Ecological Applications, 19(2), 2009, pp. 338–358

Impacts of Fire and Fire Surrogate treatments on forest soil properties: a meta-analytical approach

Ralph E. J. Boerner,[1,3] Jianjun Huang,[1] and Stephen C. Hart[2,4]

[1]*Department of Evolution, Ecology, and Organismal Biology, Ohio State University, Columbus, Ohio 43210 USA*
[2]*School of Forestry and Merriam-Powell Center for Environmental Research, Northern Arizona University, Flagstaff, Arizona 86011 USA*

Abstract. The soils underlying the 12 Fire and Fire Surrogates Network include six soil orders and >50 named soil series. Across the network, pretreatment soils varied from 3.7 to 7.1 in pH, and exhibited ranges of twofold in bulk density, fourfold in soil organic C (SOC) content, 10-fold in total inorganic N (TIN), and 200–1000-fold in extractable Ca and K. Nonmetric multidimensional (NMS) ordination of pretreatment soil conditions arrayed the FFS sites along gradients of pH/base cation status, net N transformation rates, bulk density, and SOC. At the network scale, mineral soil exposure was significantly greater in fire-only (mean of 9.2%) and mechanical + fire (5.0%) treatments than in the controls (1.5%) during the first posttreatment year, and this persisted through the later sampling year (second through fourth year, depending on site) in the fire-only treatment (fire 4.1%, control 1.1%). Bulk density was not affected significantly at the network scale. TIN concentrations during the first posttreatment year increased after all three manipulative treatments, but this effect did not persist to the later sampling year. Neither SOC content nor soil C:N ratio was affected by any of the treatments at the network scale. At the individual site scale, the combined mechanical + fire treatment produced more significant site × treatment × year effects than did the fire-only or mechanical-only treatments, though in most cases even the statistically significant differences produced by the manipulative treatments were modest in magnitude. Ordination of first-year standardized effect sizes produced no discernable separation of the three manipulative treatments but did separate the three sites with the greatest fire severity (based on proportional fuel consumption) from the majority of the network sites, with changes in pH, TIN, SOC content, and soil C:N ratio correlating most strongly with this separation. Ordination of the effect sizes from the later sampling year produced somewhat clearer separation of treatments than did the first-year ordination, though fewer sites were represented in this second ordination. Overall, the network-wide effects of the FFS treatments on soil properties appear to have been modest and transient.

Key words: *carbon; forest soil; mechanical treatment; meta-analysis; nitrogen; prescribed fire.*

Introduction

A considerable literature on the effects of wild and prescribed fire on soil properties has developed over the last half century, and has been the subject of several recent literature reviews (Ice et al. 2004, Certini 2005, Boerner 2006) and meta-analyses (Johnson and Curtis 2001, Wan et al. 2001). These syntheses suggest that the effects of fire vary considerably among forest ecosystem types, in proportion to fire severity, and over time. Perhaps more importantly, the diversity of ecosystem types, soil types, fires, response parameters, and experimental designs is so great that developing generalizations that are useful at the local management scale is problematical.

As true as this is for fire, it is even more the case for mechanical treatments (e.g., canopy or understory thinning). Although there are a suite of studies examining the impact of clear-cutting and whole-tree harvesting on forest floor and soil properties (e.g., Matson and Vitousek 1981, Rummer et al. 1997, Klepac et al. 1999), the literature on the effects of mechanical treatments at intensities useful for ecosystem restoration and wildfire hazard mitigation is sparse, at best (Boyle et al. 2005). Furthermore, what generalities can be drawn from the clear-cutting literature seem unlikely to be applicable to the more modest mechanical treatments involved in such restorative efforts.

To date, more than 30 published papers have described the effects on soil biological, chemical, and

Manuscript received 23 October 2007; revised 18 July 2008; accepted 24 July 2008. Corresponding Editor: D. McKenzie. For reprints of this Invited feature, see footnote 1, p. 283.
[3] E-mail: boerner.1@osu.edu
[4] Present address: School of Natural Sciences and Sierra Nevada Research Institute, University of California, Merced, California 95344 USA.

physical properties of the prescribed fire, mechanical treatments, and combined mechanical + fire treatments in one or more of the 12 individual sites of the Fire and Fire Surrogate Network (Appendix A). The Fire and Fire Surrogate Network project also presents a unique opportunity to examine commonalities and differences in the effects of fire and mechanical treatments on forests that differ in vegetation, soil characteristics, and macroclimate on a continental scale. Using the common experimental design and suite of response variables of the Fire and Fire Surrogate Network project, we sought to test the following hypotheses:

1) Both fire and mechanical treatment will increase the exposure of mineral soil, thus increasing the potential for erosion; in contrast, mechanical treatment but not fire will result in increased mean and/or variance in bulk density.

2) Both fire and mechanical treatment will result in increased soil pH and base cation (e.g., K^+ and Ca^{2+}) availability, but this effect will be delayed in the mechanical treatment until residues from that treatment decompose.

3) Both fire and mechanical treatment will increase N availability, at least in the short term. Increased N availability will persist longer after mechanical treatment than after fire.

4) Fire will result in no change or a small increase in mineral soil organic matter content and an increase in soil organic matter quality (measured as a decrease in the carbon-to-nitrogen mass ratio); in contrast, mechanical treatment will result in increased mineral soil organic matter quantity and reduced quality.

Methods

Study sites and methods

The 12 sites of the Fire and Fire Surrogate Network were underlain by a range of soil types, of which Alfisols, Ultisols, and Inceptisols were the most prevalent (Table 1). Mollisols were present in one site and Entisols in two. Soil textures were dominated by loams and silt loams, though sands and fine sands were present in one site (Table 1).

The designated FFS experimental design was a randomized complete block, with three blocks and four treatments (control, prescribed fire, mechanical treatment, and the combination of mechanical treatment and prescribed fire) allocated at random to those three blocks. Due to logistic constraints, three of the 12 FFS sites were established as completely randomized designs (CA-N, CA-S, WA; site codes are given in Table 1), with the four treatments allocated at random among the 12 treatment units. One site (OR) established four replicates of each treatment in a completely randomized design.

Each treatment unit consisted of a minimum of 10 ha with a buffer zone of at least 4 ha surrounding it. Both the treatment unit and the buffer received the experimental treatment designated for that unit. Among the 12 FFS sites, the treatment units ranged in size from those approximating the minimum 14 ha to as large as 80 ha.

Each treatment unit was overlain with a 50- or 100-m grid and a minimum of 36 grid points geo-located within each treatment unit. In 10 of the 12 sites, 10 0.1-ha rectangular permanent sampling plots were located at random within each treatment unit, whereas in the other two sites (CA-C, OR) a larger number of circular plots of 0.04 ha were established. In all sites the permanent sampling plots were anchored with one corner at a grid point.

To maximize the usefulness of the results for future fuels management decisions, prescribed fire and mechanical treatments were applied using prescriptions consistent with established management practices at each site (details are given in McIver 2001). To illustrate the range of treatment intensities among the network sites, the proportional change in tree biomass and the surface and ground fuels (forest floor + downed woody debris) from the pretreatment to initial posttreatment year are given in Table 2 (data from Boerner et al. 2008*b*).

Soils were typically sampled either near the corners of the permanent sampling plots or in a subplot established within the permanent sampling plot. Soils were sampled during the pretreatment year in all sites, although not all sites took a complete set of pretreatment samples. All sites sampled soils during the first posttreatment growing season and eight of the 12 sampled again during a subsequent growing season (usually the second, but the third or fourth in one to two sites each).

The organic (O) horizon, if present, was removed prior to sampling the mineral soil. If no distinct boundary occurred between the Oa subordinate organic horizon (i.e., humic subhorizon) and the A master horizon, the Oa was included in the sampling of the surface mineral soil. In sites where a distinct horizon boundary between the A and E occurred, samples were taken either for the full depth of the A horizon or to 15 cm, whichever was less. Organic horizons (i.e., forest floors) were sampled by clearing the forest floor around an area of 0.25 m^2 and removing separately each discernable organic subordinate horizon (i.e., Oi, Oe, and Oa) in that exposed 0.25-m^2 area.

The area of each treatment unit in which bare mineral soil was exposed was estimated at a minimum of 200 and maximum of 2000 points per treatment unit. Bulk density was determined gravimetrically on a minimum of 20 samples per treatment unit in nine sites, and in three sites estimated from a minimum of 200 soil strength (penetrometer) measurements per treatment unit using regressions of bulk density on soil strength derived from sites that measured both.

We attempted to standardize laboratory methods across the 12 network sites, and were, for the most part, successful. The standard methods used in all network sites were extraction of K^+ and Ca^{2+} with 1 mol/L

TABLE 1. Geographic and edaphic information for the 12 Fire and Fire Surrogate Network project study sites.

Geographic location	Site name	Code	Soil order
Southern Cascades Range, CA	Goosenest Adaptive Management Area (Klamath National Forest)	CA-N	Alfisols, Entisols
Central Sierra Nevada, CA	Blodgett Experimental Forest	CA-C	Alfisols
Northeastern Cascades Range, WA	Mission Creek (Wenatchee National Forest)	WA	Alfisols, Mollisols
Southern Sierra Nevada, CA	Sequoia-Kings Canyon National Park	CA-S	Inceptisols
Blue Mountains, OR	Hungry Bob (Wallowa-Whitman National Forest)	OR	Mollisols, Inceptisols
Northern Rocky Mountains, MT	Lubrecht Experimental Forest	MT	Alfisols, Inceptisols
Southwestern Plateau, AZ	Coconino and Kaibab National Forests	AZ	Alfisols, Mollisols
Gulf Coastal Plain, AL	Solon-Dixon Forestry and Education Center	AL	Ultisols, Entisols
Central Appalachian Plateau, OH	Tar Hollow and Zaleski State Forests, Vinton Furnace Experimental Forest	OH	Alfisols, Inceptisols
Southeastern Piedmont, SC	Clemson Forest	SC	Ultisols, Inceptisols
Southern Appalachian Mountains, NC	Green River Gamelands	NC	Ultisols, Inceptisols
Florida Coastal Plain, FL	Myakka River State Park	FL	Alfisols, Spodosols

Notes: Sites are ordered by longitude from west to east. Abbreviations are: CA, California; WA, Washington; OR, Oregon; MT, Montana; AZ, Arizona; AL, Alabama; OH, Ohio; SC, South Carolina; NC, North Carolina; FL, Florida.

