire stand conditions (timber); assessment of fire severity; identification, cover and height measurements of all vascular plant species present post-fire; and construction of custom fuel models to estimate post-fire flammability.

Figure 2. Stratifed random sampling design: sample plots were distributed randomly within strata throughout the burned landscapes of our three study areas. Landscape stratification was accomplished via overlay of several spatial data layers.

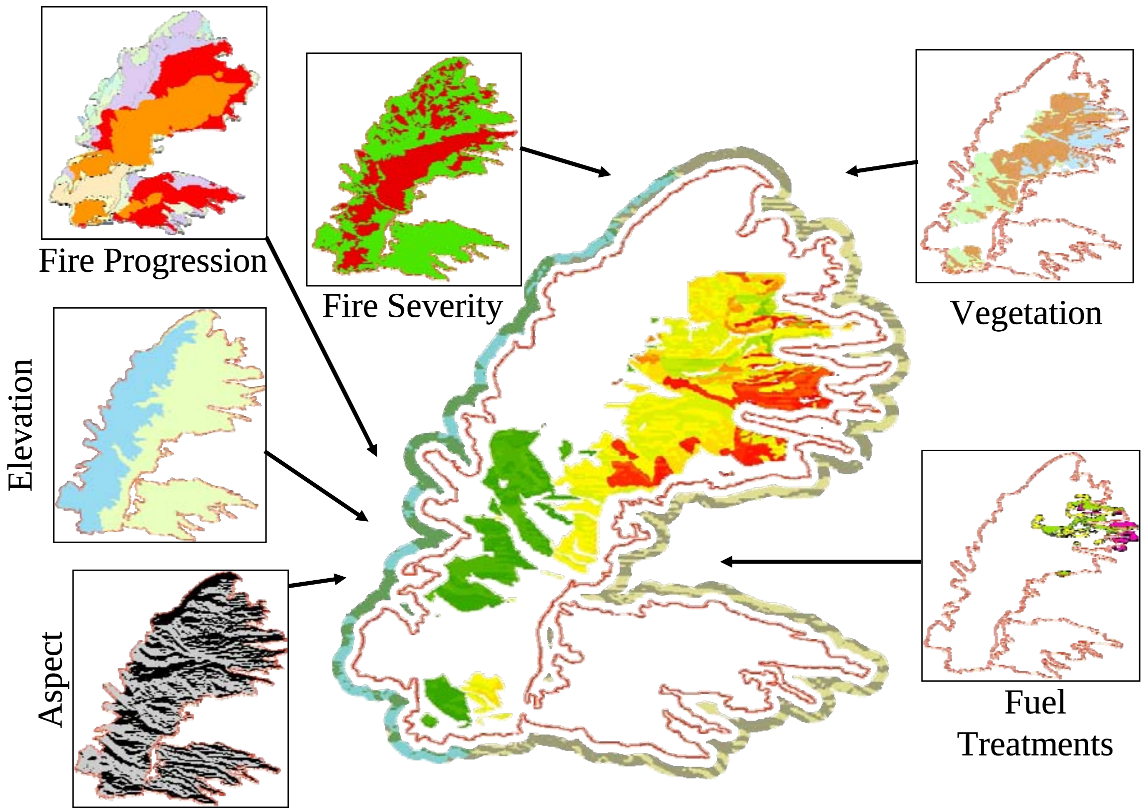
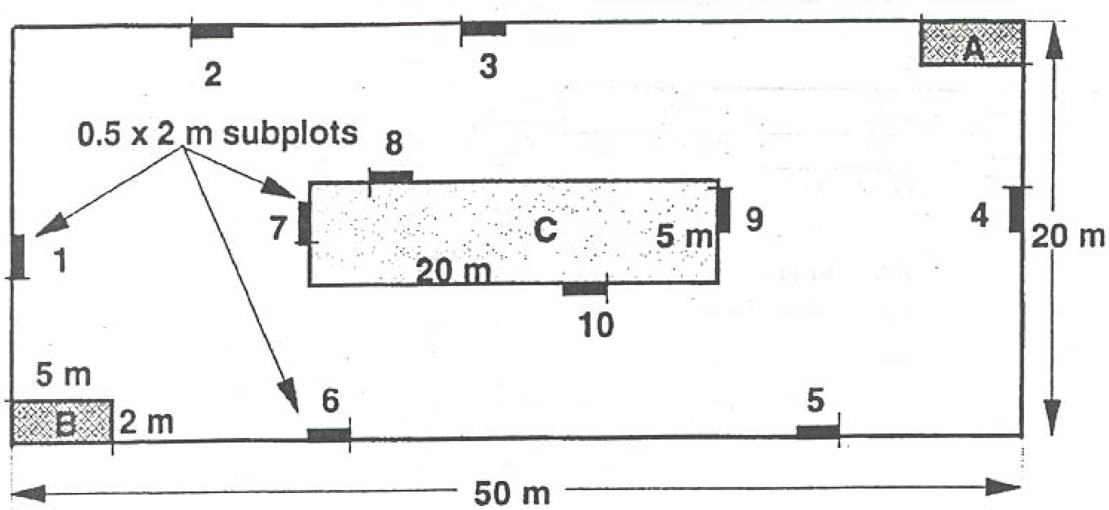


Figure 3. The Modified-Whittaker plot design used to sample fire severity, vegetation, and fuel characteristics.



2.3.1 *Stand Structure*

Pre-fire stand conditions were reconstructed from trees within variable radius plots defined by an angle gauge with a basal area factor of 2 m^2/ha (Avery and Burkhart 2002) and centered on the Modified-Whittaker plot. Measured variables included tree height, tree diameter, height to the pre-fire live crown, position in canopy, species, stand density, and basal area. Heights were calculated trigonometrically from clinometer readings. Tree diameters were measured with metric diameter tape 1.4 m above ground on the uphill side. Lower tree boles were inspected carefully for evidence of consumed branches to avoid over-estimating crown base heights in severely burned stands. Each tree's position in the canopy was rated as dominant, co-dominant, intermediate, or suppressed. Since variable radius plots are inaccurate for small trees (Stage and Rennie 1994), trees less than 10 cm in diameter were sampled separately within the fixed area 100-m^2 subplot centered within the Modified-Whittaker plot.

2.3.2 *Fire Severity*

We assessed fire severity with several measures. Bole char height, needle scorch height, and percentage of crown volume scorched and consumed were estimated on each tree included in the variable radius plots. Additionally, we assigned a stand damage rating (adapted from Omi and Kalabokidis 1991) based on the condition of all trees within the 1000-m^2 Modified-Whittaker plot used to sample post-fire vegetation. Depth of ground char ratings (adapted from Ryan and Noste 1985) were assigned to each of the ten 1-m^2 quadrats within the Modified-Whittaker plot.

2.3.3 *Floristics*

Botanists identified and measured the cover and height of all species in each 1-m^2 subplot. Cover was also recorded for any non-plant surface items encountered (i.e., wood, water, rock, roots, duff/litter, lichen, moss, soil, trail/road, dung, and other (trash, bones, etc.); Bull et al., 1998). Botanists then searched the 10-m^2, 100-m^2, and 1000-m^2 plots for any species not previously recorded and noted them as present. Plants that could not be identified to species were collected off-plot and pressed for later identification. Species codes followed the standardized USDA Natural Resource Conservation Service (NRCS) PLANTS Database codes (USDA, NRCS 1999; determined after identification). Plants that could not be identified because of growth stage retained their unknown name for use in richness analyses.

2.3.4 *Fuel Flammability*

We assessed the flammability of post-fire fuels in each 1-m^2 subplot by collecting information necessary for input into BEHAVE's fuel modeling subsystem (Burgan and Rothermel 1984). This included separate estimates of depth, bulk density, percent cover, percent green, and surface area-to-volume ratios for each fuel class (i.e., grasses, forbs, shrubs, and litter). Surface area-to-volume ratios were calculated from diameter measurements made with a digital caliper on randomly selected fuel particles.

2.4 ***Data Analysis***

We employed standard statistical software (SAS 2001) and an information-theoretic approach (Burnham and Anderson 1998) for the development and selection of multiple linear regression models to explain landscape variations in fire severity, non-native species abundance, and post-fire flammability. Spatial prediction models were also developed for the presence and abundance of non-native species within the Cerro Grande fire. Akaike's Information Criterion (AICc, corrected for small samples), was used as a guide in selecting the number of parameters to include in each of the models we developed. When maximum likelihood is used as a criterion for selecting between models of different orders, there is the possibility of finding another model with equal or greater likelihood simply by increasing the number of parameters. Therefore, AICc penalizes for each increase in the number of parameters and the model with the smallest AICc value is considered to have the most support in the data. While models are thus kept as simplistic as possible, a more complex model could be used if warranted, or several models with strong support in the data could be averaged with Akaike weights (Burnham and Anderson 1998).

2.4.1 *Fire Severity*

We developed regression models to explain the crown volume scorch and consumption observed at each of our plots. Explanatory variables considered were divided into two groups: those that described pre-fire fuel conditions and those that described topographic conditions. Though weather conditions also influence fire behavior and severity, data were not available that described the exact time and weather conditions at each of our plot locations as it burned. Instead, we attempted to minimize weather variability among our sample locations by including daily fire progression in our landscape stratification (see Section 2.2).

All possible combinations of main effects were explored, as well as two-way interactions between fuel parameters and topographic parameters. Models with very strong support in the data (i.e., the difference in AICc between the candidate model and the model with the lowest AICc (ΔAICc) was less than 3) were averaged with Akaike weights to arrive at the final models (Burnham and Anderson 1998). Transformation of dependent variables followed standard diagnostic checks and power analysis to maximize conformance with the assumptions of multiple linear regression (SAS 2001).

We considered the following topographic variables as potential predictors of fire severity at all three sites: map distances (km) from the nearest road and the nearest stream, slope steepness (%), elevation (km) above mean sea level, slope aspect (degrees), direct incident radiation ($MJ/cm^2/yr$), and topographic position (fraction of the local elevation gradient). Slope aspect was converted to radians and transformed to increase symmetrically around an axis from northeast to southwest (after Beers et al. 1966). Direct incident radiation was calculated from equations provided by McCune and Keon (2002). Topographic position was initially implemented as dummy variables indicating whether or not each plot was in a drainage (coded 1,0), on a ridge (coded 0,1), or neither (coded 0,0). To reduce the number of parameters necessary to describe topographic position, we instead calculated this variable as the fraction of the elevation gain between the nearest drainage and the nearest ridge. Exploratory analysis suggested a mid-slope moderation of fire severity, so we also considered a transformation that resulted in a maximum value on ridges and in drainages and a minimum value at mid-slope (i.e., the absolute value of the topographic position fraction minus 0.5).

Fuel variables considered at all sites were tree density (#/ha), tree basal area (m^2/ha), mean tree diameter (cm), canopy base height (m), canopy bulk density (kg/m^3), tree species composition (fraction comprised of ponderosa pine), age of pre-fire prescribed burn and mechanical thinning treatments (years inverted with untreated areas set to 0), and aspen presence (coded 1 if present, 0 if not). Canopy bulk density was calculated with the maximum running mean method recommended by Scott and Reinhardt (2001) using Brown's (1978) allometric equations for crown weights contributed by needles and fine twigs. The effective canopy base height was calculated as the lower limit of the lowest 1-ft horizontal section of the canopy in which canopy bulk density exceeded 0.037 kg/m^3 (Scott and Reinhardt 2001).

Exploratory analysis of the crown base height variable indicated a counter-intuitive relationship to fire severity, suggesting that our post-fire reconstructions may have been biased in high severity areas despite our best efforts to guard against this in the field. We attempted a post-sampling remedy through the development of an allometric relationship (p<0.0001, r^2=0.40) based on the species, diameter, and height of our unscorched sampled trees. The effective canopy base for each plot was then recalculated after setting the crown base of each tree to the lowest value between our observation and allometric prediction. Even after this adjustment, however, our analyses suggested a positive correlation between fire severity and pre-fire canopy base height at all three of our study sites. Due to our lack of confidence in our post-fire measurement of pre-fire canopy base height, we elected to drop this variable from our analyses rather than conclude that ladder fuels reduce fire severity.

2.4.2 *Non-native Species*

Species were classified as non-native according to the Natural Resources Conservation Service Plants Database (http://plants/usda.gov). Several multiple linear regression and analysis of covariance models were tested to best predict cover of non-native species. Predictor variables were separated in different models as biotic effects (native grass cover, seeded grass cover, native species richness), abiotic effects resultant from wildfire (mean char depth, canopy cover, mulch cover, total nitrogen), treatment effects (thinned, prescribed burn, and thinned + prescribed burn), and other abiotic effects (distance from streams, distance from roads, slope, incident radiation, percent clay content). Models at the 1000-m^2 scale included variables from each group and then combinations of groups. Group variables varied slightly among sites because of the nature in which the data were collected. Elevation was included as a factor at Cerro Grande because plot locations spanned a much wider elevational gradient compared to the other sampled fires. Separate analyses were conducted for treated and untreated areas at Cerro Grande, because treated areas encompassed a much smaller portion of the wildfire and didn't span the entire elevational gradient that was sampled. Fewer variables were measured and thus tested at the 1-m^2 scale. At this scale, the structured models were more similar among fires. Tested models at the 1-m^2 scale were slightly different for the Hayman fire because we sampled an extra variable, cover of straw mulch used for erosion control. Models with strong support in the data (ΔAICc < 3) were averaged with Akaike weights to obtain averaged parameter estimates and associated standard error values (Burnham and Anderson 1998). Variables were square-root or arcsine square-root transformed prior to analysis to correct for non-normal error distribution.

2.4.3 *Soil Analysis*

We collected five soil samples to a depth of 5-15 cm (depending on soil depth), one in each corner and one in the center, from each Modified-Whittaker plot and pooled these into one composite sample per plot. Soils were analyzed for indicators of nutrient (carbon and nitrogen) and moisture (texture) availability. Samples were air-dried for at least 48 h and sieved to 2-mm (number 10 standard sieve). Particle size was determined using the standard hydrometer method (Gee and Bauder 1986). Samples were ground to a fine powder, oven-dried at 55^{o}C for 48 h and analyzed for percent total carbon and nitrogen using a LECO-1000 CHN analyzer (LECO Corporation, Saint Joseph, Missouri, USA).

2.4.4 *Post-fire Flammability*

We created and tested custom fuel models for each plot with the fuel modeling subsystem of BEHAVE (Burgan and Rothermel 1983). We recoded the New Model and Test Model routines in Visual Basic for Applications to automate input from our MS Excel datasheets. The Test Model routine was used to predict fire behavior in each plot based on its custom fuel model parameters and a standard environment (Table 2). We used the flame length output of Test Model as the dependent variable in regression models to assess whether the relative abundance of non-native and seeded plant species had any influence on predicted post-fire flammability.