NH_4OAC (Thomas 1982), extraction of P with 0.01 mol/L $CaCl_2$ (Olsen and Sommers 1982), extraction of NH_4^+, NO_3^-, and Al^{3+} with 1 mol/L KCl or 0.5 mol/L K_2SO_4 (Keeney and Nelson 1982), quantification of cations by atomic absorption spectrophotometry or inductively coupled plasma photometry, quantification of soil organic carbon (C) and total N by microDumas oxidation, and quantification of inorganic N forms and P by colorimetric methods or autoanalyzer protocols. Soil pH was determined in 0.01 mol/L $CaCl_2$.

Data analysis

Although analysis of the effects of the fire and fire surrogate treatments on soil properties within a site could be analyzed in a straightforward manner using analysis of variance approaches, we felt this was not the most appropriate manner in which to analyze the results at the network scale. First, the specifics of the experimental design varied in subtle though important ways among the 12 sites. For example, some sites had sufficient pretreatment measurements to use pretreatment conditions as covariates whereas others did not. Similarly, some sites established their treatment units in a spatial manner that would permit analysis as a split-plot or complete block design whereas others did not. In light of such differences, we judged that resorting to a least-common-denominator analysis of variance model would serve little purpose. Second, the variations among network sites in initial soil properties were so great and the absolute magnitude of the effects of the fire and fire surrogate treatment were so modest as to make any single analysis of variance-based approach unproductive.

Instead, we took a meta-analytical approach, as this would allow us to treat each network site as a single experiment with $n = 3$ units for each treatment at each site (except OR in which $n = 4$). As the 12 sites had a mix of completely randomized (CRD) designs and randomized complete block (RCB) designs, we investigated whether we could treat each study site as a completely randomized design. We did this by assessing the magnitude and significance of the block variance

TABLE 2. Mean net change in aboveground biomass carbon and surface fuel carbon (forest floor + downed woody debris) as the result of treatment with prescribed fire, mechanical treatment, or their combination in 12 Fire and Fire Surrogate Network sites.

		Aboveground biomass C (%)			Surface fuel C (%)		
Site	Site code	Fire	Mechanical	Mechanical + fire	Fire	Mechanical	Mechanical + fire
Southern Cascades	CA-N	−13.5	−29.4	−22.9	−74.4	NA	NA
Central Sierra Nevada	CA-C	−15.5	−13.7	−29.9	−66.9	−22.5	−72.6
Northeastern Cascades	WA	7.8	−33.8	−35.4	14.0	51.2	14.6
Southern Sierra Nevada	CA-S	−4.4	NA	NA	−73.7	NA	NA
Blue Mountains	OR	2.5	−28.3	−58.4	−73.5	−36.2	−62.9
Northern Rocky Mountains	MT	−6.5	−44.6	−57.0	−42.0	28.2	−24.9
Southwestern Plateau	AZ	0.3	−46.4	−45.7	−10.2	108.9	−24.5
Gulf Coastal Plain	AL	−2.5	−24.3	−23.7	−17.3	−6.3	−34.7
Central Appalachian Plateau	OH	−0.7	−27.6	−22.5	−2.2	60.6	29.5
Southeastern Piedmont	SC	−9.9	−26.8	−42.0	−44.6	21.3	−16.0
Southern Appalachians	NC	−9.0	−4.4	−15.3	−35.4	15.4	−30.5
Florida Coastal Plain	FL	−17.1	−21.9	−5.3	−33.8	−22.2	293.8
FFS network mean	FFS	−5.7	−27.4	−32.6	−38.3	19.8	7.2

Notes: Data are from Boerner et al. (2008). “NA” indicates that the treatment could not be implemented at this site.

TABLE 1. Extended.

Predominant soil series	Soil textural classes
Belzar, Wintoner	loam, silt loam
Holland, Musick	loamy sand, sandy loam
Stemilt, Varelum, Cle Elum	loam, silt loam
unknown	not determined
Fivebit, Melhorn, Blocker	clay loam, loam, silt loam
Winkler, Greenough, Tevis-Mitten	silt loam, loam, sandy loam
unknown	silty clay loam, clay loam, silty clay, clay
Dothan, Bonifay	sandy loam, loamy sand
Steinsburg, Gilpin, Shelocta	silt loam, loam, sandy loam
Cecil, Madison, Pacolet	sandy loam, clay loam
Evard, Cowee, Cliffield	loam, silt loam
EauGallie, Myakka	fine sand, sand

separately for each site that used a block design using a subset of the response variables (mineral soil exposure, soil pH, soil organic C, extractable Ca^{2+}). The block effect was only significant in one site (SC), and the significances of the treatment effects in that site were not substantially different when analyzed as a RCB or a CRD. Thus, we treated all 12 of the sites as CRD for the purposes of the meta-analysis.

For each study site, the effect size (ES) was estimated as

$$\mathrm{ES} = \frac{\bar{X}_\mathrm{t} - \bar{X}_\mathrm{c}}{S_\mathrm{p}} \tag{1}$$

where $\bar{X}_\mathrm{t}$ and $\bar{X}_\mathrm{c}$ were the means of treated and control groups at a site and S_p was the pooled standard deviations for the two groups. The pooled standard deviation S_p was calculated as

$$S_\mathrm{p} = \sqrt{\frac{s_\mathrm{c}^2(n_\mathrm{c}-1) + s_\mathrm{t}^2(n_\mathrm{t}-1)}{n_\mathrm{t}+n_\mathrm{c}-2}} \tag{2}$$

where n_t and n_c were the sample sizes for the treatment (prescribed burn, mechanical, or mechanical + burn) and control groups, and s_t and s_c were the standard deviations for the treatment and control groups. However, as the effect size calculated in this manner is biased by the small number of replicates, we adjusted the effect size for the sample size of $n = 3$ per treatment per site ($n = 4$ for OR) using Hedges' d:

$$d_i = \left[1 - \frac{3}{4(n_\mathrm{t}+n_\mathrm{c})-9}\right]\mathrm{ES} \tag{3}$$

where d_i was the adjusted effect size for each individual study and ES was the unadjusted effect size. The variance of Hedges' d was estimated as

$$V_i = \frac{n_\mathrm{c}+n_\mathrm{t}}{n_\mathrm{c}n_\mathrm{t}} + \frac{d_i}{2(n_\mathrm{c}+n_\mathrm{t})} \tag{4}$$

and the corresponding 95% confidence interval (CI) of effect size for an individual study was

$$\left[d_i - 1.96^{\sqrt{V_i}},\ d_i + 1.96^{\sqrt{V_i}}\right]. \tag{5}$$

To calculate the cumulative effect size at the FFS network scale, we used a random effects model because we assumed that variability among effect sizes was due to both subject-level "noise" and true unmeasured differences across studies (Raudenbush 1994, Rosenberg et al. 2000). The cumulative effect size at the network scale was estimated as

$$\overline{\mathrm{ES}} = \frac{\sum (W_{i(\mathrm{rand})} \times d_i)}{\sum W_{i(\mathrm{rand})}} \tag{6}$$

where $\overline{\mathrm{ES}}$ was the cumulative effect size, $W_{i(\mathrm{rand})}$ was the adjusted weight using the random-effects model. $W_{i(\mathrm{rand})}$ was calculated as

$$W_{i(\mathrm{rand})} = \frac{1}{V_i + \sigma^2_\mathrm{pool}}. \tag{7}$$

This, in turn, required estimation of both the pooled study variance, σ^2_pool and the total heterogeneity of a given sample, Q_T, with the latter being used to test the hypothesis that all effect sizes were equal using the χ^2 distribution with $k - 1$ degrees of freedom (Gurevitch and Hedges 1993):

$$\sigma^2_\mathrm{pool} = \frac{Q_T - (k-1)}{\sum W_i - \left(\frac{\sum W_i^2}{\sum W_i}\right)} \tag{8}$$

$$Q_\mathrm{T} = \sum (W_i \times d_i^2) - \frac{\left[\sum (W_i \times d_i)\right]^2}{\sum W_i} \tag{9}$$

where W_i was the weight of ith study site, which is the inverse of V_i; and k was the number of the studies. When $\sigma^2_\mathrm{pool} \leq 0$, the effect sizes were calculated using a fixed-effects model, where $W_{i(\mathrm{rand})}$ in Eq. 6 was replaced by W_i.

The variance of the cumulative effect size was estimated as

$$S^2_{\overline{\mathrm{ES}}} = \frac{1}{\sum W_{i(\mathrm{rand})}}. \tag{10}$$

The 95% confidence interval of the cumulative effect size was constructed using the t distribution:

$$[\overline{\mathrm{ES}} - t_{0.025,(k-1)} \times S_{\overline{\mathrm{ES}}},\ \overline{\mathrm{ES}} + t_{0.025,(k-1)} \times S_{\overline{\mathrm{ES}}}].$$

All meta-analyses were conducted using MetaWin 2.0 (Rosenberg et al. 2000).