Table 2. Standard environment used for flammability modeling. Several variables were held constant to produce flame length predictions for custom fuel models. The custom fuel models were developed from data collected at each plot to assess the influence of non-native species on post-fire flammability.

dfmc1	dfmc10	dfmc100	hfmc	sfmc	slope	mfw
3	4	5	70	70	0	6.4

Notes:
dfmc1 = dead fuel moisture content (%) of 1-hr fuels (diameter < 0.6 cm).
dfmc10 = dead fuel moisture content (%) of 1-hr fuels (diameter < 2.5 cm).
dfmc100 = dead fuel moisture content (%) of 1-hr fuels (diameter < 7.6 cm).
hfmc = live fuel moisture content (%) of herbaceous fuels.
wfmc = live fuel moisture content (%) of woody fuels.
slope = slope steepness (%).
mfw = mid-flame wind speed (km/h).

Non-native and seeded species may increase flammability by altering fuelbed characteristics such as surface-area-to-volume ratio, fuelbed depth, horizontal continuity, and the proportion of the live fuel load that is cured. However, these parameters were not included in our regression models directly, since there would be little scientific value in developing a regression model to replicate the output of the fire behavior model. Rather, we limited additional regression parameters to those variables that would influence fire behavior independently of the species that comprised the live fuel load. These included total load and abiotic variables that influence the curing of live biomass: elevation, aspect, topographic position, canopy cover, and the date each plot was sampled.

All possible combinations of available explanatory variables and single two-way interactions were explored as predictors. Models with very strong support (ΔAICc < 3) in the data were averaged with Akaike weights to arrive at the final models (Burnham and Anderson 1998). Transformation of dependent variables followed standard diagnostic checks and power analysis to maximize conformance with the assumptions of multiple linear regression (SAS 2001).

2.4.5 *Spatial Modeling*

Data used in spatial modeling included eight bands of Landsat TM Data, six different vegetation indices, six bands of transformed tasseled cap indices (using IMAGINE 8.4 [ERDAS 2000]), topographic derived data (elevation, slope, aspect; ArcInfo 7.4 [ESRI 2000]), and vegetation data (total number of plant species, number of native plant species, number of non-native plant species, and percent cover for total, native, and non-native species). All spatial information from remotely sensed data and GIS layers were converted to a grid using ArcInfo 7.4 (ESRI 2000) and a program written in ARC Macro Language (ESRI 2000) was used to extract the data points (field plot locations) with respect to their Universal Transverse Mercator *X*- and *Y*-coordinates within the study area. All data were then used for the development of the spatial models using S-Plus software (MathSoft 2000).

The cross-correlation statistic (I_{YZ}) was used to test the null hypothesis of no spatial cross-correlation among all pairwise combinations of vegetation variables and topographic characteristics. In calculating I_{YZ}, we used the inverse distance between sample plots as a weighting factor to give more weight to values in the closest sample plots and less to those in plots that were farthest away. The null hypotheses of no spatial cross-correlation were rejected at $p<0.05$. Moran's *I*, which is a special case of I_{YZ} (Czaplewski and Reich 1993), was used to calculate the spatial auto-correlation associated with each variable. Cliff and Ord (1981) showed that I_{YZ} ranges from –1 to +1, although it can exceed these limits with certain types of spatial matrices. Data distributions that were strongly skewed were transformed prior to analysis. Aspect data were transformed using the absolute value from due south (180°; high solar radiation) (Kalkhan and Stohlgren 2000).

Stepwise multiple regression analysis was used first to identify the best linear combination of independent variables. It also allowed us to explore the variation in predicting total, non-native, and native plant species richness as a function of the eight TM bands, six derived vegetation indices, six tasseled cap transformation indices, slope, aspect, and elevation. The selected independent variables were used in the ordinary least squares (OLS) procedure to describe large-scale variability estimates.

Ordinary least squares estimators were used to fit the model if the variable of interest had a linear relationship with the geographic coordinates of the sample plots, the digital number value of any of the Landsat TM bands, and the topographic data. In addition, the least squares method fits a continuous, univariate response as a linear function of the predicted variable. This trend surface model represented continuous first-order spatial variation. We used AICc (Burnham and Anderson 1988, Akaike 1997) as a guide in selecting the number of model parameters to include in the regression model.

The residuals from the trend surface models were analyzed for spatial dependencies in the next stage of the model building process. This was accomplished using spatial auto-correlation and cross-correlation statistics. If the residuals were cross-correlated with other variables, we could use co-kriging to interpolate the residuals. However, if the residuals were not cross-correlated, we used ordinary kriging. Finally, the weights associated with the kriging and co-kriging models were estimated as a function of the spatial continuity of the data (Isaaks and Srivastiva 1989). This estimation can be accomplished using a sample variogram to describe spatial continuity. With spatial data, the variation of the samples generally changes with distance. In other words, the variogram is a measure of how the variance changes with distance. The variogram and cross-variogram models used in this analysis were considered “basic” models, meaning they are simple and isotropic (Reich et al. 1999). They include Gaussian, spherical, and exponential models (see Isaaks and Srivastiva 1989). Prior to estimating the sample variogram and cross-variogram, the data were rescaled by dividing the individual variables and the residuals by their respective maximum values. This was necessary to maintain numerical stability (Isaaks and Srivastiva 1989) by eliminating any differences in the magnitude of the variables without altering the solution. Although this was not necessary for kriging, it was important in co-kriging (Isaaks and Srivastiva 1989).

3. **Results**

3.1 ***Predictors of Fire Severity***

Fire severity within the areas we sampled was variable: the proportion of our study areas that burned with high severity ranged from 56% in the Hi Meadow fire to 67% in the Cerro Grande fire to 74% in the Hayman fire. We sampled areas of high and low severity with equal intensity to determine how much of the variability in fire severity could be explained by manageable stand conditions. We developed multiple regression models for each wildfire in an attempt to explain the fire severity we observed. Summary statistics for all variables considered in our models for each fire are presented in Table 3.

Table 3. Summary statistics for all variables considered in multiple regression models to explain fire severity at our three study sites.

Variable	Cerro Grande		Hi Meadow		Hayman	
	Mean	s.d.	Mean	s.d.	Mean	s.d.
CVS+C	104.48	(82.27)	98.85	(70.79)	133.37	(65.92)
potr	0.09	(0.29)	0	(0.00)	0.09	(0.29)
pipo	57.94	(43.78)	70.28	(34.46)	58.14	(41.47)
burn	3.33	(1.83)	1.74	(1.52)	8.92	(2.78)
thin	1.45	(0.52)	10.38	(2.78)	2.6	(1.88)
dbh	27.19	(8.64)	24.53	(8.68)	23.15	(8.83)
ba	17.08	(8.24)	16.08	(6.46)	14.28	(8.40)
dns	555.07	(897.00)	569.03	(545.38)	444.63	(502.50)
cbd	0.07	(0.04)	0.08	(0.04)	0.08	(0.06)
rd	0.31	(0.45)	0.33	(0.21)	0.63	(0.57)
strm	0.42	(0.41)	0.23	(0.21)	0.5	(0.36)
elev	2.34	(0.20)	2.3	(0.09)	2.36	(0.12)
topo	0.49	(0.32)	0.58	(0.31)	0.53	(0.30)
slp	25.69	(16.41)	25.07	(12.14)	30.52	(13.45)
asp	0.7	(0.61)	0.86	(0.72)	0.97	(0.77)

Notes:

Parameter abbreviations: *CVS+C* = canopy volume scorch (%) plus consumption (%). *potr* = dummy variable indicating the presence (coded 1) or absence (coded 0) of aspen. *burn* = age (yr) of prescribed burn treatments. *thin* = age (yr) of mechanical thinning treatments. *dbh* = mean tree diameter (cm) at breast height (1.4 m from tree base on the uphill side). *ba* = tree basal area (m^2/ha). *dns* = tree density (#/ha). *cbd* = canopy bulk density (kg/m^3). *rd* = distance (km) from nearest road. *strm* = distance (km) from the nearest stream. *elev* = elevation (km) above mean sea level. *topo* = topographic position expressed as the fraction of the elevation gradient between the nearest drainage and the nearest ridge. *slp* = slope steepness (%). *asp* = slope aspect (degrees) transformed to increase continuously from NE (value = 0) to SW (value = 2) in both directions (after Beers et al. 1966) with the function

COS(RADIANS(225-asp))+1.

3.1.1 *Cerro Grande*

Regression models for the Cerro Grande fire explained 46% of the variability in the canopy damage we observed (Table 4). The most significant variables were elevation, mean tree diameter and the age (inverted) of prescribed fire treatments. Fire severity increased with increasing elevation and the transition from pinyon-juniper woodland to ponderosa pine to mixed conifer forest. Larger trees and prescribed-burn areas were associated with lower fire severity, though an interaction term suggests that the effect of tree diameter diminished with increasing distance from roads. Other important fuel variables were aspen presence and canopy bulk density. Aspen were associated with reduced fire severity, as would be expected from their high fuel moisture content and preference for mesic sites. Fire severity decreased with increasing canopy bulk density, in contrast to expectation from fire behavior theory. However, an interaction term indicates that the effect of canopy bulk density tended to reverse with proximity to ridgelines. Though stand density was insignificant as a main effect, an interaction term indicates that this variable did significantly increase fire severity on southwesterly aspects.

Table 4. Parameter estimates for models selected to explain fire severity (percent canopy scorch + consumption) within the Cerro Grande burn area (n = 64, adjusted r^2 = 0.46).

Selected Models [a]	Adjusted r^2	Akaike Weight [b]	Parameter Estimates [c]		p-value [d]
burn+potr+dbh+cbd+asp+elev+topo			Intercept	-5.3703	0.1939
+cbdXtopo	0.46	0.35	elev	8.5568	0.0002
burn+potr+dbh++dns+cbd+asp+elev+topo			burn	-5.3964	0.0009
+cbdXtopo	0.47	0.19	dbh	-0.1160	0.0032
burn+potr+dns+cbd+asp+elev+topo			dbhXrd	0.0298	0.0116
+dnsXasp	0.45	0.17	asp	-1.3746	0.0117
burn+potr+dbh+cbd+slp+asp+elev+topo			dnsXasp	0.0003	0.0145
+cbdXtopo	0.46	0.15	cbdXtpos	50.0560	0.0219
burn+potr+dbh+cbd+asp+elev+rd+topo			potr	-2.6268	0.0351
+dbhXrd	0.46	0.14	topo	-4.9182	0.0582
			cbd	-39.9756	0.0606
			dns	0.0002	0.2278
			slp	-0.0036	0.2949
			rd	-1.0713	

Notes:

[a] Selected models were those with strong support in the data (i.e., those within 3 points of the model with the lowest AICc (Akaike's Information Criterion) value (after Burnham and Anderson 1998)). All selected models were significant at the $p<0.0001$ level.

[b] Akaike weights indicate the probability that a given model is the most informative of the models considered. When no single model has overwhelming support in the data, Akaike weights can be used for model averaging to account for selection uncertainty (Burnham and Anderson 1998).

[c] See Table 3 for explanation of parameter abbreviations. However, *burn* is inverted (1/yr) with areas that had no record of pre-fire prescribed burns set to equal 0. Model parameters predict the square root of the arcsine transform (Zar 1984), t(p), of the sum, y, of mean crown volume scorch (%) and mean crown volume consumption (%):

$$t(p) = (360/(2\pi)) * (\arcsin(\sqrt{p}))$$

where

$$p = 1 / (4*n) \text{ if } y=0,\ y/n \text{ if } 1 \leq y \leq n-1,\ (n-0.25)/n \text{ if } y=n$$

and

$$n=200.$$

[d] Statistical significance cannot be interpreted and is thus not reported for main effects that occur only in conjunction with a multiplicitive interaction between it and another variable.

3.1.2 *Hi Meadow*

Regression models for the Hi Meadow fire explained 16% of the variability in the canopy damage we observed (Table 5). The most significant variables were tree density, basal area, an interaction between tree species composition and slope, and an interaction between the age of prescribed burn treatments and the distance to the nearest stream. Fire severity increased with increases in tree density, but decreased with increases in basal area. Basal area is determined by both the size and number of trees in a stand. The absence of mean tree diameter from the set of informative variables implies that basal area acted as a surrogate: at a given density, an increase in basal area results from larger, more fire-resistant trees that reduce observed fire severity.

Table 5. Parameter estimates for models selected to explain fire severity (percent canopy scorch + consumption) within the Hi Meadow burn area (n = 71, adjusted r^2 = 0.16).

Selected Models [a]	Adjusted r^2	Akaike Weight [b]	Parameter Estimates [c]		p-value [d]
dns+cbd+ba	0.15	0.20	Intercept	5.6687	0.0002
dns+pipo+slp+pipoXslp	0.17	0.17	pipoXslp	-0.0242	0.0131
dns+cbd+ba+asp	0.16	0.15	dns	0.0012	0.0263
dns+cbd+ba+rd	0.15	0.14	burnXstrm	-0.8697	0.0268
dns+burn+strm+burnXstrm	0.15	0.10	ba	-0.0735	0.0392
dns+burn+asp+rd+burnXrd	0.17	0.08	burnXrd	0.4509	0.0521
dns+rd+dnsXrd	0.13	0.08	cbd	10.5880	0.0841
dns+cbd+ba+rd+cbdXrd	0.16	0.08	asp	-0.1110	0.1589
			cbdXrd	-1.4734	0.2788
			dnsXrd	0.0001	0.3543
			pipo	0.5101	
			burn	-0.0222	
			slp	0.0160	
			rd	0.5318	
			strm	0.1637	

Notes:

[a-b] See Table 4 notes. All selected models were significant at the p<0.01 level.

[c] See Table 3 for explanation of parameter abbreviations. However, *burn* is inverted (1/yr) with areas that had no record of pre-fire prescribed burns set to equal 0. Model parameters predict the square root of the arcsine transform (see Table 4 for explanation).

[d] Statistical significance cannot be interpreted and is thus not reported for main effects that occur only in conjunction with a multiplicitive interaction between it and another variable.

Though the main effects of ponderosa pine concentration and slope steepness were insignificant, a multiplicative interaction between these variables suggests that fire severity was significantly lower on steep slopes where the concentration of ponderosa pine was high than on steep slopes where the concentration of ponderosa pine was low (i.e., in Douglas-fir stands). The age of prescribed burn treatments and distance from streams also interacted to significantly influence fire severity. Fire severity was significantly lower within prescribed burn areas that were removed from streams than in those that were near streams. Higher productivity in the mesic areas close to streams may have hastened the recovery of surface fuels to pre-treatment conditions. Prescribed burns also interacted with distance from roads, though the effect on fire severity was only marginally significant. Fire severity was lower within prescribed burn areas that were close to roads than in those that were removed from roads. Roads likely acted as a fuel break that augmented the effect of the prescribed burns. However, the main effect of roads was insignificant: roads had no effect on fire severity outside of prescribed burn areas where surface fuels had been reduced.

3.1.3 *Hayman*

Regression models for the Hayman fire explained 15% of the variability in the canopy damage we observed (Table 6). The most significant variables were the age of prescribed fire treatments, mean tree diameter, and an interaction between prescribed burn treatments and distance from roads. Fire severity decreased with increases in mean tree diameter and recency of the last prescribed fire treatment. The interaction between prescribed fire treatments and roads suggests that fire severity was greater in burn treatments that were near roads than in those that were removed from roads.