Nonmetric multidimensional scaling (NMS) ordination using PC-ORD Version 4 was used to visualize the multivariate effects of the FFS treatments at the network and site levels. In order to minimize the influence of pretreatment variations in soil properties

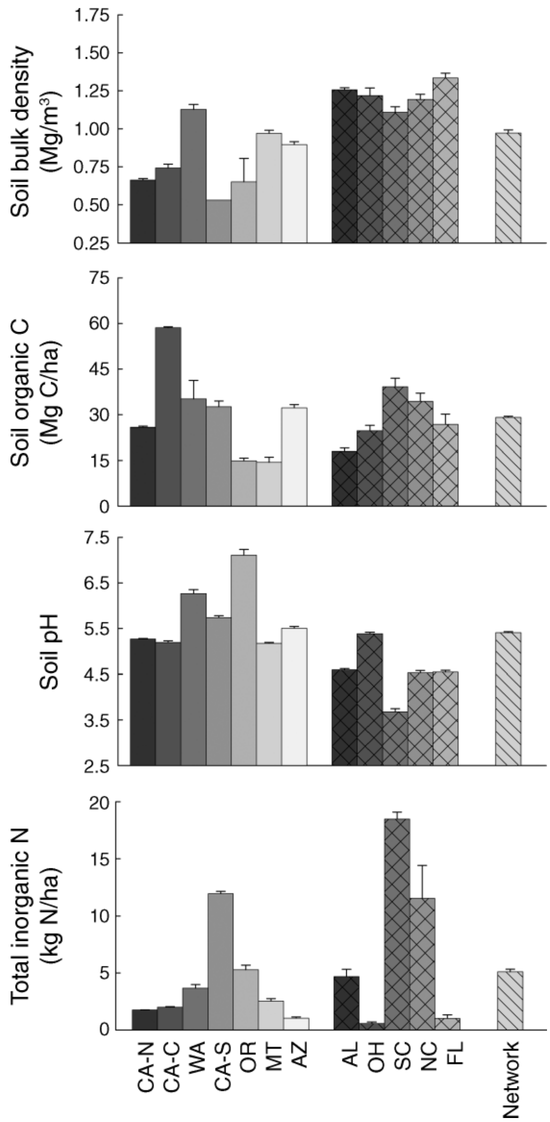

FIG. 1. Variations in soil properties among Fire and Fire Surrogate Network sites. Sites are arrayed from west to east with a gap between the western and eastern sites. Means and standard errors based on the three or four control units are shown. Site codes follow Table 1.

among sites, the standardized effect sizes from the meta-analysis were used as inputs to the ordination.

RESULTS

Variations in initial soil properties

Mean soil bulk density varied among sites from 0.53 Mg/m^3 at CA-S and 0.65 Mg/m^3 at OR to 1.26 Mg/m^3 at AL and 1.34 Mg/m^3 at FL (site codes follow Table 1), with the sites in the eastern half of North America having generally greater soil bulk density than those in the western half (Fig. 1; Appendix B [note: full tabular presentation of pretreatment (Appendix B) and post-treatment means and standard errors by site and treatment (Appendices C and D) is available through *Ecological Archives*]). In the absence of any manipulative treatment, the proportion of the mineral soil that was exposed at the surface ranged from <0.1 % in several sites to 3.7% at CA-C (Appendix B).

Mean soil pH varied from 3.68 at OH to 7.11 at OR, and the western sites typically had somewhat higher soil pH than the eastern sites (Fig. 1, Appendix B). Extractable K^+ and Ca^{2+} did not, however, follow this geographical trend. Although availability of these two cations varied by 200 to1000 fold among sites, there was no apparent longitudinal trend, as soil parent materials were likely more important than macroclimate in cation content (Appendix B). Total inorganic N (TIN) extracted from soil ranged from means of 12–18 kg N/ha at the OH and NC sites to 1–2 kg N/ha at the CA-N, AZ, and FL sites (Fig. 1). The two hardwood forest

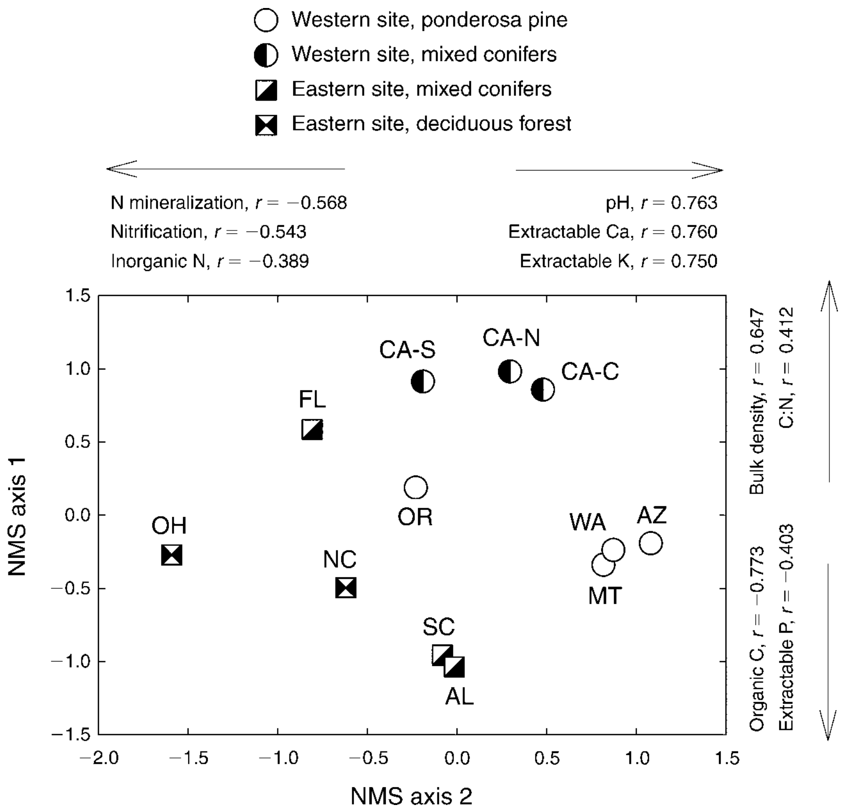

FIG. 2. Nonmetric multidimensional (NMS) ordination of pretreatment soil conditions among the Fire and Fire Surrogate Network sites. Coefficients of variation for each of the axes and Pearson product-moment correlations between axes and individual soil properties significant at $P < 0.05$ are shown. Symbols represent major vegetation types: open circles represent ponderosa pine-dominated forests, half-filled circles represent western mixed-conifer forests, half-filled squares indicate southern pine forests, and hourglass-filled squares indicate eastern deciduous forests. Site codes follow Table 1. For NMS axis 1, $r^2 = 0.182$; for NMS axis 2, $r^2 = 0.527$.

sites (OH, NC) and the CA-S mixed conifer site had the greatest TIN content among the 12 FFS sites.

Soil organic C content varied by approximately fourfold among sites (Fig. 1, Appendix B), but when CA-C was eliminated from the comparison, the variation is less than threefold across the remaining sites. The soil organic carbon-to-nitrogen mass ratio (C:N ratio) was in the range of 20–26 for most of the sites; CA-S and OR were notable exceptions, with soil C:N ratios of 37–39 (Appendix B).

Nonmetric multidimensional (NMS) ordination of the 12 sites based on 12 initial soil properties arrayed the sites along two axes that accounted for approximately 71% of the variance (Fig. 2). The WA, AZ, and MT sites were located at the upper end of axis 2 (which accounted for approximately 53% of the variance), with the OH site at the lower end. This axis was positively correlated with soil pH and extractable base cation content, and negatively correlated with net N mineralization rate, net nitrification rate, and the TIN pool size (Fig. 2). The three CA sites (i.e., CA-C, CA-N, and CA-S) and the FL site were located at the upper end of axis 1 (which accounted for approximately 18 % of the variance), with the SC and AL sites at the lower end of that axis. Axis 1 was positively correlated with bulk density and C:N ratio, and negatively correlated with soil organic C content and extractable P (Fig. 2).

When general vegetation types were overlain on the ordination pattern, the ponderosa pine-dominated sites (except for the OR site) and the western mixed conifer sites each formed a relatively tight cluster, and the two hardwood forest sites were located together at the lower end of axis 2. In contrast, two of the southern pine sites were clustered together while the third was spatially arrayed with the western mixed-conifer sites (Fig. 2).

FFS treatment effects on soil properties

At the network scale, fire increased mineral soil exposure both in the first growing season following treatment and in the later sampling year (i.e., two or three years posttreatment), and the same was the case for the combined mechanical + fire treatment during the first posttreatment year (Fig. 3). In contrast, mechanical treatment alone did not significantly affect mineral soil exposure during either sampling year (Fig. 3). At the individual site level, fire alone increased mineral soil exposure at CA-S and CA-C sites during the first posttreatment sampling year and at the OH and CA-S