Table 6. Parameter estimates for models selected to explain fire severity (percent canopy scorch + consumption) within the Hayman burn area (n=110, adjusted r^2 = 0.15).

Selected Models [a]	Adjusted r^2	Akaike Weight [b]	Parameter Estimates [c]		p-value
burn+dbh	0.14	0.23	Intercept	77.0508	0.0001
burn+dbh+rd+strm+burnXrd	0.17	0.20	burn	-33.2540	0.0052
burn+dbh+topo[1]	0.14	0.17	dbh	-0.5757	0.0157
burn+dbh+ba	0.14	0.15	burnXrd	-28.5276	0.0392
burn+dbh+topo[1]+dbhXtopo[1]	0.15	0.14	strm	-2.4091	0.0875
burn+dbh+rd	0.14	0.12	dbhXtopo[1]	-0.3383	0.1612
			topo[1]	2.0690	0.1988
			ba	0.0482	0.2352
			rd	-0.6105	0.3049

Notes:

[a-b] See Table 4 notes. All selected models were significant at the p<0.001 level.

[c] See Table 3 for explanation of parameter abbreviations. However, *burn* is inverted (1/yr) with areas that had no record of pre-fire prescribed burns set to equal 0 and *topo* is transformed to minimize at mid-slope with the function:

$$topo^1 = |0.5 - topo|.$$

Model parameters predict the arcsine transform, rather than its square root as in Tables 3 and 4 (see Table 4 for explanation).

3.2 ***Predictors of Non-native Presence and Abundance***

We developed multiple regression models to explain the abundance of non-native species found in each post-burn landscape. Models were developed for two different scales of observation: 1000-m^2 and 1-m^2. Summary statistics for all variables considered in our models for each fire are presented in Table 7.

3.2.1 *Cerro Grande*

Since treated plots occurred in ponderosa pine areas only, separate analyses were conducted for treated and non-treated areas. At the 1000-m^2 scale in treated areas, the best models accounted for up to 42% of the variability in non-native species cover and included a treatment effect, seeded grass cover, native grass cover, percent slope, incident radiation, and percent clay content (Table 8). All parameter estimates except for native species richness had 95% confidence intervals that overlapped zero. Non-native species cover was positively associated with native species richness. Non-native species cover also had a marginal negative association with native grass cover and percent slope. The cover of non-native species was significantly greater than zero in ponderosa pine plots that were thinned prior to the wildfire.

However, the confidence intervals of all treatment types overlapped the confidence interval for untreated plots in ponderosa pine, indicating no significant treatment effect.

Table 7. Summary statistics for all variables considered in multiple regression models to explain percent cover of non-native species at the 1000-m^2 scale at each of our three study sites.

Variable	Cerro Grande		Hi Meadow		Hayman	
	mean	s.d.	mean	s.d.	mean	s.d.
non-native	5.46	(4.76)	7.34	(6.13)	0.66	(2.02)
seed	7.41	(5.67)	4.60	(8.51)	0.26	(0.76)
grass	8.57	(7.51)	14.06	(7.08)	1.03	(1.84)
rich	32.71	(10.20)	42.12	(10.42)	42.07	(12.03)
mulch	n/a	n/a	n/a	n/a	4.81	(13.90)
char	1.28	(0.96)	1.19	(0.81)	1.49	(0.62)
canopy	38.04	(22.72)	44.28	(20.39)	34.32	(21.83)
soil	35.79	(26.01)	24.30	(27.85)	44.12	(33.76)
N	0.14	(0.13)	0.20	(0.14)	0.17	(0.07)
clay	16.52	(5.59)	13.50	(2.32)	13.82	(2.95)
slope	24.60	(16.5)	24.40	(14.60)	30.20	(13.70)
elevation	2357.55	(244.68)	n/a	n/a	n/a	n/a
radiation	0.59	(0.18)	0.67	(0.22)	0.72	(0.24)
road	288.41	(422.77)	324.85	(209.32)	693.95	(612.86)
stream	430.67	(431.85)	235.66	(210.96)	507.39	(334.57)

Notes:
Explanation of variables: *non-native* = cover (%) of non-native species. *seed* = seeded grass cover (%). *grass* = native grass cover (%). *rich* = native species richness (#). *mulch* = cover (%) of straw mulch. *char* = mean char depth (0-3 rating). *canopy* = canopy cover (%). *soil* = exposed bare soil (%). *N* = total soil nitrogen (%). *clay* = clay-size particles (%) in soil. *slope* = slope steepness (%). *elevation* = elevation (m) above mean sea level. *radiation* = direct incident radiation (MJ/cm^2/yr) calculated from percent slope and aspect (McCune and Keon 2002). *road* = plot distance (m) from nearest road. *stream* = plot distance (m) from nearest stream.

Two models had considerable support in the data at the 1000-m^2 scale in areas where no fuel treatments were implemented prior to the wildfire and explained up to 31% of the variability in non-native species cover (Table 9). Informative variables in these models included canopy cover, char depth, total nitrogen, seeded grass cover, native grass cover, and native species richness. Non-native species cover was positively associated with seeded grass cover and native species richness. The 95% confidence intervals for all other parameter estimates overlapped zero. Though the effects were not significant, non-native species cover was positively associated with char depth and negatively associated with native grass cover.

Three models had considerable support in the data at the 1-m^2 scale in areas where fuel treatments were implemented prior to the wildfire and explained up to 6% of the variability in non-native species cover (Table 10). Predictors in these models included native grass cover, seeded grass cover, native species richness, bare ground exposure, and char depth. However, only seeded grass cover and native species richness had 95% confidence that did not overlap zero. Non-native species cover was positively associated with both seeded grass cover and native species richness. Although estimates were only marginally significant, non-native species cover was positively associated with char depth and negatively associated with native grass cover.

Three models had considerable support in the data at the 1-m^2 scale in areas where fuel treatments were not implemented prior to the wildfire and explained up to 4% of the variability in non-native species cover (Table 11). Informative variables in these models included native grass cover, seeded grass cover, native species richness, bare ground exposure (%) and char depth. However, only native species richness and native grass cover had 95% confidence intervals that did not overlap zero. Non-native species cover was positively associated with native species richness and negatively associated with native grass cover.

Table 8. Parameter estimates for models selected to explain non-native species cover at the 1000-m^2 scale in areas treated for fuels reduction prior to the Cerro Grande wildfire (n=38 for all models).

Selected Models [a]	Adjusted r^2	Akaike Weight [b]	Parameter Estimates [c]		95% C.I. [d]
slope+radiation+clay+seed+grass+rich	0.42	0.66	Intercept	-0.508	-15.90, 14.93
grass+seed+rich	0.28	0.17	**rich**	**0.353**	**0.16, 0.54**
treat+seed+grass+rich	0.40	0.13	slope	-0.202	-0.45, 0.05
treat	0.24	0.02	grass	-1.363	-3.48, 0.76
			clay	0.241	-0.15, 0.63
			seed	0.077	-0.22, 0.38
			radiation	-0.35	-20.20, 19.50
			thin	10.485	7.86, 13.11
			none	6.953	3.44, 10.47
			thin/burn	6.325	2.30, 10.35
			burn	3.814	-0.51, 8.14

Notes:

[a-b] See Table 4 notes. All selected models were significant at the p<0.001 level.

[c] See Table 7 for explanation of parameter abbreviations. However, *grass* was square-root transformed, *burn* = least square mean for ponderosa pine that was treated prior to wildfire with prescribed burning, *thin* = least square mean for ponderosa pine that was treated prior to the wildfire with thinning, *thin/burn* = least square mean for ponderosa pine that was treated prior to the wildfire with thinning and prescribed burning, *none* = least square mean for ponderosa pine that received no fuel treatment prior to wildfire. Model parameters predict mean cover (%) of non-native plant species.

[d] Confidence intervals that do not include zero indicate a significant effect at the p<0.05 level (emboldened).

Table 9. Parameter estimates for models selected to explain non-native species cover at the 1000-m^2 scale in areas that were not treated for fuels reduction prior to the Cerro Grande wildfire (n=53 for all models).

Selected Models [a]	Adjusted r^2	Akaike weight [b]	Parameter Estimates [c]		95%C.I. [d]
grass + seed + rich	0.31	0.83	Intercept	-0.857	-3.68, 1.97
char + canopy + N + grass + seed + rich	0.31	0.17	**rich**	**0.140**	**0.06, 0.22**
			seed	**0.218**	**0.08, 0.36**
			char	0.760	-0.30, 1.82
			grass	-0.417	-1.01, 0.18
			N	-1.721	-6.70, 3.25
			canopy	0.003	-0.03, 0.03

Notes:

[a-b,d] See Table 4 notes. All selected models were significant at the p<0.001 level.

[c] See Table 7 for explanation of parameter abbreviations. However, *grass* and *N* were square-root transformed. Model parameters predict mean cover (%) of non-native plant species.

Table 10. Parameter estimates for models selected to explain non-native species cover at the 1-m^2 scale in areas that were treated for fuels reduction prior to the Cerro Grande wildfire (n=240 for all models).

Selected Models [a]	Adjusted r^2	Akaike weight [b]	Parameter Estimates [c]		95% C.I. [d]
seed + grass + rich	0.05	0.44	Intercept	0.134	-0.23, 0.50
seed + grass + rich + char + soil	0.06	0.38	**seed**	**0.160**	**0.04, 0.28**
seed	0.05	0.19	**rich**	**0.210**	**0.01, 0.41**
			grass	-0.110	-0.23, 0.01
			char	0.280	-0.04, 0.59
			soil	-0.100	-0.24, 0.04

Notes:
[a-b,d] See Table 4 notes. All selected models were significant at the p<0.01 level.
[c] See Table 7 for explanation of parameter abbreviations. However, all variables were arcsine square-root transformed, including non-native species cover (%).

Table 11. Selected multiple regression models for non-native species cover at the 1-m^2 scale in areas that were not treated for fuels reduction prior to the Cerro Grande wildfire (n=550 for all models).

Selected Models [a]	Adjusted r^2	Akaike weight [b]	Parameter Estimate [c]		95% C.I. [d]
seed + grass + rich	0.04	0.75	Intercept	0.057	-0.08, 0.20
seed + grass + rich + char + soil	0.03	0.15	**rich**	**0.120**	**0.05, 0.19**
grass	0.02	0.10	**grass**	**-0.088**	**-0.15, -0.03**
			char	0.040	-0.06, 0.14
			seed	0.030	-0.05, 0.11
			soil	-0.003	-0.06, 0.06

Notes:
[a-b,d] See Table 4 notes. All selected models were significant at the p<0.001 level.
[c] See Table 7 for explanation of parameter abbreviations. However, all variables were arcsine square-root transformed, including non-native species cover (%).

3.2.2 *Hi Meadow*

Eleven multiple linear regression models were tested to predict cover of non-native species at the Hi Meadow fire at the 1000-m^2 scale. Three models had considerable support in the data and accounted for up to 30% of the variability in non-native species cover (Table 12). Only three variables (char depth, native grass cover, and distance from roads) had parameter estimates with 95% confidence intervals that did not overlap zero. Non-native species cover was positively associated with char depth, native grass cover, and distance from roads.

Six multiple linear regression models were tested to predict non-native species cover in the Hi Meadow fire at the 1-m^2 scale. All variables were arcsine-square-root transformed prior to analysis to correct for non-normal error distribution. Only one model had support in the data and accounted for 7% of the variability in non-native species cover (Table 13). Three variables, seeded grass cover, native grass cover, and char depth, had parameter estimates with 95% confidence intervals that did not overlap zero. Non-native species cover was negatively associated with seeded grass cover and native grass cover and positively associated with char depth.

Table 12. Parameter estimates for models selected to explain non-native species cover at the 1000-m^2 scale in the Hi Meadow fire (n=92 for all models).

Selected Models [a]	Adjusted r^2	Akaike Weight [b]	Parameter Estimates [c]		95% C.I. [d]
char+canopy+N+grass+seed+rich	0.29	0.56	Intercept	-2.646	-11.8, 6.47
char+canopy+N+slope+clay+rd+strm+radiation	0.30	0.23	**char**	**4.311**	**2.53, 6.09**
char+canopy+N	0.25	0.21	**road**	**0.007**	**0.00, 0.01**
			grass	**0.181**	**0.00, 0.36**
			stream	-0.004	-0.01, 0.00
			seed	-0.410	-1.09, 0.27
			clay	0.309	-0.21, 0.83
			rich	0.062	-0.05, 0.17
			N	4.172	-4.64,13.0
			slope	-0.033	-0.12, 0.06
			canopy	-0.020	-0.08, 0.04
			radiation	1.812	-3.65, 7.27

Notes:
[a-b,d] See Table 4 notes. All selected models were significant at the p<0.0001 level.
[c] See Table 7 for explanation of parameter abbreviations. However, *seed* and *N* were square-root transformed. Model parameters predict mean cover (%) of non-native plant species.

Table 13. Parameter estimates for models selected to explain non-native species cover at the 1-m^2 scale in the Hi Meadow fire (n=920 for all models).

Selected Models [a]	Adjusted r^2	Akaike Weight [b]	Parameter Estimates [c]		95% C.I.[d]
seed + grass + rich + char + soil	0.07	1.00	Intercept	-0.053	-0.20, 0.10
			char	**0.310**	**0.21, 0.41**
			seed	**-0.140**	**-0.22, -0.06**
			grass	**-0.070**	**-0.13, -0.01**
			rich	0.100	-0.02, 0.22
			soil	-0.002	-0.06, 0.06

Notes:
[a-b,d] See Table 4 notes. The selected model was significant at the p<0.0001 level.
[c] See Table 7 for explanation of parameter abbreviations. However, all variables were arcsine square-root transformed, including non-native species cover (%).

3.2.3 *Hayman*

Eleven multiple linear regression models were tested to predict cover of non-native species at the 1000-m^2 scale at the Hayman fire. Two models had considerable support in the data and accounted for up to 26% of the variation in non-native species cover (Table 14). Only one variable, native species richness, had parameter estimates with a 95% confidence interval that did not overlap zero. The association was positive between non-native species cover and native species richness. The positive relationship between char depth and non-native species cover was nearly significant.

Table 14. Parameter estimates for models selected to explain non-native species cover at the 1,000-m^2 scale in the Hayman fire (n=102 for all models). Models with Akaike weights greater than 0.01 were used to calculate averaged parameter estimates.

Selected Models [a]	Adjusted r^2	Akaike Weight [b]	Parameter Estimates [c]		95% C.I. [d]
char+canopy+N+mulch+grass+seed+rich	0.26	0.97	**Intercept**	**-0.872**	**-1.46, -0.29**
slope+clay+road+radiation+rd+strm+grass+seed+rich	0.22	0.03	**rich**	**0.020**	**0.01, 0.03**
			strm	0.100	0.00, 0.30
			char	0.160	-0.02, 0.34
			N	1.090	-0.15, 2.33
			canopy	-0.002	-0.01, 0.00
			rd	-0.100	-0.30, 0.10
			mulch	0.030	-0.03, 0.09
			clay	0.010	-0.03, 0.05
			grass	0.029	-0.11, 0.17
			slope	-0.002	-0.01, 0.01
			radiation	0.050	-0.36, 0.46
			seed	-0.035	-0.33, 0.26

Notes:
[a-b,d] See Table 4 notes. All selected models were significant at the p<0.0001 level.
[c] See Table 7 for explanation of parameter abbreviations. However, *seed*, *grass*, and *mulch* were square-root transformed and *road* and *stream* are expressed in km. Model parameters predict mean cover (%) of non-native plant species.