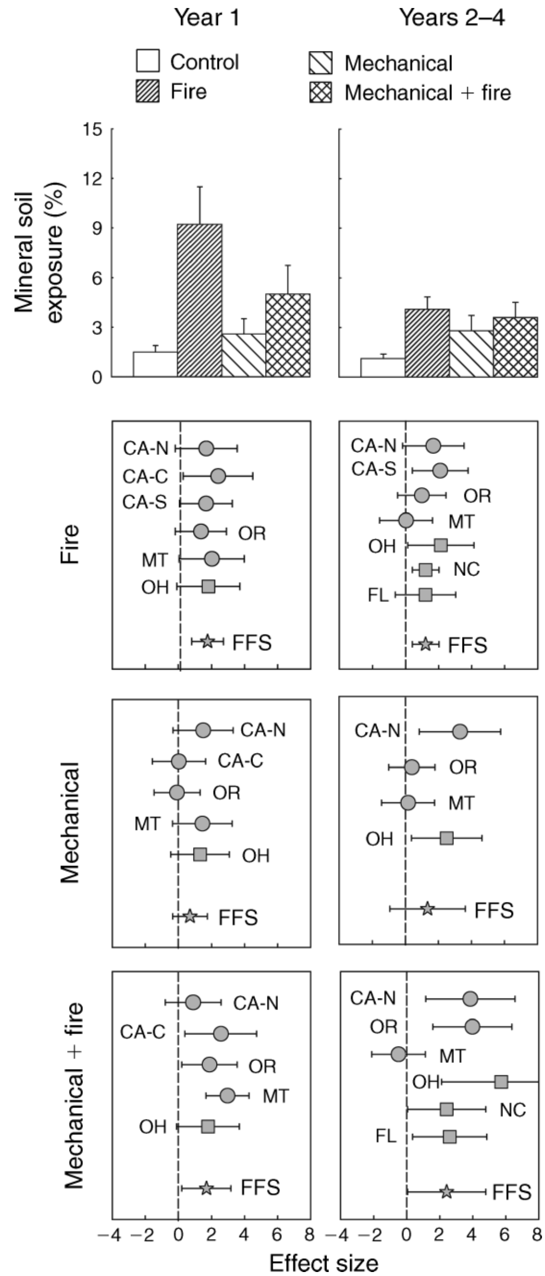

FIG. 3. Meta-analysis of the effects of Fire and Fire Surrogate treatments on mineral soil exposure. Mean effect sizes and corresponding 95% confidence intervals are shown; site codes follow Table 1. The two histograms show network means (with standard errors) for the four treatments during each sampling year.

sites during the later sampling year (Fig. 3). Mechanical treatment alone resulted in increased mineral soil exposure only at the CA-N and OH sites during the later sampling year. The combination of fire and mechanical treatment had a significant, immediate effect on mineral soil exposure at the CA-C and OR sites and a significant, delayed effect in CA-N, OR, OH, and FL (Fig. 3).

The effects of the FFS treatments on soil bulk density were fewer (Fig. 4). There were no significant network-wide effects of any of the three treatments on soil bulk density in either sampling year, and site-level effects were limited to a significant first year decreases in bulk density in CA-N following the fire and mechanical + fire treatments and significant first year increases following fire in OR and following both the mechanical and mechanical + fire treatments in AL (Fig. 4).

At the network scale, soil pH was significantly higher in soils of the mechanical + fire treatment than in control soils during the first year post treatment but not during

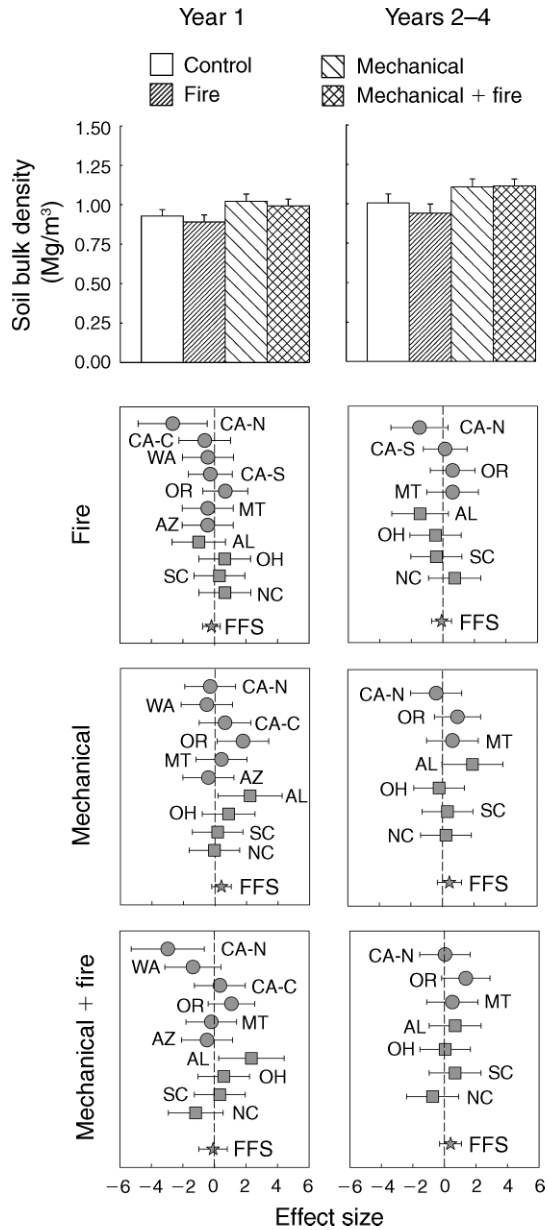

FIG. 4. Meta-analysis of the effects of Fire and Fire Surrogate treatments on soil bulk density. Mean effect sizes and corresponding 95% confidence intervals are shown; site codes follow Table 1. The two histograms show network means (with standard errors) for the four treatments during each sampling year.

the later year (Fig. 5). At the site scale, during the first posttreatment year fire alone significantly increased soil pH in CA-N and CA-C, and the combination of mechanical treatment and fire resulted in higher soil pH at CA-C only, but neither of these effects was present in the later sampling year (Fig. 5). Mechanical treatment alone did not have a significant effect on soil pH at any of the sites during the first-post treatment year, but did significantly increase soil pH in SC during the later sampling interval (Fig. 5).

There were no significant network-scale effects of the three manipulative treatments on either extractable Ca^{2+} (Fig. 6) or extractable K^{+} (Fig. 7) during either sampling period, but had the a priori α been 0.07 instead of 0.05, the first year effects of fire alone would have been judged to be significant (Figs. 5 and 6). Site-level effects of the FFS treatments on extractable Ca^{2+} and K^{+} were uncommon. Significant increases in extractable Ca^{2+} were present during the first year after mechanical treatment in OR and during the later sampling period following the combined mechanical + fire treatment in OR and OH (Fig. 6). The only significant effect on extractable K^{+} was a significant decrease in NC during the later sampling interval (Fig. 7).

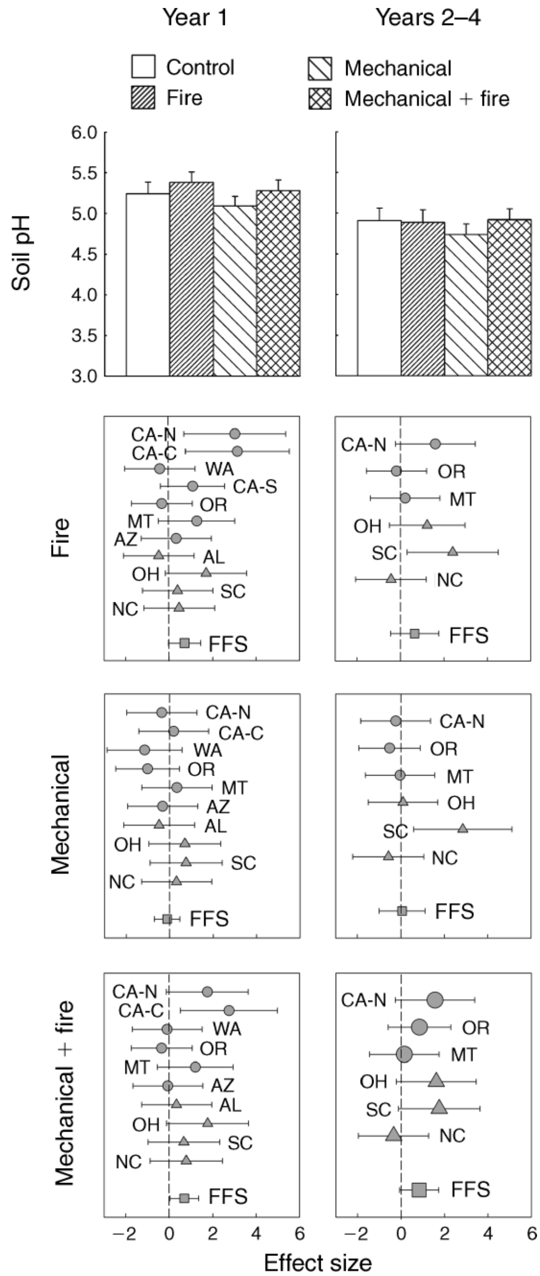

FIG. 5. Meta-analysis of the effects of Fire and Fire Surrogate treatments on soil pH. Mean effect sizes and corresponding 95% confidence intervals are shown; site codes follow Table 1. The two histograms show network means (with standard errors) for the four treatments during each sampling year. Site codes follow Table 1.

At the network scale, there were significant increases in TIN soil pool sizes during the first year after all three manipulative treatments, but not during the later sampling year (Fig. 8). At the individual site level, TIN increased significantly during the first year after treatment as a result of fire alone in CA-N, CA-C, and MT (and marginally [$P < 0.07$] in CA-S), as a result of mechanical treatment alone in CA-C and OR, and as a result of the mechanical + fire treatment in CA-N, CA-C, and MT (and marginally in OR; Fig. 8). There were no significant effects of the three manipulative treatments on TIN at any individual site sampled during the later sampling year (Fig. 8). There were no significant effects of the FFS treatments on plant available P during either year at the network or individual site scale (Fig. 9).

Network-scale soil organic C content was not significantly affected by any of the treatments during the first posttreatment year, and only marginally reduced by fire alone during the later sampling year

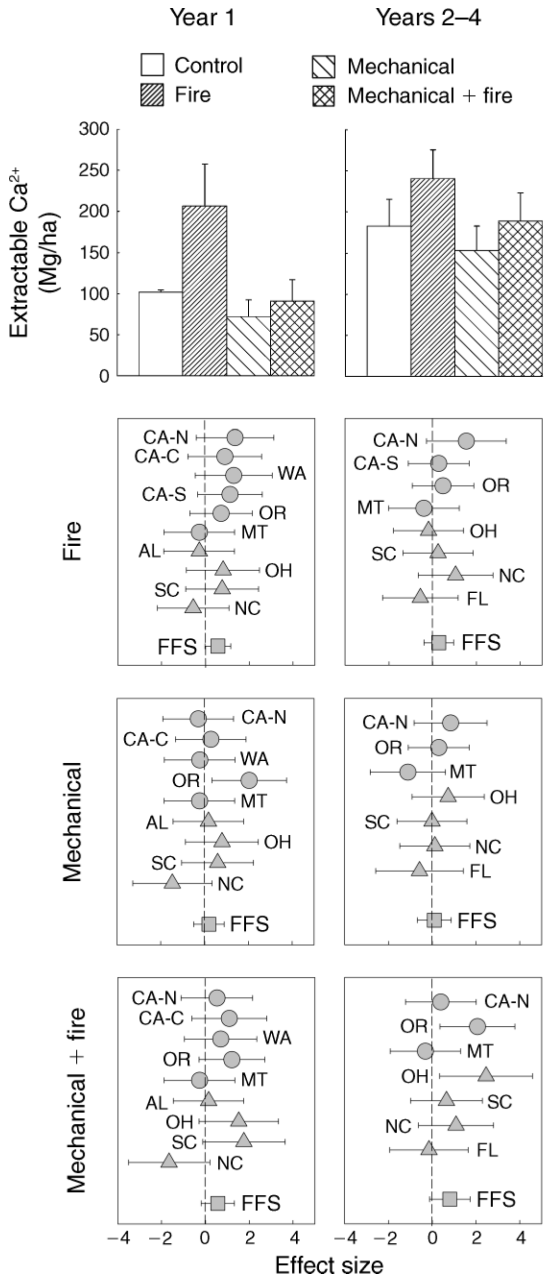

FIG. 6. Meta-analysis of the effects of Fire and Fire Surrogate treatments on extractable Ca^{2+}. Mean effect sizes and corresponding 95% confidence intervals are shown; site codes follow Table 1. The two histograms show network means (with standard errors) for the four treatments during each sampling year.

(Fig. 10). At CA-S soil organic C was reduced marginally ($P < 0.06$) by fire alone during the first posttreatment year, and this effect was significant at $P < 0.05$ during the later sampling year (Fig. 10). Neither network-scale nor individual site total soil N was affected significantly by any of the three manipulative treatments in either sampling year (Fig. 11). Given the modest effects of the FFS treatments on soil organic C and total soil N, significant effects on soil C:N ratio were limited to a reduction following mechanical + fire treatment in SC (Fig. 12).

NMS ordination of FFS treatment effects

Nonparametric multidimensional scaling ordination of the FFS first posttreatment year effect sizes (not the posttreatment parameter means) arrayed most of the site–treatment combinations in a loose grouping at the upper end of NMS axis 2, with five site–treatment

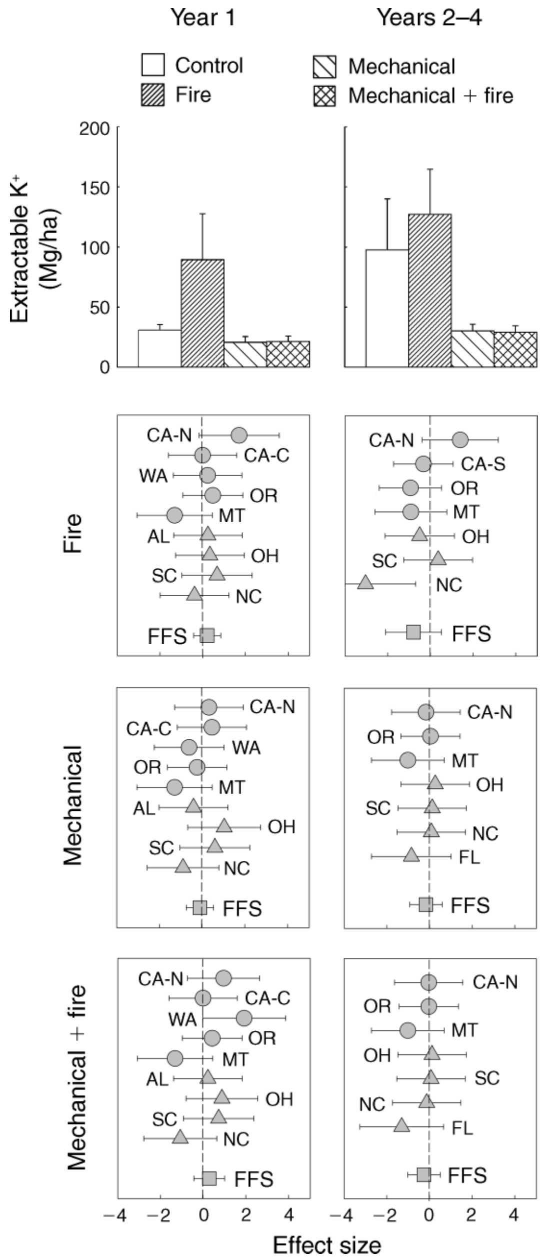

FIG. 7. Meta-analysis of the effects of Fire and Fire Surrogate treatments on extractable K^+. Mean effect sizes and corresponding 95% confidence intervals are shown; site codes follow Table 1. The two histograms show network means (with standard errors) for the four treatments during each sampling year.

combinations separated from the main group and arrayed along the lower half that axis (Fig. 13). These five site-treatment combinations corresponded to the fire-only treatments at CA-C, CA-N, and MT and the mechanical + fire treatments at CA-C and CA-N (Fig. 13).

NMS axis 2 accounted for approximately 87% of the variance in the effect size matrix and was significantly, positively correlated with the magnitude of the effects on soil organic C concentration, soil C:N ratio, and soil bulk density (Fig. 13). This axis was also negatively correlated with the magnitude of the effect of the treatments on soil pH and TIN. Thus, the five site–treatment combinations located at the lower end of Axis 2 were those site-treatment combinations with the strongest positive effects on pH and TIN pool sizes and the largest negative effects on soil organic C content, bulk density, and C:N ratio.

NMS axis 1 accounted for only approximately 15% of the variance in the effect size matrix, and was

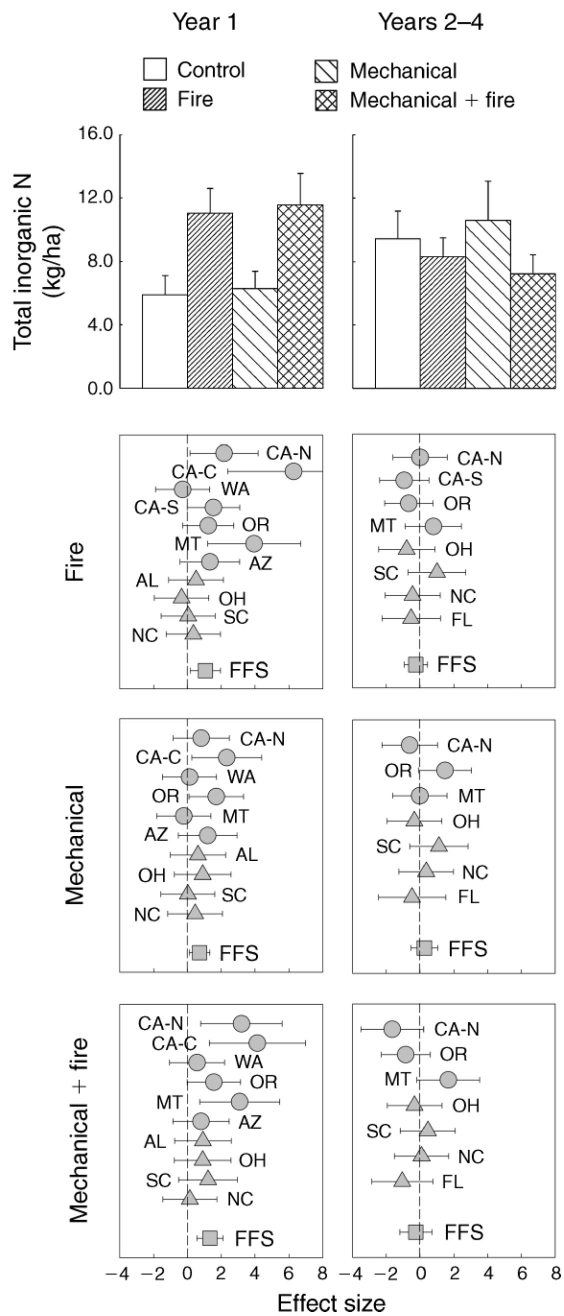

FIG. 8. Meta-analysis of the effects of Fire and Fire Surrogate treatments on total inorganic N. Mean effect sizes and corresponding 95% confidence intervals are shown; site codes follow Table 1. The two histograms show network means (with standard errors) for the four treatments during each sampling year.

significantly and negatively correlated with the magnitude of the effects of the treatments on extractable Ca^{2+} and K^+. There was no clear separation of treatments or site groupings along axis 1.

We were not able to separate the three manipulative treatments in this ordination, as the spread of site–treatment combinations was dominated by the five points that separated from the larger cluster of points. This suggested that the treatments in CA-N, CA-C, and MT that included fire had effects that were quantitatively distinct from the remaining site–treatment combinations.