Four multiple linear regression models were tested to predict non-native species cover at the 1-m^2 scale at the Hayman fire. All variables were arcsine square-root transformed prior to analysis to correct for non-normal error distribution. Only one model had considerable support in the data and it accounted for 6% of the variability in non-native species cover (Table 15). Four variables had parameter estimates with 95% confidence intervals that did not overlap zero: non-native species cover was positively associated with seeded grass cover, native species richness, and char depth, and negatively associated with bare soil exposure.

Table 15. Parameter estimates for models selected to explain non-native species cover at the 1-m^2 scale in the Hayman fire (n=1060 for all models).

Selected Models [a]	Adjusted r^2	Akaike Weight [b]	Parameter Estimate [c]		95% C.I. [d]
Seed mulch grass rich char soil	0.06	1.00	Int	-0.037	-0.16, 0.23
			rich	**0.22**	**0.16, 0.20**
			seed	**0.14**	**0.04, 0.24**
			soil	**-0.05**	**-0.09, -0.01**
			char	**0.11**	**0.01, 0.21**
			mulch	-0.02	-0.06, 0.18
			grass	-0.01	-0.07, 0.20

Notes:
[a-b,d] See Table 4 notes. The selected model was significant at the p<0.0001 level.
[c] See Table 7 for explanation of parameter abbreviations. However, all variables were arcsine square-root transformed, including non-native species cover (%).

3.3 ***Predictors of Post-fire Fuel Flammability***

We developed custom fuel models (after Burgan and Rothermel 1984) for each of the plots sampled in our vegetation surveys to determine whether non-native species had any influence on post-fire flammability. Summary statistics for all variables considered in our models for each fire are presented in Table 16.

Table 16. Summary statistics for all variables considered in multiple regression models to explain post-fire fuelbed flammability (predicted flame length) at our three study sites.

Variable	Cerro Grande		Hi Meadow		Hayman	
	mean	s.d.	mean	s.d.	mean	s.d.
flame length	45.49	(44.32)	37.43	(33.30)	21.57	(23.50)
xtc	5.84	(9.33)	6.39	(10.57)	6.62	(9.90)
seed	19.80	(22.41)	8.22	(17.98)	5.32	(14.00)
load	0.83	(1.00)	0.87	(0.84)	0.66	(1.10)
cnpy	36.12	(22.09)	44.44	(20.35)	34.42	(21.64)
day	26.03	(12.38)	22.66	(12.98)	28.82	(15.22)
elev	2.35	(0.24)	2.30	(0.10)	2.35	(0.13)
topo	0.48	(0.32)	0.53	(0.31)	0.54	(0.30)
asp	0.75	(0.63)	0.82	(0.70)	0.95	(0.76)

Notes:

Explanation of variables: *Flame length* is the flame length (cm) output of the BEHAVE fire behavior prediction and fuel modeling system (Burgan and Rothermel 1984). *xtc* = cover (%) of non-native species relative to total live surface cover. *seed* = cover (%) of species included in the post-fire rehabilitation seed mix relative to total live surface cover. *load* = surface biomass (kg/ha) excluding logs greater than 7.6 cm in diameter. *cnpy* = canopy cover (%). *day* = sampling day (day 1 = June 20 at Cerro Grande, June 24 at Hi Meadow, and June 17 at Hayman). *elev* = elevation (km) above mean sea level. *topo* = topographic position expressed as the fraction of the elevation gradient between the nearest drainage and the nearest ridge. *asp* = slope aspect (degrees) transformed to increase continuously from NE (value = 0) to SW (value = 2) in both directions (after Beers et al. 1966) with the function

COS(RADIANS(225-asp))+1.

3.3.1 *Cerro Grande*

Regression models for the Cerro Grande fire explained 61% of the variability in post-fire flammability (i.e. BEHAVE (Burgan and Rothermel 1984) flame length prediction). The most significant variables were elevation, aspect, and an interaction between total fuel load and the relative cover of non-native species (Table 17). However, a fire will burn only if there is fuel available: a condition barely met in many of the severely burned areas we sampled. While fire potential increased with increasing fuel load as expected at the Cerro Grande fire, the interaction between total fuel load and the relative cover of non-native species indicates that the effect of increasing fuel loads was increasingly exacerbated by the relative abundance of non-native species. Post-fire flammability also increased with conditions that facilitated the curing of live biomass, such as xeric conditions associated with lower elevations and southwesterly aspects. Topographic position and sample date were also found to be marginally significant predictors of post-fire flammability: curing of live biomass and post-fire flammability was enhanced by proximity to ridges and the progression of summer.

Table 17. Parameter estimates for models selected to explain fuelbed flammability within the Cerro Grande burn area 1-year post-fire (n = 79, adjusted r^2 = 0.61).

Selected Models [a]	Adjusted r^2	Akaike Weight[b]	Parameter	Estimates[c]	p-value [d]
elev+load+xtc+asp+topo+day+xtcXload	0.61	0.66	Intercept	14.8782	0.0001
elev+load+xtc+asp+topo+day+cnpy+xtcXload	0.61	0.18	elev	-5.3939	0.0001
elev+load+xtc+asp+topo+day+seed+xtcXload	0.61	0.16	xtcXload	0.0853	0.0012
			asp	0.7753	0.0367
			topo	1.3267	0.0636
			day	0.0329	0.0790
			cnpy	0.0008	0.6965
			seed	0.0004	0.8372
			xtc	-0.0361	
			load	1.9084	

Notes:

[a,b] See Table 4 notes. All selected models were significant at the p<0.0001 level.

[c] Model parameters predict a square root transformation of flame length as predicted by the BEHAVE fire behavior prediction and fuel modeling system (Burgan and Rothermel 1984) for the sampled fuel conditions and a standard weather environment. See Table 16 for explanation of parameter abbreviations.

[d] Statistical significance cannot be interpreted and is thus not reported for main effects that occur only in conjunction with a multiplicitive interaction between it and another variable.

3.3.2 *Hi Meadow*

Regression models for the Hi Meadow fire explained 19% of the variability in post-fire flammability (Table 18). The most significant variables were total fuel load, an interaction between fuel load and canopy cover, and an interaction between sample date and elevation. The relative cover of non-native species was included in the set of most informative models, but its influence on flammability was not significant. Flammability increased significantly with increases in fuel load. But the effect of fuel load was moderated by canopy cover, as indicated by the interaction between these two variables. High canopy cover shades surface fuels and slows the curing rate of live biomass, reducing flammability. Seasonal curing, as indicated by sample date, was a flammability enhancer that was moderated by elevation. The interaction between sample date and elevation indicates that seasonal curing and consequent increases in flammability progressed fastest at low elevations.

3.3.3 *Hayman*

Regression models for the Hayman fire explained 7% of the variability in post-fire flammability (Table 19). The most significant variables were total fuel load and an interaction between elevation and non-native species cover. Flammability tended to be lower at high elevations, but this dampening effect was lessened by non-native species. Flammability increased significantly with increases in fuel load and increased marginally with curing associated with southwesterly aspects and later sampling dates.

Table 18. Parameter estimates for models selected to explain fuelbed flammability within the Hi Meadow burn area 2-years post-fire (n = 94, adjusted r^2 = 0.19).

Selected Models [a]	Adjusted r^2	Akaike Weight [b]	Parameter	Estimates [c]	p-value
load+day+elev+dayXelev	0.20	0.25	Int	0.1362	0.1362
load+day+cnpy+loadXcnpy	0.19	0.23	load	1.9451	0.0003
load+day+cnpy+asp+loadXcnpy	0.20	0.15	dayXelev	-0.2469	0.0191
load+day+cnpy+elev+loadXcnpy	0.19	0.08	loadXcnpy	-0.0172	0.0198
load+day+elev+cnpy+dayXelev	0.19	0.08	day	0.5340	0.0800
load+day+elev+topo+dayXelev	0.19	0.07	asp	0.0629	0.2078
load+day+elev+xtc+dayXelev	0.19	0.07	elev	4.3197	0.4746
load+day+elev+seed+dayXelev	0.19	0.07	cnpy	0.0104	0.6141
			topo	-0.0142	0.7936
			xtc	0.0004	0.8075
			seed	-0.0001	0.9453

Notes:

[a, b] See Table 4 notes. All selected models were significant at the p<0.001 level.

[c] Model parameters predict the log transformation of flame length as predicted by the BEHAVE fire behavior prediction and fuel modeling system (Burgan and Rothermel 1984) for the sampled fuel conditions and a standard weather environment. See Table 16 for explanation of parameter abbreviations.

Table 19. Parameter estimates for models selected to explain fuelbed flammability within the Hayman burn area 1-year post-fire (n = 106, adjusted r^2 = 0.07).

Selected Models [a]	Adjusted r^2	Akaike Weight [b]	Parameter	Estimates [c]	p-value [d]
load+asp+day+elev+aspXload	0.06	0.40	Intercept	1.6423	0.0013
load+asp+day+elev+xtc+xtcXelev	0.08	0.39	load	0.0852	0.0222
load+asp+day+cnpy+aspXcnpy	0.06	0.21	xtcXelev	0.0397	0.0322
			day	0.0061	0.0522
			asp	0.0494	0.0611
			cnpyXasp	0.0011	0.0831
			aspXload	0.0502	0.1731
			xtc	-0.0940	
			elev	-0.3529	
			cnpy	-0.0012	

Notes:

[a] See Table 4 notes. All selected models were significant at the p<0.05 level.

[c] Model parameters predict a log transformation of flame length as predicted by the BEHAVE fire behavior prediction and fuel modeling system (Burgan and Rothermel 1984) for the sampled fuel conditions and a standard weather environment. See Table 16 for explanation of parameter abbreviations.

[d] Statistical significance cannot be interpreted and is thus not reported for main effects that occur only in conjunction with a multiplicitive interaction between it and another variable.

3.4 ***Spatial Prediction Models***

We used the 79 data points from the Cerro Grande fire (based on Modified-Whittaker nested plots of 1000-m^2) to represent different variables that were extracted from Landsat TM data, topographic data, and vegetation characteristics (Table 20). Total plant species richness, including species of unknown origin and specimens that could not be identified, ranged from 14 to 78 per plot. Typically, nonnative species represented >10% of the total species at a site and about 5% of the foliar cover (Table 20).

The results for our field data using Moran's *I* (Moran 1948, Mantel 1967*)* and the bivariate cross correlation-statistic I_{YZ} (Czaplewski and Reich 1993, Bonham et al. 1995) to test for spatial auto-correlation and cross-correlation with residuals suggested that, at large-scales, the probability of non-native plant species being present and their percent cover were both spatially independent throughout the study site (Table 21). That is, the spatial relationships were not statistically significant. Native species richness was not spatially independent (Kalkhan and Stohlgren 2000). However, these results may be different for individual plant species (Kalkhan et al. 2000). In general, large-scale patterns of species distribution were controlled by topographic factors such as elevation, aspect, and slope with complex spatial patterns. This may explain why negative spatial auto-correlation and cross-correlation resulted when large-scale plots were used (Kalkhan et al. 2000). These results may have been different if individual native or non-native plant species had been used in the analysis (Kalkhan et al. 2000).

The results of modeling the large-scale and small-scale variability in predicting total, native, and non-native species richness and percent cover of non-native and native plant species within the Cerro Grande fire site are shown in Table 21. Models were developed for large-scale variability of the total number of plants (both native and non-native species) and percent plant cover (total, native, and non-native). The trend surface models identified using stepwise multiple regressions explained 10 to 59 percent of the variability in the dependent variables and all models were significant.

Small-scale variability models were used to examine the spatial continuity of variability and were developed using ordinary kriging based on the Gaussian semi-variogram model which was based on AICc (Table 21). Model parameters were estimated using weighted least squares (Cressie 1985). The residuals were also analyzed for spatial auto-correlation and cross-correlation (Czaplewski and Reich 1993, Reich et al. 1995) with the geographic variables (e.g., elevation, slope, aspect, etc.). Inverse distance weighting was used to define the spatial weights matrix. The kriging models were cross-validated to assess the variability in the prediction errors. The cross-validation included deleting one observation from the data set and predicting the deleted observation using the remaining observations (Reich et al. 1999). This process was repeated for all observations in the data set. The final models (trend surface plus the kriged residuals) explained 60 to 84 percent of the variability in our data. In addition, the accuracies of the kriging models were assessed using the relative mean squared error suggested by Havesi et al. (1992).

Table 20. Summary statistics for all variables used in developing spatial statistical models for the Cerro Grande fire, Los Alamos, New Mexico, 2001.

Variable	Minimum	Median	Mean	Maximum
Total plant species	14	44	51	78
Native plant species	8	31	40	57
Non-native plant species	0	4	4.1	9
Native cover (%)	4.2	22.3	25.9	76.3
Non-native cover (%)	0	0.6	1.3	7.9
Elevation	1972	2266	2356	3023
Slope	1.4	10.02	12.46	32.5
Absolute aspect	5.2	80	86.9	180
Thematic Mapper band				
1	60	80	81.3	116
2	45	65	66.3	106
3	38	71	73.5	131
4	29	48	49.9	111
5	43	100	98.9	168
6	112	188	185.1	222
7	26	92	92.2	169
8	34	47	49.2	85
Band ratio				
(5/4)	63	127	133.5	191
(4/3)	1	1	1.038	2
(3/1)	85	85	88.2	170
(4–3)	22	42	54.9	184
NDVI[a]	0	1	0.620	1
TNDVI[b]	0	0	0.4975	115
Tassel Cap				
Band 1	111	168	173.4	265
Band 2	–80	–53	–49.8	3
Band 3	–83	–41	38.7	7
Band 4	19	27	26.7	34
Band 5	–71	–39	–37.7	–12
Band 6	–20	–15	–15.2	–11

Notes:
[a]NDVI = Normalized Difference Vegetation Index.
[b]TNDVI = Transformed Normalized Difference Vegetation Index.

Table 21. Summary statistics for large- and small-scale variability models to predict total, native, and non-native plant species richness and percent cover within the Cerro Grande fire, Los Alamos, New Mexico, 2001.

Variable	Large-scale variability (OLS model)[a]			Large- and small-scale variability (OLS and kriging–variogram model)[b]		
	R^2	SE	AICc[c]	Model	R^2	SE
Total plant species	0.14	11.1	610.3	Gaussian	0.64	7.0
Native plant species	0.44	8.6	571.6	Gaussian	0.60	7.0
Non-native plant species	0.58	1.6	309.5	Gaussian	0.61	1.5
Probability of non-native spp.	0.59	1.97	342.1	No spatial auto-correlation		
Total plant cover (%)	0.44	13.3	639.6	Gaussian	0.82	7.3
Native plant cover (%)	0.46	13.3	639.9	Gaussian	0.84	6.9
Non-native plant cover (%)	0.10	0.5	125.2	No spatial auto-correlation		

Notes:

[a] P significant at $\alpha < 0.05$ for the (Ordinary Least Squares) OLS models.