The NMS ordination of the later posttreatment sampling year effect sizes arrayed the site–treatment combinations along two axes that accounted for approximately 75% of the variance in the effect size

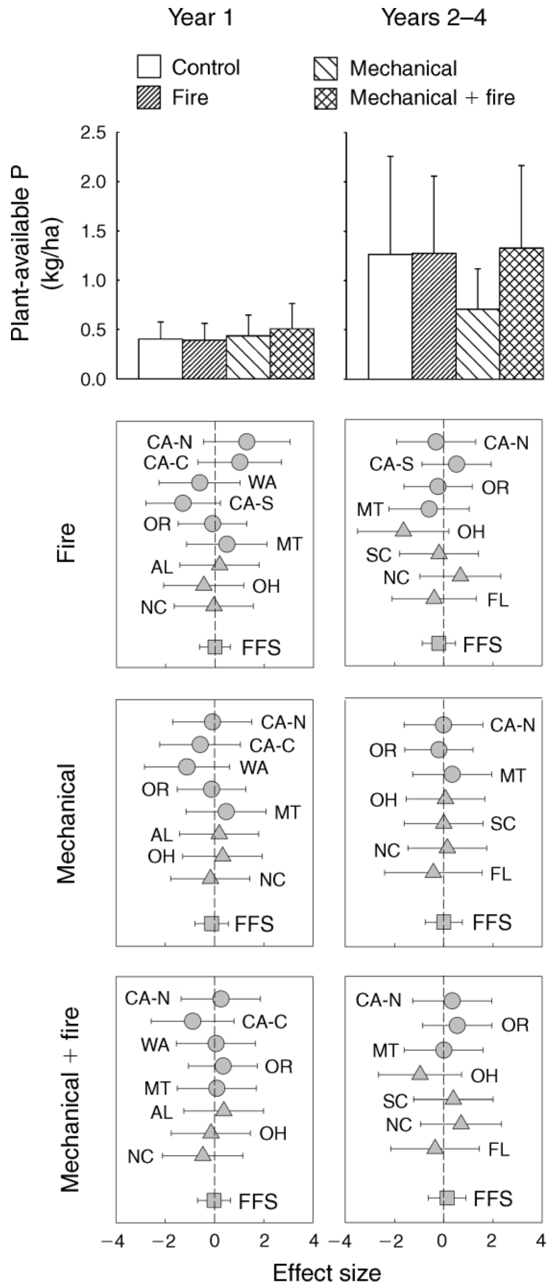

FIG. 9. Meta-analysis of the effects of Fire and Fire Surrogate treatments on plant-available P. Mean effect sizes and corresponding 95% confidence intervals are shown; site codes follow Table 1. The two histograms show network means (with standard errors) for the four treatments during each sampling year.

matrix (Fig. 14). NMS axis 1 was positively correlated with the magnitude of the effect on TIN and soil C:N ratio, and negatively correlated with the magnitude of the effect on mineral soil exposure and extractable Ca^{2+} (Fig. 14). Thus, the three site–treatment combinations located at the lower end of axis 1 (mechanical + fire in OH, OR, CA-N) were the ones in which the largest effect on mineral soil exposure and extractable Ca^{2+} pools but the smallest effects on TIN and soil C:N ratio were present.

NMS axis 2 was positively correlated with the effect on soil pH and extractable K^{+}, and negatively correlated with the magnitude of the effect on soil organic C concentration (Fig. 14). The site–treatment combinations at the extremes of axis 2 were the fire-only treatment in NC at the lower end, and the mechanical-only treatment in SC at the upper end (Fig. 14).

The point corresponding to the overall network mean for the mechanical + fire treatment was arrayed lower on NMS Axis 1 than were those of the other two

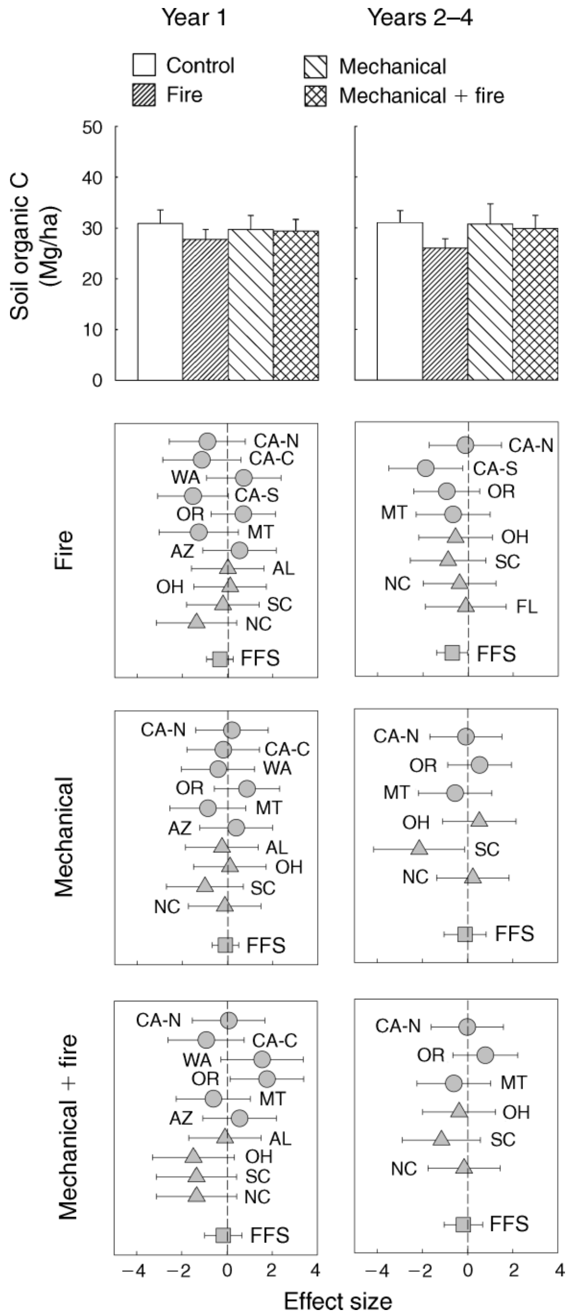

FIG. 10. Meta-analysis of the effects of Fire and Fire Surrogate treatments on soil organic C content. Mean effect sizes and corresponding 95% confidence intervals are shown; site codes follow Table 1. The two histograms show network means (with standard errors) for the four treatments during each sampling year.

treatments, and five of the points arrayed lowest on NMS Axis 1 corresponded to mechanical + fire treatments. This suggested that the combined treatment had somewhat greater effects on soil TIN and extractable Ca^{2+} pool sizes, soil C:N ratio, and mineral soil exposure than did the mechanical-only and fire-only treatments. The points corresponding to the fire-only and mechanical-only treatments were interspersed along the middle and upper portions of NMS axis 1, and their respective network means were almost indistinguishable in ordination space (Fig. 14).

The fire-only treatment points were arrayed along the full range of axis 2, whereas those corresponding to the mechanical-only and mechanical + fire treatments were clumped in the middle of axis 2 (Fig. 14). Thus, the variability in the effect of fire alone on soil pH,

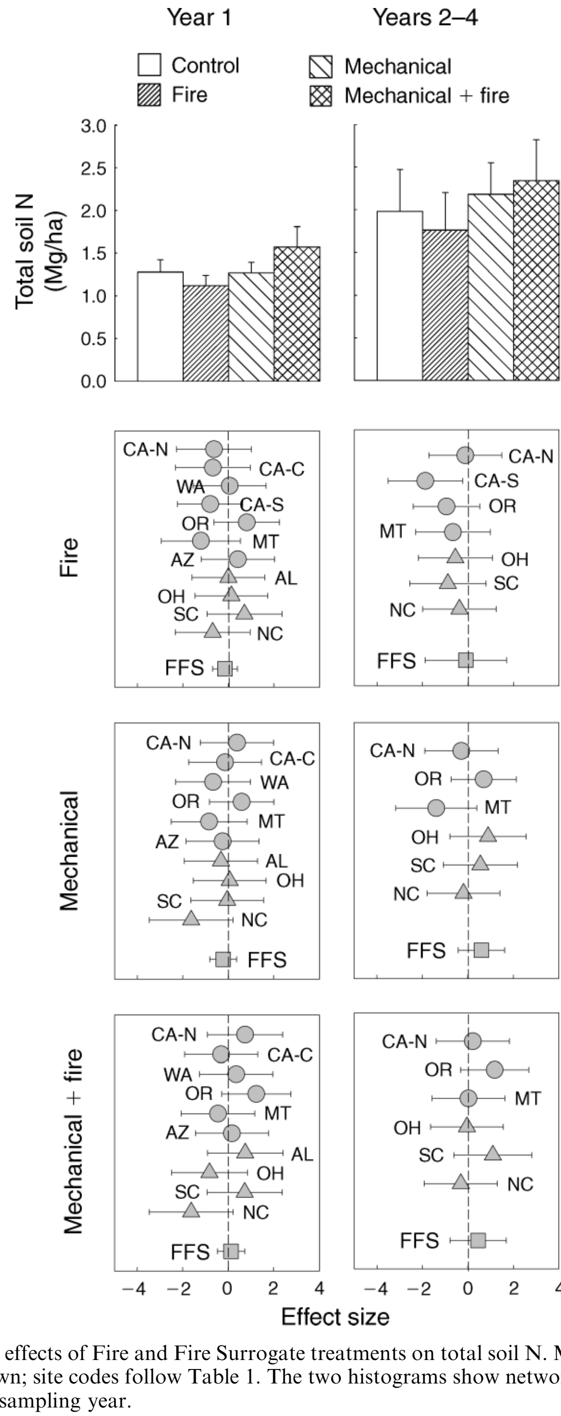

FIG. 11. Meta-analysis of the effects of Fire and Fire Surrogate treatments on total soil N. Mean effect sizes and corresponding 95% confidence intervals are shown; site codes follow Table 1. The two histograms show network means (with standard errors) for the four treatments during each sampling year.

extractable K^+, and soil organic C content was considerably greater than what resulted from mechanical treatment alone or the combination of mechanical treatment and fire.

DISCUSSION

Wildfires on steep terrain can result in considerable erosion due to dry ravel, overland flow, and slope failure, and these impacts can be exacerbated by logging (Ice et al. 2004). All of these erosional processes are affected by the local landforms and by the proportion of the mineral soil surface exposed by fire (or mechanical treatment). In contrast, low-severity fires that do not consume the entire forest floor or fires that impact only part of a watershed may not produce hydrological changes that can be resolved by typical monitoring

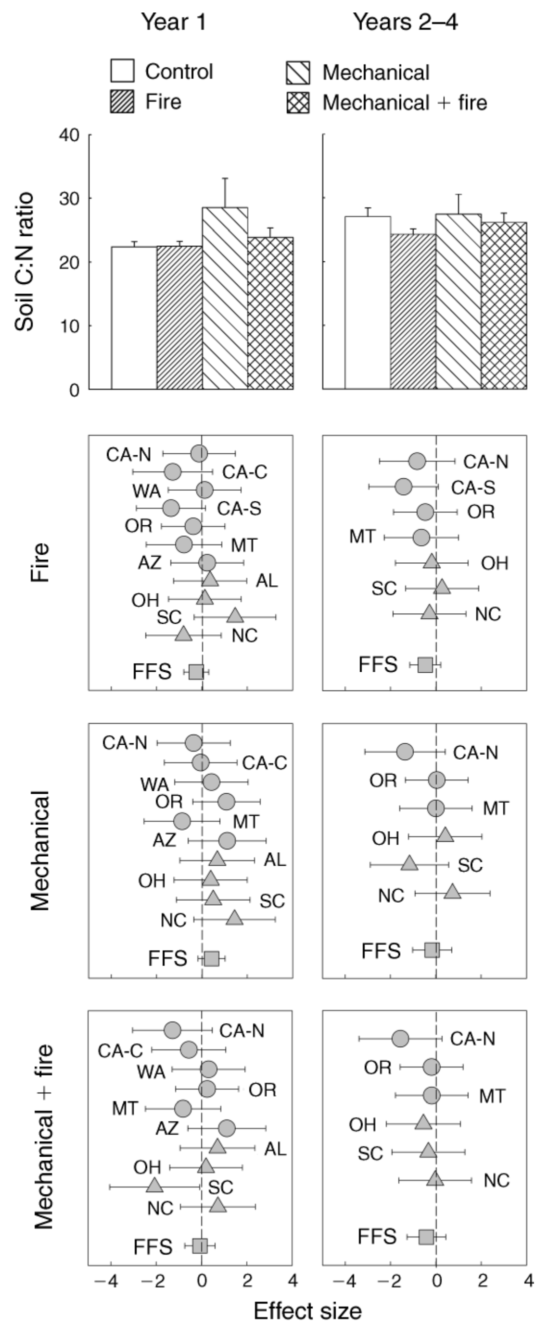

FIG. 12. Meta-analysis of the effects of Fire and Fire Surrogate treatments on soil C:N ratio. Mean effect sizes and corresponding 95% confidence intervals are shown; site codes follow Table 1. The two histograms show network means (with standard errors) for the four treatments during each sampling year.

methods (Bethlalmy 1974). Prescribed fires typically have lower severity than wildfires on similar sites because the timing of prescribed fire can be manipulated such that fires occur when fuels and soil moisture is greater (Walstad et al. 1990).

At the FFS network scale, both prescribed fire and the combination of fire and mechanical treatment increased mineral soil exposure as the result of forest floor combustion and, in the case of mechanical + fire treatment combination, as the result of vehicle operations. Mineral soil exposure tended to be greater in sites that lacked a well defined, continuous Oa horizon (e.g., OH) or where fire severity was greater than was typical across the network (e.g., CA-S). Yet, in only two of twenty-five site-by-fire or mechanical + fire treatment combinations did first year mineral soil exposure exceed

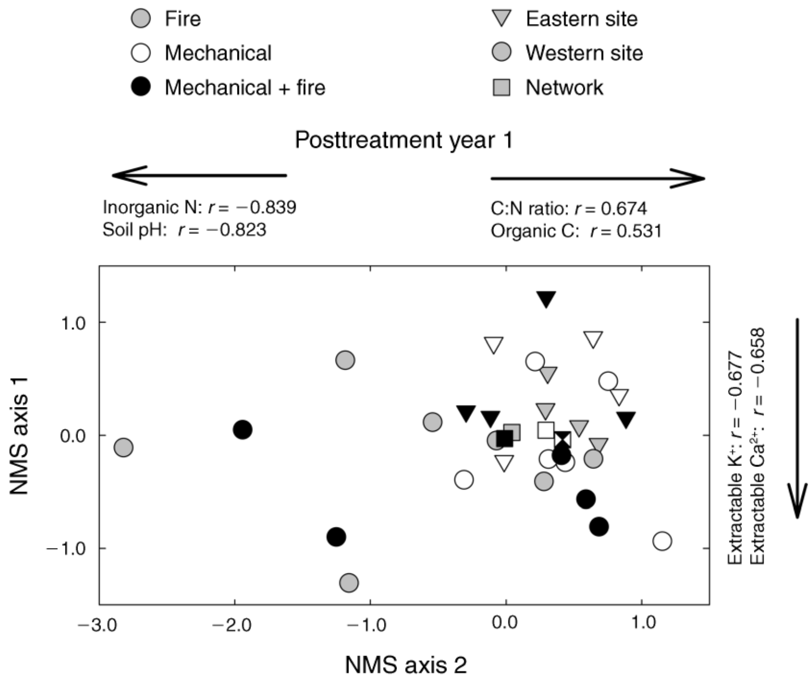

FIG. 13. Nonmetric multidimensional ordination of standardized, first-year effect sizes of three Fire and Fire Surrogate manipulative treatments on soil properties. Correlations significant at $P < 0.05$ between axis scores and soil parameters are shown. For MNS axis 1, $r^2 = 0.148$; for NMS axis 2, $r^2 = 0.869$.

15% of the ground area, and none exceeded 10% by the second or later posttreatment year.

Mechanical treatment alone had no significant effect at the network scale and few significant effects at individual study sites. The proportion of the soil exposed by mechanical treatment in these forests was somewhat lower than that reported after harvesting in other studies. For example, Rummer et al. (1997) reported that mineral soil exposure in upland hardwood forests in Alabama averaged as much as 25% of the ground area, depending on cutting intensity, and Klepac et al. (1999) observed soil exposure averaging 15% or more after mechanical treatment of conifer stands in Washington.

We observed no significant increase in soil bulk density as a result of fire, mechanical treatment, or the combination of these treatments. Although it has been demonstrated in western conifer forests that severe or repeated burning has the potential to increase soil bulk density, such effects are typically less evident after low severity fires (Moehring et al. 1966, Agee 1993), such as those typical of most of the prescribed fires in the FFS sites. Matson and Vitousek (1981) reported a similar lack of consistent change in bulk density as the result of clear-cutting of mixed-oak forests in Indiana. Other studies, however, have shown significant soil compaction (i.e., increase in soil bulk density and corresponding reduction in total porosity) following tree harvesting (e.g., Rummer et al. 1997, Berger et al. 2004).

One factor contributing to the apparent lack of such an effect in this study may have been the considerable variation among sites in the intensity and type of vehicle use. Many of the western FFS sites were vehicle intensive, in comparison both to common commercial harvest treatments and to the practices in some of the eastern sites. For example, CA-N used whole-tree harvesting that required intensive vehicle access, while MT used similar methods but left activity fuels on site. In contrast, CA-C used a self-propelled masticator that impacted a great amount of the soil surface whereas logs were removed by helicopter in WA, thereby minimizing wheeled vehicle impact. Among the eastern sites, mechanical treatments included understory mastication at FL, understory shrub removal with no vehicle traffic at NC, and heavy vehicle traffic at OH. Another contributing factor may have been the variation in sampling protocols among sites, with some sites assessing compaction randomly while others stratified their sampling into areas impacted by vehicle traffic and unimpacted areas (e.g., CA-C [Moghaddas and Stephens 2008]).

Other commonly reported effects of wildfire on soil physical properties include changes in permeability, water infiltration rate, and development of water-repellant (hydrophobic) layers. Changes in surface soil permeability or porosity may occur as the result of the volatilization of organic compounds that had served to cement soil aggregates (Dyrness and Youngberg 1957). This can result in reduced porosity as impacted

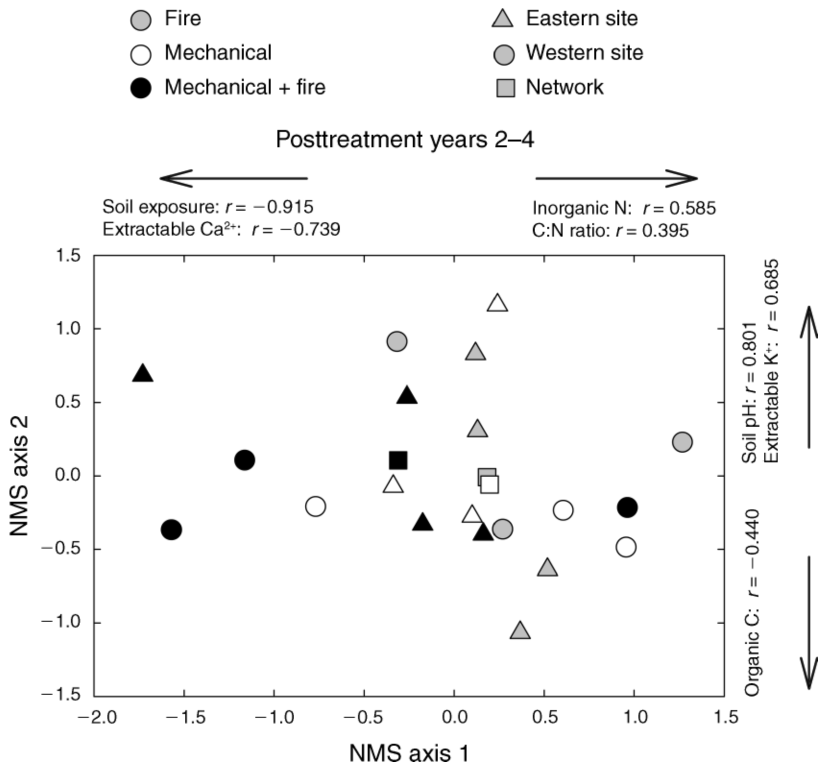

FIG. 14. Nonmetric multidimensional ordination of standardized, second- to fourth-year effect sizes of three Fire and Fire Surrogate treatments on soil properties. Correlations significant at $P < 0.05$ between axis scores and soil parameters are shown. For NMS axis 1, $r^2 = 0.235$; for NMS axis 2, $r^2 = 0.518$.

aggregates crumble and plug large soil pores (Moehring et al. 1966). Water-repellent layers often form after relatively intense fire over soils with a significant organic matter content (Ice et al. 2004), especially when the forest floor material is rich in waxes and other volatile organic compounds. Water-repellant layers are more likely to form in coarse, sandy soils than in more fine-textured soils (Neary et al. 2004), and though temporary in nature, may reduce water infiltration by several orders of magnitude while they are present (Ice et al. 2004).