[b] P significant at $\alpha < 0.01$ for the variogram models.

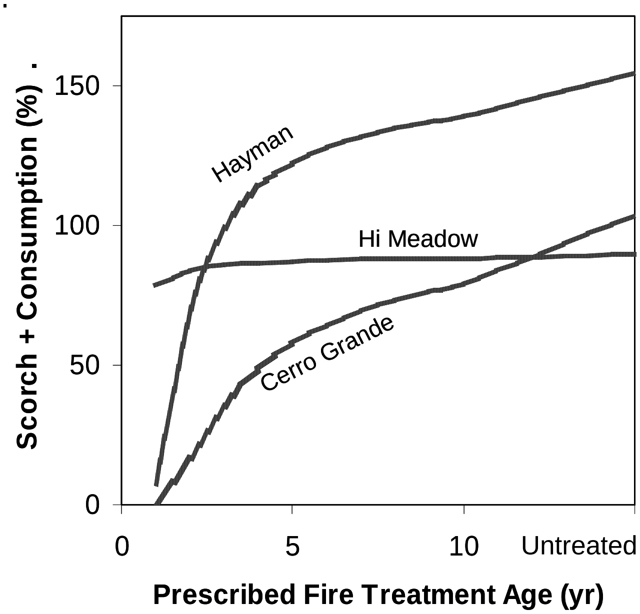
[c] AICc = Akaike's Information Criterion corrected for small samples.

4. **Discussion**

4.1 ***Influence of Stand Structure and Management Activities on Fire Severity***

Fuel conditions explained a significant portion of the variability in the severity of each of the fires we sampled. Management actions that alter fuel conditions can influence the severity of future fires in montane conifer forests such as those that we sampled. Though the relationship between fuel variables and fire severity varied substantially among our three study sites, fuel treatment by prescribed fire consistently appeared as an informative and significant mitigating variable at all three sites. Prescribed fires reduce surface and ladder fuels, at least in the short term. The effect of this fuel modification on fire severity was most evident in recent prescribed burns at the Hayman and Cerro Grande sites (Figure 4). Several previous studies corroborate this result, albeit on a more limited scale (Pollet and Omi 2002, Omi and Martinson 2002, Wagle and Eakle 1979).

Figure 4. Effect of prescribed burning on the severity of the three sampled fires when all other predictors are held constant at their mean values in untreated areas. Distances from roads and streams were set to their 1st and 3rd quartile values, respectively for the Hi Meadow fire, since interactions with these variables erased the effect of prescribed burns at average distances (Table 4).

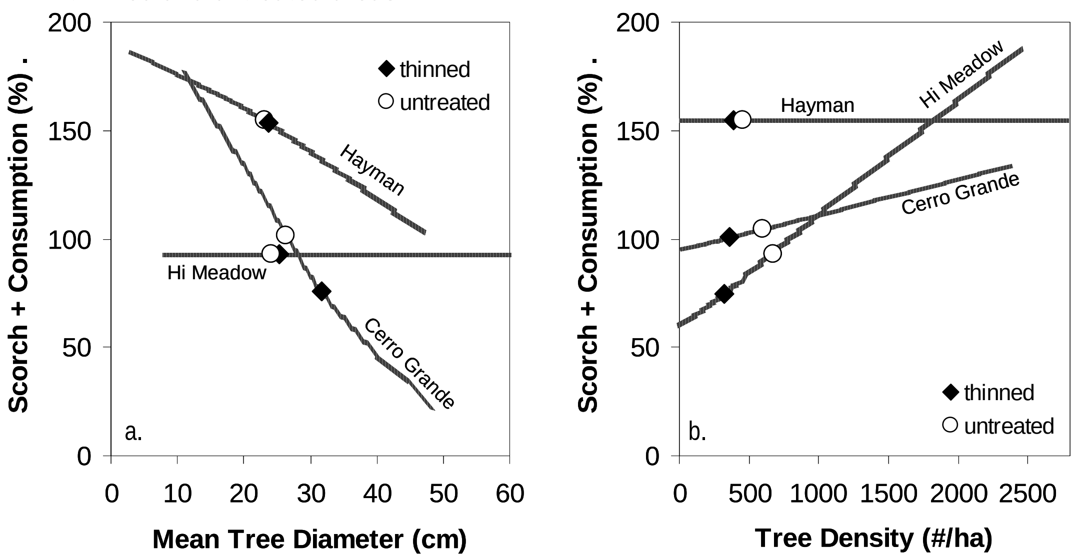


The only other consistency across all three sites in relation to the effect of fuels on fire severity was the exclusion of thinning treatments from all sets of informative models. Mechanical thinning reduces canopy fuels, but the resultant slash may increase surface fuels if not followed by prescribed fire or other means of removal. The effect of mechanical thinning on fire severity is therefore less certain than that of prescribed fire. Some previous studies have found thinning to reduce fire severity even without slash treatment (Omi et al. 2004), while others have observed logging slash to increase fire severity (Vihanek and Ottmar 1993). But since canopy fuel variables were included explicitly in our models, the thinning variable represented only the effect of the alteration to surface fuels when all other variables were held constant. So we were surprised to find that the additional surface fuels in thinned areas did not increase the severity of any of the fires. Nonetheless, the strong effect of recent prescribed burns at all three sites illustrates the importance of treating surface fuels, whether natural or activity generated.

Mechanical thinning will also alter canopy fuel variables (Graham et al. 1999), many of which we found to be significant predictors of fire severity in at least one of the three sampled fires. However, only tree diameter, stand density, and canopy bulk density were at least marginally significant at more than one site. Fire severity decreased significantly with increases in mean tree diameter in both the Cerro Grande fire and the Hayman fire. Larger trees tend to have thicker bark and crowns removed from the ground, increasing their resistance to damage from surface fire (Ryan and Reinhardt 1988). Removal of small trees effectively increased average tree diameter in thinned areas within the Cerro Grande fire and lessened its severity (Figure 5a). However, there was little difference in tree diameters, and thus fire severity, between thinned and untreated areas of the Hayman fire.

Higher stand density increased fire severity in the Cerro Grande fire as well as in the Hi Meadow fire. Higher stand density results in a greater and more continuous canopy fuel load. The effect of thinning on reducing stand density and fire severity was greatest in the Hi Meadow fire, but some effect was evident at the Cerro Grande fire, as well (Figure 5b). Since stand density is determined primarily by small trees, this variable may also be an indicator of the abundance of ladder fuels. Canopy base height would be a better measure of ladder fuels, but severe fire obscured this variable and made post-fire reconstruction unreliable.

Figure 5. Effect of mean tree diameter and stand density on the severity of the three sampled fires when all other predictors are held constant at their mean values in untreated areas. Markers indicate mean values for tree diameter and stand density in thinned and untreated areas.



Canopy bulk density is a key variable in crown fire prediction models (Scott and Reinhardt 2001) and may be a more direct measure of canopy fuels than stand density. However, we found canopy bulk density to be only marginally significant as a predictor of fire severity in both the Cerro Grande and Hi Meadow fires. Also, the effect of increases in canopy bulk density on fire severity was positive in the Hi Meadow fire but negative in the Cerro Grande fire. While a reduction in canopy bulk density would decrease the likelihood of crown fire propagation, greater exposure of surface fuels to solar radiation and wind could increase surface fire intensity. But quantification of canopy bulk density was prone to greater error than our other canopy fuel indicators since it was not measured directly, rather it was derived allometrically from imperfect equations based on data from a different geographic region (Brown 1978).

Fuel variables appeared to have a more consistent influence on fire severity among our study sites than did topographic variables. The only topographic variable found to be significant in all three fires was distance to roads. But roads might be better classified as a fuel manipulation, albeit not generally installed for the purpose of fire hazard mitigation. We would expect roads to act as a fuel break and disrupt fire spread to reduce fire severity. Roads did appear to augment the mitigating effect of prescribed burns in the Hi Meadow fire and of large trees in the Cerro Grande fire. However, roads diminished the mitigating effect of prescribed burns in the Hayman fire. This may have been due to an association between roads and drainages in the Hayman area, since there was a marginally significant increase in the severity of this fire with proximity to streams.

While our models explained a significant portion of the variability in fire severity, the explanatory power of our models varied among sites. The explanatory power of our fire severity models was about three times greater for Cerro Grande than for Hayman and High Meadow. Unexplained variability in fire severity was presumably caused by vagaries in the weather.

Weather conditions were most extreme during the Hayman fire and least extreme during the Hi Meadow fire (we calculated the Energy Release Component of the National Fire Danger Rating System with Fire Family Plus software (USDA Forest Service 2000) to be in the 97th percentile of the historical average during the Hayman fire, 96th percentile during the Cerro Grande fire, and 87th percentile during the Hi Meadow fire). Yet the amount of variability left unexplained by our models was nearly the same for the Hayman and Hi Meadow sites. We hypothesize that historic fire regime may influence the degree to which fire behavior and severity can be explained by fuel variables versus weather variables.

The Historic fire regime of the Cerro Grande area was typified by frequent, small, low intensity fires (Touchan et al. 1996). Fires were historically less frequent in the Hayman and Hi Meadow area and the fire regime included occasional extensive crown fire (Brown et al. 1999). Bessie and Johnson (1995) argue that fuels have little influence over fire events in systems where the historic fire regime was characterized by relatively infrequent crown fire occurring only under extreme weather conditions, such as boreal and subalpine forests. Keeley et al. (1999) make a similar argument for California chaparral, implying that there is little benefit to be gained by manipulating fuels in these systems. Most of the evidence of fuel treatment effectiveness has been found in areas characterized by short fire return intervals, such as the Cerro Grande system (Martinson and Omi 2003). Though the Hayman and Hi Meadow area is not at the opposite end of the fire regime spectrum from the Cerro Grande area, the relative explanatory power of our models relating fuel conditions to fire severity suggests caution in applying fuel treatments outside of short fire return interval systems.

4.2 *Influence of Management Activities and Fire Severity on Non-native Plants*

Disturbance theory suggests a high potential for non-native species establishment in fuel treatment areas (Sieg et al. 2003). But the literature contains very little empirical evidence demonstrating high establishment and spread rates of non-native species following fuel treatments (Griffis et al. 2001; Fornwalt et al. 2003; Albella and Covington 2004; Wienk et al. 2004). Our results confirm that there is a potential for higher establishment of non-native species in thinned areas as we found a slightly higher incidence of non-native species in thinned areas in the Cerro Grande fire. However, we found no significant effect of fuel treatments on non-native species cover at either the Hi Meadow or Hayman fires, indicating that the overall potential for establishment of non-native species following fuel treatments is low in these systems.

The influence of fuel treatments is less than that of wildfire on the establishment of non-native species. There are many documented cases in which intense wildfires result in increased establishment of invasive species (Crawford et al. 2001; Griffis et al. 2001; Keeley et al. 2003). Depth of char, an indicator of the downward heat pulse produced by a fire, was a consistent predictor of higher non-native species cover at all fires and both spatial scales. Non-native species cover was positively associated with char depth at the Hi Meadow and Hayman fires. Fire severity was a more important predictor of non-native species establishment than other abiotic variables that have proven impact on non-native species establishment in other studies. Results from this study suggest that the occurrence of wildfires may be one of the more important mechanisms for continued spread of non-native species in the western US.

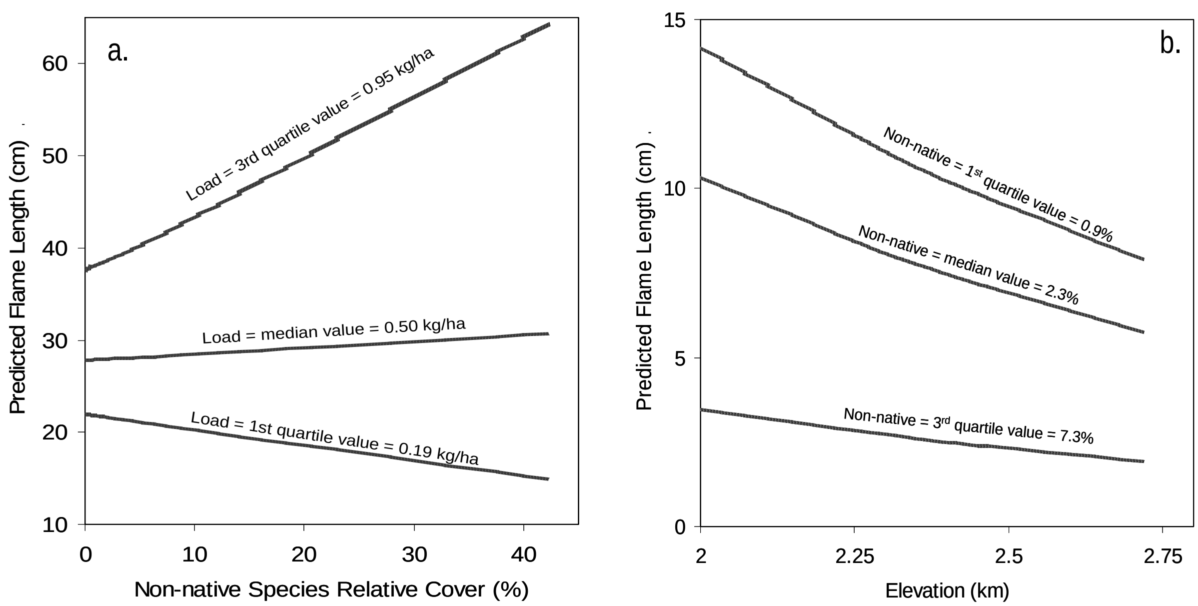
Spread and establishment of non-native species following wildfire may be deterred through appropriate post-fire management actions. However, there is a potential for introduction of non-native species through application of seed mixes and straw mulch for erosion control following wildfire (Beyers 2004). Although seed mixes have acceptable purity, they are usually contaminated with non-native species. The application of very large amounts of seed ensures that a large number of non-native weed seeds are distributed over the landscape. Results from our study show that non-native species cover is positively associated with seeded grass cover. The Hi Meadow fire showed a deviation from this trend and we suspect that is because of the method of seed application. At the Cerro Grande and Hayman fires, seed mixes were aerially applied and resulted in very low cover of seeded grasses over broad areas of the burned landscape. At the Hi Meadow fire, seed mixes were applied by hand or with a seed drill and resulted in very high cover of seeded grasses in a smaller portion of the burned landscape. Similarly, when cover of native grasses was high, establishment of non-native species was deterred. Post-fire treatments that encourage high vegetative cover, without introducing new non-native species in contaminated seed mixes, would best prevent further spread of non-native species. Our results suggest that hand application of native grass seed mixes would be preferable to broad aerial application of non-native grass seed. While we examined the effects of straw mulch at only one fire (Hayman), we found no effect of mulch application on establishment of non-native species on our plots.

4.3 ***Influence of Non-native Plants on Post-fire Flammability***

Numerous factors interact to influence the flammability of a fuel bed, including the characteristic surface-area-to-volume ratio, bulk density, depth, packing ratio, and the load distribution among live and dead fuel size classes. Non-native species could influence any of these and all were included in the creation of custom fuel models to predict post-fire flammability. However, it was not our intent to determine how non-native species influence individual fuel components or how individual fuel components influence flammability. Rather, our objective was to determine if variations in the abundance of non-native species affected the output of the BEHAVE (Burgan and Rothermel 1984) fire prediction system. We therefore refrained from adding to our models any variables that might have been influenced by the presence of non-native species, even though their inclusion would have increased the explanatory power of our models. Fuel bed depth and surface-area-to-volume ratio, in particular, are two variables we measured that could explain much of the variability in fire prediction outputs. However, these variables are also two of the primary means by which non-native species might influence flammability and their explicit inclusion in our models would have diminished our ability to attribute variations in flammability to non-native species.

Though the explanatory power of our flammability models was thus rather low, the relative cover of non-native species was included in the set of informative models for all three study areas and had a significant effect on post-fire flammability at both the Cerro Grande and Hayman sites. However, the effect of non-native species was not consistent between the Cerro Grande and Hayman fires. The suite of non-native species found at each site varied (Appendix B) and different species will uniquely influence the fuel bed parameters that determine flammability. Non-native species tended to exacerbate post-fire flammability in the Cerro Grande area, particularly where the post-fire fuel load was greater than average (Figure 6a). The main effect of non-natives was to decrease flammability after the Hayman fire, but non-natives did act to decrease the rate at which post-fire flammability was dampened by increases in elevation (Figure 6b).

Figure 6. Effect of non-native species on post-fire flammability at the Cerro Grande fire (a) and Hayman fire (b) study sites.



Fuel load and elevation were significant predictors of post-fire flammability at all three sites. Since severely burned areas may be completely denuded of fuel, post-fire flammability was determined primarily by total fuel load, but flammability decreased under increasingly mesic conditions associated with higher elevations. Though the BEHAVE (Burgan and Rothermel 1984) inputs for fuel moisture content were kept constant for all plots (Table 2), greenness of live biomass was a measured variable influenced by elevation that had a significant effect on predicted flame length. Sample date also affected greenness through seasonal curing, which resulted in significant increases in flammability as summer progressed at all three sites.

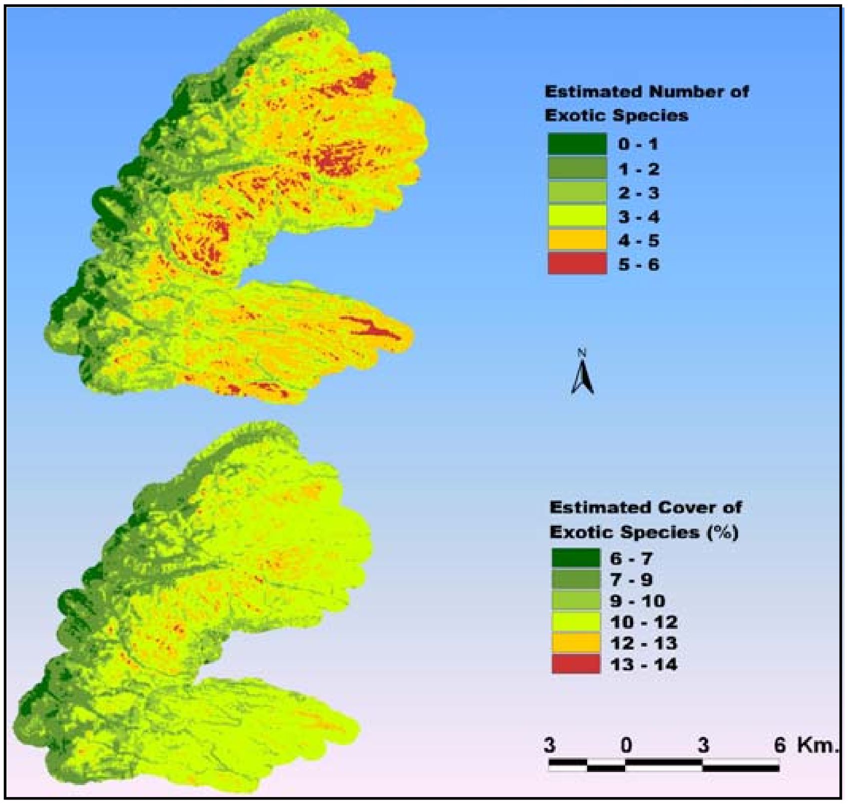
We expected seeded species would have an effect on post-fire flammability similar to that of non-native species, since the seed mixes used at all three sites included non-native grasses (annual ryegrass (*Lolium multiflorum*) and common barley (*Hordeum vulgare*) at Cerro Grande, hard fescue (*Festuca trachyphylla*) at Hi Meadow, common barley and common wheat (*Triticum aestivum*) at Hayman). Though seeded species were included in the set of informative models developed for Cerro Grande and Hi Meadow, their effect on flammability was not significant. However, the influences that non-native and seeded species have on flammability may become more pronounced as total vegetation cover increases over time.

4.4 ***Potential of Spatial Prediction Models***

Investigating spatial relationships among fuels, wildfire severity, and post-fire invasion by non-native plant species through the linkage of a multiphase sampling design and multiscale nested sampling field plots, pre- and post-fire, can be accomplished by the integration of remotely sensed data, GIS, and spatial statistical models. This technique provided useful information and tools for describing landscape-scale patterns of plant diversity within the Cerro Grande fire site. The various components of vegetation (e.g., forest structure, surface fuels, non-native species) are not always correlated with existing vegetation characteristics because of past management activities and random disturbance in the form of individual tree or plant mortality. Thus, collecting intensive fuel data and vegetation measurements using unbiased multiscale sampling within the forest landscape provides an excellent data source and input for spatial models similar to those presented here. These spatial models can provide unbiased estimates of the various components of the landscape, as well as estimates of the prediction variance associated with individual estimates. Models covering such areas as the Cerro Grande site enable the spatial integration of estimates of non-native species and fuel loads to a wide range of spatial scales, along with estimates of the level of uncertainty.

The information gained from integration of remotely sensed data, GIS, and field data can be used to produce spatial statistical maps; for example of invasive species richness (Figure 7). Integrating spatial information technology permits predictive modeling on multiple scales with more focused and unbiased sampling designs, thus reducing cost. Consequently, natural resource management teams can utilize this as a cost-effective tool in identifying areas vulnerable to non-native plant species invasion and increased potential for wildfire.

Figure 7. Examples of predictive spatial statistical maps based on the trend surface model (OLS) and kriging (variogram) on species richness and cover of non-native plant species within the Cerro Grande fire site.



5. Conclusions

Our sampling approach provided comprehensive data sets for the three individual wildfires we studied, but the low explanatory power of most of our models necessitates caution in generalizing our results beyond our study areas. Nonetheless, our findings do highlight some of the ecological risks and benefits associated with fire management activities, particularly pre-fire fuel treatments and post-fire seeding. Wildfires may be one of the more important mechanisms for continued spread of non-native species in the western US. We found a consistent positive correlation between fire severity and non-native plants, and fire severity was a more important predictor of non-native species establishment than other abiotic variables. Once established, non-native species increase post-fire flammability in some cases, possibly increasing the likelihood of severe fires in the future. Thus, activities that mitigate fire severity may also deter the establishment and spread of non-native species.

We found fire severity to be most consistently mitigated by recent prescribed burns. Stand conditions that can be managed by mechanical thinning, such as tree density and mean tree diameter, also influenced fire severity: fire severity decreased with increases in mean tree diameter and/or decreases in stand density. However, fuel variables best explained fire severity at our study site where historic fire frequency was greatest. Fuel manipulations may be less effective in mitigating fire severity in areas where low intensity fires were historically less common. Also, disturbance caused by fuel treatments may produce additional opportunities for non-native species establishment. We did find a slightly higher incidence of non-native species in the thinned areas of one of our study sites.

Establishment and spread of non-native species following wildfire also may be deterred through appropriate post-fire management actions. But seed mixes are often contaminated with non-native species and their application on landscape scales may introduce a large number of non-native weed seeds. We found a positive association between the cover of non-native species and seeded grasses where seed mixes were extensively applied. However, where seed mixes were intensively applied on a more limited scale, post-fire seeding successfully deterred non-native species establishment. Post-fire treatments that encourage high vegetative cover, without introducing new non-native species in contaminated seed mixes, would best prevent further spread of non-native species.

Areas vulnerable to non-native plant species invasion can be identified with spatial statistical prediction maps. We integrated remotely sensed data, geographic information systems, and field data to produce spatial statistical models based on large- and small-scale variability to predict patterns of non-native plant invasions. The predicted standard errors for non-native species richness in the Cerro Grande fire were less than 40% of the mean number of non-native species per plot, even at the farthest distance from a sampled point. This relatively low error indicates the potential utility of spatial statistical prediction maps for directing management activities to deter invasion by non-native plants.

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Appendix A: Dissemination

A.1 ***Manuscripts***

Chong, G., T. Stohlgren., C. Crosier, S. Simonson, G. Newman, and E. Petterson. 2003. Key invasive non-native plants. Pages 244-249 in R.T. Graham (Tech. Ed.) Hayman Fire Case Study. USDA Forest Service General Technical Report RMRS-GTR-114. URL: http://www.fs.fed.us/rm/pubs/rmrs_gtr_114.html

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Hunter, M.E. and P.N. Omi. *In review*. Response of native and exotic grasses to increased soil nitrogen and relation to recovery in a post-fire environment.

Martinson, E.J., P.N. Omi, and W.D. Shepperd. 2003. Effects of fuel treatments on fire severity. Pages 96-122 *in* R.T. Graham (Tech. Ed.) Hayman Fire Case Study. USDA Forest Service General Technical Report RMRS-GTR-114. URL: http://www.fs.fed.us/rm/pubs/rmrs_gtr_114.html

Kalkhan, M.A., E.J. Martinson, P.N. Omi, T.J. Stohlgren, G.W. Chong, and M.E. Hunter. 2004. Integrating remote sensing, GIS, and spatial statistics: a case study of invasive plants and wildfire on the Cerro Grande Fire, Los Alamos, New Mexico. Tall Timbers Fire Ecology Conference Proceedings 22:191-199. URL: http://www.talltimbers.org/info/pubcategories.html#FECP

Omi, P.N, E.J. Martinson, M.A. Kalkhan, G.W. Chong, M.E. Hunter, and T.J. Stohlgren. 2004. Fuels, fire severity, and invasive plants within the Cerro Grande fire, Los Alamos, NM. Tall Timbers Fire Ecology Conference Proceedings 22:141-148. URL: http://www.talltimbers.org/info/pubcategories.html#FECP

Williams, V. 2003. Evaluation of wildfire burn severity classification, utilising ground and remote sensing methodologies, Southern Colorado, USA. Master's Thesis, University of Edinburgh, Great Britian.

A.2 ***Presentations***

Ecological Society of America Annual Meeting, August 2004, Portland, Oregon:
"Effects of pre-fire fuel reduction treatments on post-wildfire non-native plant species richness and cover"

Joint Fire Science Program Annual Principal Investigator Workshop, March 2004, Phoenix, AZ:
"Spatial Interactions among Fuels, Wildfire, and Invasive Plants"

Second International Fire Congress, November 2003, Orlando, Florida:
"Effects of Fuel Treatments, Post-Fire Rehabilitation Treatments and Wildfire on Establishment of Invasive Species"
"Fuels, Fires, Invasions, and Some Effects of Active Management in the Eastern Rockies"

Joint Fire Science Program Annual Principal Investigator Workshop, March 2003, Phoenix, AZ:
"Spatial Interactions among Fuels, Wildfire, and Invasive Plants"

Society for Range Management Annual Meeting, February 2003, Casper, Wyoming:

"The Effects of Reseeding For Post-Fire Rehabilitation on Native Vegetation Recovery and Establishment of Invasive Species"
"New approach for estimating vegetation distribution, presence, patterns, and fuel loading: Examples from the Cerro Grande fire and High Meadow sites, Rocky Mountain Regions"

Association for Fire Ecology Conference, December 2002, San Diego, California:
"New Techniques for Estimating Post-fire Vegetation, Fuels, and Flammability"
"The Ecological, Hydrological and Geological Consequences of Burn Severity and Social Application of Those Results: How do we assess and do all that?"
Ecological Society of America Annual Meeting, August 2002, Tucson, Arizona:
"Invasive plants and wildfire on the Cerro Grande fire, Los Alamos: Integration of spatial information and spatial statistics"
Joint Fire Science Program Annual Principal Investigator Workshop, March 2002, San Antonio, Texas:
"Spatial Interactions among Fuels, Wildfire, and Invasive Plants"
Colorado Weed Management Association Meeting, December 2001, Denver, Colorado:
"Rapid assessment, inventory, and monitoring tools for managing non-native species invasions"
Tall Timbers 22nd Fire Ecology Conference, October 2001, Kananaskis, Alberta:
"*Fuels, Fire Severity, and Invasive Plants within the Cerro Grande Fire, Los Alamos, NM*"

A.3 ***Posters***
Second International Fire Congress, November 2003, Orlando, Florida:
"True Mountain Mahogany Sprouting Behavior Following Fire"
Third USGS Wildland Fire Workshop, November 2002, Denver, Colorado:
"Fuels, Fire Severity, and Invasive Plants: An Example from the Cerro Grande Fire, Los Alamos, New Mexico"
Conference on Fire, Fuel Treatments, and Ecological Restoration, April 2002, Fort Collins, Colorado:
"Invasive Plants and Wildfire on the Cerro Grande Fire, Los Alamos: Integration of Spatial Information and Spatial Statistics"
Tall Timbers 22nd Fire Ecology Conference, October 2001, Kananaskis, Alberta:
"Integration of Spatial Information and Spatial Statistics: a Case Study of Invasive Plants and Wildfire on the Cerro Grande Fire, Los Alamos, New Mexico, USA"

A.4 ***Field Trips and Training***
Student: University of Wyoming, October 2003, Hayman Fire, Colorado.
Managers: USFS National Program for Fire Systems Research, August 2003, Ft. Collins, Colorado.
Student: University of Taiwan, August 2003, Hayman Fire, Colorado.
Student: University of Edinburgh, June-July 2003, Hayman Fire, Colorado.
Researchers: USFS Rocky Mountain Research Station, June 2003, Hayman Fire, Colorado.
Researchers: CSU Department of Bioagricultural Sciences and Pest Management, June 2003, Hayman Fire, Colorado.
Researchers: USGS Wildland Fire Workshop, November 2002, Hayman Fire, Colorado.
Managers: USFS National Fuels Specialists Group, April 2002, Cerro Grande Fire, New Mexico.
Managers: US Bureau of Land Management, November 2001, Fort Collins, Colorado.

Researchers: USGS Central Region Water Resources Division, June 2001, Cerro Grande Fire, New Mexico.
Managers: Los Alamos Volunteer Task Force, July 2001, Los Alamos, New Mexico.

Appendix B: Non-native Species List

Table B. Non-native species frequency of occurrence (%) on the 1000-m^2 plots sampled at each of our study sites.

Species	Cerro Grande	Hi Meadow	Hayman
Chenopodium album	73.42	58.51	75.23
Verbascum thapsus	26.58	71.28	80.73
Lactuca serriola	32.91	46.81	47.71
Taraxacum officinale	45.57	39.36	36.7
Hordeum vulgare	70.89*	0	33.94*
Tragopogon dubius	32.91	27.66	27.52
Bromus tectorum	49.37	12.77	25.69
Lolium multiflorum	75.95*	0	0.92
Triticum aestivum	1.27	0	69.72*
Cirsium arvense	0	63.83	6.42
Erysimum cheiranthoides	0	13.83	40.37
Festuca trachyphylla	1.27	32.98*	0
Polygonum erectum	32.91	0	0
Poa pratensis	16.46	6.38	5.5
Thinopyrum ponticum	24.05	0	0
Conringia orientalis	0	17.02	0.92
Carduus nutans	0	15.96	0.92
Arabis hirsute	2.53	11.7	1.83
Bromus inermis	15.19	0	0
Sisymbrium altissimum	7.59	6.38	0.92
Descurainia Sophia	7.59	2.13	2.75
Chenopodium lanceolatum	0	1.06	9.17
Festuca ovina	7.59	0	0.92
Amaranthus retroflexus	0	1.06	7.34
Linaria vulgaris	0	2.13	5.5
Trifolium pretense	0	0	7.34
Chorispora tenella	6.33	0	0
Bromus mollis	0	3.19	1.83
Salsola iberica	0	0	4.59
Camelina microcarpa	0	1.06	2.75
Euphorbia agrarian	3.8	0	0
Cirsium vulgare	2.53	1.06	0
Trifolium repens	1.27	1.06	0.92
Achillea millefolium	0	3.19	0
Bromus erectus	0	3.19	0
Anthemis cotula	0	0	2.75
Bromus hordaceus	0	0	2.75
Polygonum aviculare	0	0	2.75
Aegilops cylindrical	2.53	0	0
Agropyron cristatum	2.53	0	0
Artemisia biennis	2.53	0	0
Raphanus sativus	2.53	0	0
Ulmus pumila	2.53	0	0
Poa compressa	1.27	0	0.92
Cerastium vulgatum	0	2.13	0
Gypsophila paniculata	0	1.06	0.92
Fallopia convolvulus	0	0	1.83
Polygonum convolvulus	0	0	1.83
Capsella bursa-pastoris	1.27	0	0
Elaeagnus angustifolia	1.27	0	0

Malus sylvestris	1.27	0	0
Medicago lupulina	1.27	0	0
Melandrium album	1.27	0	0
Myosotis alpestris	1.27	0	0
Thlaspi arvense	1.27	0	0
Zea mays	1.27	0	0
Agropyron repens	0	1.06	0
Asperugo procumbens	0	1.06	0
Avena sativa	0	1.06	0
Dactylis glomerata	0	1.06	0
Myosotis scorpioides	0	1.06	0
Anisantha tectorum	0	0	0.92
Bromus secalinus	0	0	0.92
Erodium cicutarium	0	0	0.92
Matricaria discoidea	0	0	0.92
Onopordum acanthium	0	0	0.92
Panicum miliaceum	0	0	0.92

Notes:

* Species included in the seed mix applied for post-fire rehabilitation.

Appendix C: Database Metadata

C.1 ***Fuels and Fire Severity***

C.1.1 *Cerro Grande*

a.. Project: Spatial interactions among fuels, wildfire, and non-native plants.
b.. Dataset: Fuels&Severity: Cerro Grande, NM.
c.. Publication Date: Unpublished.
d.. Originator: Western Forest Fire Research Center (WESTFIRE) and the Natural Resource Ecology Laboratory (NREL), Colorado State University.
e.. Abstract of the data set: The data are from the 2000 Cerro Grande wildfire on the Santa Fe National Forest. Plots were distributed randomly across the landscape within strata determined by fire severity level, aspect, vegetation type, and management activity. Data collected describe stand conditions and fire severity at each plot.
f.. Purpose: The data were collected to assess the influence of stand conditions on wildfire severity.
g.. Format: MS Excel database.
h.. Date collected: Summer 2001.
i.. Location: Northern New Mexico between UTM Eastings 371,192 and 390,095 and between UTM Northings 3,966,876 and 3,981,432 (Zone 13S, NAD27).
j.. Access Constraints: Data are owned by Colorado State University and will be used in publications currently in preparation. Data access requests will be considered on a case-by-case basis.
k.. Use Constraints: Data are owned by Colorado State University and will be used in publications currently in preparation. Data use requests will be considered on a case-by-case basis. Data use without the express written consent of either WESTFIRE or NREL is prohibited.
l.. Keywords: Fuel treatments, prescribed fire, mechanical thinning, stand conditions, wildfire severity, New Mexico, Santa Fe National Forest, ponderosa pine, pinyon-juniper, mixed conifer.
m.. Contact: Erik J. Martinson
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n.. Publications:
Omi, P.N, E.J. Martinson, M.A. Kalkhan, G.W. Chong, M.E. Hunter, and T.J. Stohlgren. 2004. Fuels, fire severity, and invasive plants within the Cerro Grande fire, Los Alamos, NM. Tall Timbers Fire Ecology Conference Proceedings 22:141-148.
o.. Data quality and accuracy: Error checks have been completed.
p.. Completeness: The dataset contains no omissions.
q.. Methodology: See Section 2 of this report.
r.. Spatial Data:
1. Plot coordinates are available as points indicating the origin of each 20m X 50m Modified-Whittaker plot. The bearing from the origin of the 20m and 50m sides are also indicated.
2. Coordinates are projected in Universal Transverse Mercator, North American Datum 1927. Units are in meters.

s.. Attributes:
1. Plot information: plot name, plot stratum, sample date, measurer, recorder, GPS coordinates, plot orientation.
2. Topographic information: aspect (degrees), slope (percent), elevation (m), distance to nearest road (m), distance to nearest stream (m).
3. Pre-fire stand conditions: tree density (#/ha), basal area (m^2/ha), mean tree height (m), mean diameter at breast height (cm), canopy base height (m), canopy bulk density (kg/m3), species composition (percent ponderosa pine).
4. Fire severity information: stand damage rating (0-4), depth of char rating (0-3), needle scorch height (m), bole char height (m), crown volume scorch (%), crown volume consumption (%).

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C.1.2 *Hi Meadow*

a.. Project:See entry for Section C.1.1.
b.. Dataset: Fuels&Severity: Hi Meadow, CO.
c.. Publication Date: See entry for Section C.1.1.
d.. Originator: See entry for Section C.1.1.
e.. Abstract of the data set: : The data are from the 2000 Hi Meadow wildfire on the Pike National Forest. Plots were distributed randomly across the landscape within strata determined by fire severity level, aspect, vegetation type, and management activity. Data collected describe stand conditions and fire severity at each plot.
f.. Purpose:See entry for Section C.1.1.
g.. Format: See entry for Section C.1.1.
h.. Date collected: Summer 2002.
i.. Location: Central Colorado between UTM Eastings 465,873 and 474,672 and between UTM Northings 4,357,509 and 4,361,295 (Zone 13S, NAD27).
j.. Access Constraints: See entry for Section C.1.1.
k.. Use Constraints: See entry for Section C.1.1.
l.. Keywords: Fuel treatments, prescribed fire, mechanical thinning, stand conditions, wildfire severity, Colorado, Pike National Forest, ponderosa pine, Douglas-fir.
m.. Contact: See entry for Section C.1.1.
n.. Publications: In preparation.
o.. Data quality and accuracy: See entry for Section C.1.1.
p.. Completeness: See entry for Section C.1.1.
q.. Methodology: See Section 2 of this report.
r.. Spatial Data: See entry for Section C.1.1.
s.. Attributes: See entry for Section C.1.1.
t.. Distributor: See entry for Section C.1.1.

C.2.3 *Hayman*

a.. Project: See entry for Section C.1.1.
b.. Dataset: Fuels&Severity: Hayman, CO.

c.. Publication Date: See entry for Section C.1.1.
d.. Originator: See entry for Section C.1.1.
e.. Abstract of the data set: The data are from the 2002 Hayman wildfire on the Pike National Forest. Plots were distributed randomly across the landscape within strata determined by fire severity level, aspect, vegetation type, and management activity. Data collected describe stand conditions and fire severity at each plot.
f.. Purpose: See entry for Section C.1.1.
g.. Format: See entry for Section C.1.1.
h.. Date collected: Summer 2003.
i.. Location: Central Colorado between UTM Eastings 467,615 and 487,972 and between UTM Northings 4,328,641 and 4,350,786 (Zone 13S, NAD27).
j.. Access Constraints: See entry for Section C.1.1.
k.. Use Constraints: See entry for Section C.1.1.
l.. Keywords: Fuel treatments, prescribed fire, mechanical thinning, stand conditions, wildfire severity, Colorado, Pike National Forest, ponderosa pine, Douglas-fir.
m.. Contact: See entry for Section C.1.1.
n.. Publications:
Martinson, E.J., P.N. Omi, and W.D. Shepperd. 2003. Effects of fuel treatments on fire severity. Pages 96-122 *in* R.T. Graham (Tech. Ed.) Hayman Fire Case Study. USDA Forest Service General Technical Report RMRS-GTR-114.
o.. Data quality and accuracy: See entry for Section C.1.1.
p.. Completeness: Information is unavailable for 2 plots (312 and 616).
q.. Methodology: See Section 2 of this report.
r.. Spatial Data: See entry for Section C.1.1.
s.. Attributes: See entry for Section C.1.1.
t.. Distributor: See entry for Section C.1.1.

C.2 ***Floristics***

C.2.1 *Cerro Grande*
a.. Project: Spatial interactions among fuels, wildfire, and non-native plants.
b.. Dataset: Plants: Cerro Grande, NM.
c.. Publication Date: Unpublished.
d.. Originator: Western Forest Fire Research Center (WESTFIRE) and the Natural Resource Ecology Laboratory (NREL), Colorado State University.
e.. Abstract of the data set: The data are from the 2000 Cerro Grande wildfire on the Santa Fe National Forest. Plots were distributed randomly across the landscape within strata determined by fire severity level, aspect, vegetation type, and management activity. Data collected describe plant species composition including percent cover, height, nativity, and growth form by species at two plot scales: 1-m^2 and 1000-m^2.
f.. Purpose: The data were collected to assess influences on the presence and abundance of non-native plants in post-fire landscapes, with foci on fire severity and management activities.
g.. Format: MS Access database.
h.. Date collected: Summer 2001.
i.. Location: Northern New Mexico between UTM Eastings 371,192 and 390,095 and between UTM Northings 3,966,876 and 3,981,432 (Zone 13S, NAD27).

j.. Access Constraints: Data are owned by Colorado State University and will be used in publications currently in preparation. Data access requests will be considered on a case-by-case basis. Once all publications have been submitted, data will be archived with the USGS National Institute of Invasive Species Science at http://129.82.104.51/cwis438/niiss/index.html.

k.. Use Constraints: Data are owned by Colorado State University and will be used in publications currently in preparation. Data use requests will be considered on a case-by-case basis. Data use without the express written consent of either WESTFIRE or NREL is prohibited.

l.. Keywords: Non-native, invasive, exotic, fuel treatments, prescribed fire, mechanical thinning, seeding, wildfire severity, New Mexico, Santa Fe National Forest, ponderosa pine, pinyon-juniper, mixed conifer.

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n.. Publications:

Kalkhan, M.A., E.J. Martinson, P.N. Omi, T.J. Stohlgren, G.W. Chong, and M.E. Hunter. 2004. Integrating remote sensing, GIS, and spatial statistics: a case study of invasive plants and wildfire on the Cerro Grande Fire, Los Alamos, New Mexico. Tall Timbers Fire Ecology Conference Proceedings 22:191-199.

Omi, P.N, E.J. Martinson, M.A. Kalkhan, G.W. Chong, M.E. Hunter, and T.J. Stohlgren. 2004. Fuels, fire severity, and invasive plants within the Cerro Grande fire, Los Alamos, NM. Tall Timbers Fire Ecology Conference Proceedings 22:141-148.

o.. Data quality and accuracy: Error checks have been completed.

p.. Completeness: Soil information is not available for one plot (plot #003).

q.. Methodology: See Section 2 of this report.

r.. Spatial Data:
1. Plot coordinates are available as points indicating the origin of each 20m X 50m Modified-Whittaker plot. The bearings from the origin of the 20m and 50m sides are also indicated.
2. Coordinates are projected in Universal Transverse Mercator, North American Datum 1927. Units are in meters.

s.. Attributes:
1. Plot information (plot name, plot stratum, sample date, botanist, recorder, GPS coordinates, plot orientation).
2. Plant information (scientific name, USDA Natural Resources Conservation Service plant species code, growth form, duration (annual, biennial, perennial), origin (native or introduced), percent cover, height).
3. Percent cover of auxiliary items (rock, soil, duff, litter, wood, moss, lichen).
4. Soil information (chemistry (percent total nitrogen and carbon) and texture (percent sand, silt, and clay).

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C.2.2 *Hi Meadow*

a.. Project: See entry for Section C.2.1.
b.. Dataset: Plants: Hi Meadow, CO.
c.. Publication Date: See entry for Section C.2.1.
d.. Originator: See entry for Section C.2.1.
e.. Abstract of the data set: The data are from the 2000 Hi Meadow wildfire on the Pike National Forest. Plots were distributed randomly across the landscape within strata determined by fire severity level, aspect, and management activity. Data collected describe plant species composition including percent cover, height, nativity, and growth form by species at two plot scales: 1-m^2 and 1000-m^2.
f.. Purpose: See entry for Section C.2.1.
g.. Format: See entry for Section C.2.1.
h.. Date collected: Summer 2002.
i.. Location: Central Colorado between UTM Eastings 465,873 and 474,672 and between UTM Northings 4,357,509 and 4,361,295 (Zone 13S, NAD27).
j.. Access Constraints: See entry for Section C.2.1.
k.. Use Constraints: See entry for Section C.2.1.
l.. Keywords: Non-native, invasive, exotic, fuel treatments, prescribed fire, mechanical thinning, seeding, wildfire severity, Colorado, Pike National Forest, ponderosa pine, Douglas-fir.
m.. Contact: See entry for Section C.2.1.
n.. Publications: In preparation.
o.. Data quality and accuracy: See entry for Section C.2.1.
p.. Completeness: The dataset contains no omissions.
q.. Methodology: See Section 2 of this report.
r.. Spatial Data: See entry for Section C.2.1.
s.. Attributes: See entry for Section C.2.1.
t.. Distributor: See entry for Section C.2.1.

C.2.3 *Hayman*

a.. Project: See entry for Section C.2.1.
b.. Dataset: Plants: Hayman, CO.
c.. Publication Date: See entry for Section C.2.1.
d.. Originator: See entry for Section C.2.1.
e.. Abstract of the data set: The data are from the 2002 Hayman wildfire on the Pike National Forest. Plots were distributed randomly across the landscape within strata determined by fire severity level, aspect, and management activity. Data collected describe plant species composition including percent cover, height, nativity, and growth form by species at two plot scales: 1-m^2 and 1000-m^2.
f.. Purpose: See entry for Section C.2.1.
g.. Format: See entry for Section C.2.1.
h.. Date collected: Summer 2003.
i.. Location: Central Colorado between UTM Eastings 467,615 and 487,972 and between UTM Northings 4,328,641 and 4,350,786 (Zone 13S, NAD27).
j.. Access Constraints: See entry for Section C.2.1.
k.. Use Constraints: See entry for Section C.2.1.

l.. Keywords: Non-native, invasive, exotic, fuel treatments, prescribed fire, mechanical thinning, seeding, wildfire severity, Colorado, Pike National Forest, ponderosa pine, Douglas-fir.
m.. Contact: See entry for Section C.2.1.
n.. Publications:
Chong, G., T. Stohlgren., C. Crosier, S. Simonson, G. Newman, and E. Petterson. 2003. Key invasive non-native plants. Pages 244-249 in R.T. Graham (Tech. Ed.) Hayman Fire Case Study. USDA Forest Service General Technical Report RMRS-GTR-114.
o.. Data quality and accuracy: See entry for Section C.2.1.
p.. Completeness: Plant information for 16 plots (307-308, 328, 702-704, 720-723, 804-805, 902, 904, 909) was lost due to technical difficulties with Palm-top computers. Soil information is unavailable for an additional two plots (404 and 501).
q.. Methodology: See Section 2 of this report.
r.. Spatial Data: See entry for Section C.2.1.
s.. Attributes: See entry for Section C.2.1.
t.. Distributor: See entry for Section C.2.1.

C.3 ***Post-fire Flammability***

C.3.1 *Cerro Grande*
a.. Project: Spatial interactions among fuels, wildfire, and non-native plants.
b.. Dataset: Flammability - Cerro Grande, NM.
c.. Publication Date: Unpublished.
d.. Originator: Western Forest Fire Research Center (WESTFIRE) and the Natural Resource Ecology Laboratory (NREL), Colorado State University.
e.. Abstract of the data set: The data are from the 2000 Cerro Grande wildfire on the Santa Fe National Forest. Plots were distributed randomly across the landscape within strata determined by fire severity level, aspect, vegetation type, and management activity. Data collected describe post-fire fuel model parameters and fire behavior predictions at each plot.
f.. Purpose: The data were collected to assess the influence of non-native plant species on fuelbed flammability.
g.. Format: MS Excel database.
h.. Date collected: Summer 2001.
i.. Location: Northern New Mexico between UTM Eastings 371,192 and 390,095 and between UTM Northings 3,966,876 and 3,981,432 (Zone 13S, NAD27).
j.. Access Constraints: Data are owned by Colorado State University and will be used in publications currently in preparation. Data access requests will be considered on a case-by-case basis.
k.. Use Constraints: Data are owned by Colorado State University and will be used in publications currently in preparation. Data use requests will be considered on a case-by-case basis. Data use without the express written consent of either WESTFIRE or NREL is prohibited.
l.. Keywords: Non-native, exotic, invasive, seeded, custom fuel models, flammability, New Mexico, Santa Fe National Forest, ponderosa pine pinyon-juniper, mixed conifer.
m.. Contact: Erik J. Martinson
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n.. Publications: In preparation.
o.. Data quality and accuracy: Error checks have been completed.
p.. Completeness: The dataset contains no omissions.
q.. Methodology: See Section 2 of this report.
r.. Spatial Data:
1. Plot coordinates are available as points indicating the origin of each 20m X 50m Modified-Whittaker plot. The bearing from the origin of the 20m and 50m sides are also indicated.
2. Coordinates are projected in Universal Transverse Mercator, North American Datum 1927. Units are in meters.
s.. Attributes:
1. Plot information: plot name, plot stratum, sample date, measurer, recorder, GPS coordinates, plot orientation.
2. Fuel modeling output: Fuel load (g/m^2, separated by fuel moisture timelag class), fuel bed depth (cm), surface area-to-volume ratio (m^2/m^3), relative packing (packing ratio divided by optimal packing ratio).
3. Fire behavior prediction output: Fireline intensity (kw/m), rate of spread (m/min), flame length (cm).
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C.3.2 *Hi Meadow*

a.. Project: See entry for Section C.3.1.
b.. Dataset: Flammability - Hi Meadow, CO.
c.. Publication Date: See entry for Section C.3.1.
d.. Originator: See entry for Section C.3.1.
e.. Abstract of the data set: : The data are from the 2000 Hi Meadow wildfire on the Pike National Forest. Plots were distributed randomly across the landscape within strata determined by fire severity level, aspect, vegetation type, and management activity. Data collected describe post-fire fuel model parameters and fire behavior predictions at each plot.
f.. Purpose: See entry for Section C.3.1.
g.. Format: See entry for Section C.3.1.
h.. Date collected: Summer 2002.
i.. Location: Central Colorado between UTM Eastings 465,873 and 474,672 and between UTM Northings 4,357,509 and 4,361,295 (Zone 13S, NAD27).
j.. Access Constraints: See entry for Section C.3.1.
k.. Use Constraints: See entry for Section C.3.1.
l.. Keywords: Non-native, exotic, invasive, seeded, custom fuel models, flammability, Colorado, Pike National Forest, ponderosa pine, Douglas-fir.
m.. Contact: See entry for Section C.3.1.
n.. Publications: In preparation.
o.. Data quality and accuracy: See entry for Section C.3.1.
p.. Completeness: See entry for Section C.3.1.

q.. Methodology: See Section 2 of this report.
r.. Spatial Data: See entry for Section C.3.1.
s.. Attributes: See entry for Section C.3.1.
t.. Distributor: See entry for Section C.3.1.

C.3.3 *Hayman*
a.. Project: See entry for Section C.3.1.
b.. Dataset: Flammability - Hayman, CO.
c.. Publication Date: See entry for Section C.3.1.
d.. Originator: See entry for Section C.3.1.
e.. Abstract of the data set: The data are from the 2002 Hayman wildfire on the Pike National Forest. Plots were distributed randomly across the landscape within strata determined by fire severity level, aspect, vegetation type, and management activity. Data collected describe post-fire fuel model parameters and fire behavior predictions at each plot.
f.. Purpose: See entry for Section C.3.1.
g.. Format: See entry for Section C.3.1.
h.. Date collected: Summer 2003.
i.. Location: Central Colorado between UTM Eastings 467,615 and 487,972 and between UTM Northings 4,328,641 and 4,350,786 (Zone 13S, NAD27).
j.. Access Constraints: See entry for Section C.3.1.
k.. Use Constraints: See entry for Section C.3.1.
l.. Keywords: Non-native, exotic, invasive, seeded, custom fuel models, flammability, Colorado, Pike National Forest, ponderosa pine, Douglas-fir.
m.. Contact: See entry for Section C.3.1.
n.. Publications: See entry for Section C.3.1.
o.. Data quality and accuracy: See entry for Section C.3.1.
p.. Completeness: Information is unavailable for 2 plots (312 and 616).
q.. Methodology: See Section 2 of this report.
r.. Spatial Data: See entry for Section C.3.1.
s.. Attributes: See entry for Section C.3.1.
t.. Distributor: See entry for Section C.3.1.

C.4 ***Spatial Prediction Maps***

C.4.1 *Cerro Grande*
a.. Project: Spatial interactions among fuels, wildfire, and non-native plants.
b.. Dataset: Invasion Predictions - Cerro Grande, NM.
c.. Publication Date: Unpublished.
d.. Originator: Western Forest Fire Research Center (WESTFIRE) and the Natural Resource Ecology Laboratory (NREL), Colorado State University.
e.. Abstract of the data set: The data show predicted cover and richness of non-native species in the post-fire landscape of the 2000 Cerro Grande wildfire on the Santa Fe National Forest. The predictions were derived from spatial statistical models based on field sampling augmented by full-coverage remotely sensed data layers. Sample plots were distributed randomly across the landscape within strata determined by fire severity level, aspect, vegetation type, and management activity.

f.. Purpose: The maps were developed to show the spatial distribution of predicted hotspots of non-native species invasions into the sampled burn areas.
g.. Format: Arc GRID export file.
h.. Date collected: Summer 2001.
i.. Location: Northern New Mexico between UTM Eastings 370,723 and 390,260 and between UTM Northings 3,964,358 and 3,985,773 (Zone 13S, NAD27).
j.. Access Constraints: Data are owned by Colorado State University and will be used in publications currently in preparation. Data access requests will be considered on a case-by-case basis.
k.. Use Constraints: Data are owned by Colorado State University and will be used in publications currently in preparation. Data use requests will be considered on a case-by-case basis. Data use without the express written consent of either WESTFIRE or NREL is prohibited.
l.. Keywords: Non-native, exotic, invasive, spatial statistics, trend surface, variogram, kriging, New Mexico, Santa Fe National Forest, ponderosa pine pinyon-juniper, mixed conifer.
m.. Contact: Mohammed A. Kalkhan
Address: 1499 Campus Delivery, Colorado State University, Fort Collins, CO 80523
Telephone: (970) 491-5262
Email: mohammed@nrel.colostate.edu
n.. Publications: In preparation.
Kalkhan, M.A., E.J. Martinson, P.N. Omi, T.J. Stohlgren, G.W. Chong, and M.E. Hunter. 2004. Integrating remote sensing, GIS, and spatial statistics: a case study of invasive plants and wildfire on the Cerro Grande Fire, Los Alamos, New Mexico. Tall Timbers Fire Ecology Conference Proceedings 22:191-199.
o.. Data quality and accuracy: Error checks have been completed.
p.. Completeness: The dataset contains no omissions.
q.. Methodology: See Section 2 of this report.
r.. Spatial Data:
1. Data are in raster format.
2. Coordinates are projected in Universal Transverse Mercator, North American Datum 1927. Units are in meters.
s.. Attributes:
1. Percent cover of non-native species predicted for each grid cell.
2. Number of different non-native species predicted for each grid cell.
t.. Distributor: Mohammed A. Kalkhan
Address: 1499 Campus Delivery, Colorado State University, Fort Collins, CO 80523
Telephone: (970) 491-5262
Email: mohammed@nrel.colostate.edu

C.4.2 *Hi Meadow*
a.. Project: See entry for Section C.4.1.
b.. Dataset: : Invasion Predictions - Hi Meadow, CO.
c.. Publication Date: See entry for Section C.4.1.
d.. Originator: See entry for Section C.4.1.
e.. Abstract of the data set: : The data show predicted cover and richness of non-native species in the post-fire landscape of the 2000 Hi Meadow wildfire on the Pike National Forest. The

predictions were derived from spatial statistical models based on field sampling augmented by full-coverage remotely sensed data layers. Sample plots were distributed randomly across the landscape within strata determined by fire severity level, aspect, vegetation type, and management activity.

f.. Purpose: See entry for Section C.4.1.
g.. Format: See entry for Section C.4.1.
h.. Date collected: Summer 2002.
i.. Location: Central Colorado between UTM Eastings 464,590 and 474,749 and between UTM Northings 4,356,363 and 4,366,131 (Zone 13S, NAD27).
j.. Access Constraints: See entry for Section C.4.1.
k.. Use Constraints: See entry for Section C.4.1.
l.. Keywords: Non-native, exotic, invasive, spatial statistics, trend surface, variogram, kriging, Colorado, Pike National Forest, ponderosa pine, Douglas-fir.
m.. Contact: See entry for Section C.4.1.
n.. Publications: In preparation.
o.. Data quality and accuracy: See entry for Section C.4.1.
p.. Completeness: See entry for Section C.4.1.
q.. Methodology: See Section 2 of this report.
r.. Spatial Data: See entry for Section C.4.1.
s.. Attributes: See entry for Section C.4.1.
t.. Distributor: See entry for Section C.4.1.

C.3.3 *Hayman*

a.. Project: See entry for Section C.4.1.
b.. Dataset: : Invasion Predictions - Hayman, CO.
c.. Publication Date: See entry for Section C.4.1.
d.. Originator: See entry for Section C.4.1.
e.. Abstract of the data set: The data show predicted cover and richness of non-native species in the post-fire landscape of the 2002 Hayman wildfire on the Pike National Forest. The predictions were derived from spatial statistical models based on field sampling augmented by full-coverage remotely sensed data layers. Sample plots were distributed randomly across the landscape within strata determined by fire severity level, aspect, vegetation type, and management activity.
f.. Purpose: See entry for Section C.4.1.
g.. Format: See entry for Section C.4.1.
h.. Date collected: Summer 2003.
i.. Location: Central Colorado between UTM Eastings 461,452 and 491,453 and between UTM Northings 4,314,388 and 4,352,888 (Zone 13S, NAD27).
j.. Access Constraints: See entry for Section C.4.1.
k.. Use Constraints: See entry for Section C.4.1.
l.. Keywords: Non-native, exotic, invasive, spatial statistics, trend surface, variogram, kriging, Colorado, Pike National Forest, ponderosa pine, Douglas-fir.
m.. Contact: See entry for Section C.4.1.
n.. Publications: See entry for Section C.4.1.
o.. Data quality and accuracy: See entry for Section C.4.1.
p.. Completeness: See entry for Section C.4.1.

q.. Methodology: See Section 2 of this report.
r.. Spatial Data: See entry for Section C.4.1.
s.. Attributes: See entry for Section C.4.1.
t.. Distributor: See entry for Section C.4.1.

Appendix D: Outline for Potential Workshop

Format: Special Conference Session.

Venue: Third International Fire Ecology and Management Congress, 13-17 November 2006, San Diego, CA.

Title: Fire Management and Invasive Species: Fuel Treatments Versus Wildfires.

Abstract: Fuel treatments have expanded substantially in recent years to mitigate the threat of extreme wildfire. However, widespread disturbances created by treatments may exacerbate threats posed by invasion of non-native species. While the effect of fuel treatments on invasive species may be less exacerbating than that of wildfires, there is little published evidence to support this hypothesis. However, in recent years, the Joint Fire Science Program has funded at least 10 research projects to address the relationship between fire management and invasive species. This Special Session will provide a forum to compare and contrast recent findings on the relative effects of fuel treatments and wildfires on non-native plant invasions.

Topic:	Candidate Speaker:
Rocky Mountains	
Wildfires	Molly Hunter, Colorado State University
Fuel Treatments	Merrill Kauffman, USFS
Cascade Mountains	
Wildfires	To be determined
Fuel Treatments	Carl Fiedler, University of Montana
Sierra-Nevada Mountains	
Wildfires	Jon Keeley, USGS
Fuel Treatments	Jan Beyers, USFS
Great Basin	
Wildfires	Lisa Floyd-Hanna, Prescott College
Fuel Treatments	Jeanne Chambers, USFS
Southern Piedmont	
Wildfires	To be determined
Fuel Treatments	Ross Phillips, USFS
Mid-western Grasslands	
Wildfires	To be determined
Fuel Treatments	Fred Giese, USFWS
Hawaiian Islands	
Wildfires	Rhonda Loh, NPS
Fuel Treatments	Michael Castillo, USFWS
Scaling Predictions from Plots to Landscapes	Mohammed Kalkhan, Colorado State University
Summary and Implications	Philip Omi, Colorado State University