Although there was no specific protocol established for assessing water repellency as a potential impact of the FFS treatments, none of the FFS sites reported significant erosion or mass wasting after the fire or mechanical treatments were applied. Based on the fire severity classification described by Ice et al. (2004), the prescribed fires applied to the FFS treatment units fell in the very low, low, and moderate severity classes, of which only the last would be expected to have produced any significant water repellency (Ice et al. 2004).

The network-scale effects of the FFS treatments on soil pH and the availability of Ca, Mg, K, and P were modest, and were limited to an increase in extractable Ca^{2+} during the first year after the combination of mechanical treatment and prescribed fire and an increase in soil pH following the same treatment during the later sampling year. The individual sites in which significant effects on soil pH or extractable Ca^{2+} were observed were those in which fire severity was the greatest (CA-C and CA-N) or in which pretreatment base status was the lowest (SC).

Previous studies of the impact of fire on soil N pools and processes in western conifer stands have demonstrated a general pattern characterized by an almost immediate increase in the soil NH_4^+ pool size, an increase in the NO_3^- pool size that is delayed for up to a year, and a lack of any significant difference in inorganic-N pool sizes between burned and reference sites after a few years (e.g., Covington et al. 1991, Covington and Sackett 1992). In an extensive meta-analysis of the effects of fire on N, Wan et al. (2001) confirmed that general pattern, and interpreted the pulse of NH_4^+ as being the result of a combination of liberation from organic matter degraded during the fire, increased activity of heterotrophic soil biota, and N-fixation by symbionts of newly established plants. The delayed peak in soil NO_3^- was interpreted as the result of enhanced NH_4^+ availability and increased activity of autotrophic, nitrifying bacteria. When the results were stratified by fire type or intensity, however, Wan and others (2001) concluded that high intensity wildfires and slash fires resulted in increased soil NO_3^- and NH_4^+ pools, whereas prescribed burning did not.

We observed a significant, positive effect of all three manipulative treatments on total inorganic N (TIN) during the first posttreatment year, but this effect had dissipated by the later sampling year. Thus, the transitory increase in TIN was consistent with what has been reported in many other studies. At the same time, we observed no significant network-scale effect of either fire or mechanical + fire treatment on the net N mineralization rate, as measured by incubations in situ (Boerner et al. 2008*a*). This result contrasted with those of the many studies that have demonstrated increases in net N mineralization after single fires (reviews by Raison 1979, Wan et al. 2001, Boerner 2006). Increases in net N mineralization are often attributed to the alteration of organic matter by fire in such a manner as to render it more susceptible to microbial attack, to increases in microbial activity, and to changes in microclimate (Hart et al. 2005). However, Boerner et al. (2000, 2004) quantified soil organic matter contents and net N mineralization rates in four southern Ohio mixed-oak forests subjected to annual or periodic burning and found no consistent or persistent change in any index of microbially mediated net N mineralization at the full watershed scale. In that study, pre-fire conditions and landscape characteristics were more important in explaining changes in soil C and N dynamics than was fire behavior (Boerner et al. 2000). A similar lack of fire effect on net N mineralization has been reported for oak-pine forests in Georgia and Tennessee (Hubbard et al. 2003) and oak–pine stands in North Carolina (Knoepp et al. 2004). Thus, the increases in TIN we observed after fire and mechanical + fire treatments must either have been result of physiochemical factors independent of the activity of N-mineralizing organisms, or of a magnitude and variance that made resolving a significant effect on net N mineralization unlikely given our sampling design.

We observed no significant effect of the FFS treatments on soil organic C content or on soil C:N ratio at the full network scale, and few significant effects at the individual study sites. The effect of fire and intensive harvesting on soil organic C has been studied extensively and frequently reviewed (e.g., Ice et al. 2004, Certini 2005, Boerner 2006). It is common to observe losses of organic C from the surface mineral soils during and shortly after fire, followed by gains in soil organic C over a period of years thereafter, but these initial losses are likely from just the top few centimeters of soil. As our sampling integrated the top 15 cm of soil, it would require considerable loss from the top few centimeters to produce a significant decrease in soil organic C in the full 0–15 cm stratum.

Johnson and Curtis (2001) evaluated the effects of disturbance on soil organic matter in forests using a meta-analysis, and they concluded that ecosystems that had experienced fire approximately 10 years earlier experienced an average 8% gain in soil organic C. They attributed this change to a combination of factors, including infiltration of organic matter from partially combusted fuels into the mineral soil, conversion of labile (easily decomposed) organic matter into recalcitrant (stable) organic matter, and the effects of the colonization of burned areas by plants which harbor N-fixing symbionts. In contrast, Eivasi and Bayan (1996) could not detect significant changes in soil organic C content in the soils of a Missouri oak flatwoods ecosystem even after more than 40 years of annual or periodic burning.

Ordination of the first-year standardized effects of the three manipulative treatments suggested that the effects of the three treatments were confounded by differences in fire severity (measured as the proportion of ground fuels consumed) among sites. Five site-treatment combinations covering three western sites (CA-C, CA-N, MT) and both fire and mechanical + fire treatments separated from the remaining site-treatment combinations along an ordination axis in a manner that was positively correlated with the magnitude of the effects on pH and TIN and negatively correlated with magnitude of the effect on soil organic C content and C:N ratio. We suggest that greater fire severity in these sites than the others increases soil pH and TIN and decreases in organic matter quantity and quality that were atypical for the FFS network as a whole. Thus, the lack of uniformity among fire treatments made resolving the first-year network-scale effects of the three manipulative treatments problematic.

In contrast, by the later sampling year (the second, third, or fourth posttreatment growing season, depending on site), the effects of the mechanical + fire treatment diverged from those attributable to fire-only or mechanical-only treatments, with the mechanical + fire treatments showing increased impacts on mineral soil exposure and extractable Ca^{2+} and lesser impact on TIN and soil C:N ratio than the other two treatments. In addition, the site groupings tended to separate along second ordination axis in the second, third, or fourth year post treatment, with the western sites in the center of the axis and the eastern sites at the upper and lower ends. This suggested that the eastern sites had both the greatest and least effects on pH, extractable K^+, and soil organic C content across the FFS network, with the western sites being less variable among sites and treatments.

Comparisons between the ordinations representing the two sampling intervals must be done with considerable caution, as fewer sites are represented in the later than the earlier sampling interval. Still, the ordination of the first year effects indicated a strong interaction between sites and treatments, whereas the variations among sites and among treatments began to resolve somewhat into separate patterns by the second and third years following treatment.

Across the full network and in most of the individual study sites the impact of the FFS treatments on soil physical and chemical properties were both modest in magnitude and transient in duration. This general conclusion must be tempered by the understanding that the both sampling design and the meta-analytical methods we employed in this synthesis were unable to capture several potentially important, scale-dependent factors.

The first of these involves the study sites themselves. All but perhaps two of the study sites have considerable, landscape-scale variation among and within treatment units in elevation, aspect, shape profile, and parent materials. In some of the study sites (e.g., WA, CA-N), the investigators restricted the treatment units to a single aspect and elevation range in an effort to control this landscape-scale variation. In other study sites, a synthetic landscape metric (e.g., the landscape ecosystem classification of Carter et al. [2000] at the NC site and the integrated moisture index of Iverson et al. [1997] at the OH site) was used to stratify the sampling locations within and among treatment units. While such approaches can be incorporated as covariates into within-site, analysis of variance-based approaches or into structural equation modeling approaches, the meta-analysis we used was not able to account for this source of variation.

The second source of scale-dependent variation arises as the result of the treatments themselves. Fire is inherently patchy in space and time, and mechanical treatments that involve the removal of a modest number of individual trees create a patchy environment defined by the pattern of cutting. The latter, in turn, is the result of the intersection of ecological decisions (e.g., which trees to cut to foster restoration or fuel hazard reduction), economic decisions (e.g., what products can we sell at a profit), and the legacies of past human activities and natural disturbances. At a point or sample plot scale, this patchiness can be defined by surrogate measures of fire intensity (e.g., loss of forest floor mass and tree basal area) or harvesting (e.g., tree basal area loss by species/functional species group). In some cases, these surrogates can be extracted directly from the FFS database, as they were measured utilizing the same spatial sampling protocol as were the soils (e.g., tree basal area and species composition); in others, geostatistical methods will be necessary to generate estimates for points where soils were sampled because the FFS design called for sampling those variables using a different spatial sampling structure (e.g., forest floor mass loss). Once again, such measures of spatial variation can be incorporated into within-site analysis of variance-based approaches or among-site structural equation modeling approaches, but cannot readily be accounted for with meta-analytical approaches.

Acknowledgments

This is contribution number 154 of the Fire and Fire Surrogate Project, funded by the Joint Fire Sciences Program. We thank the site managers and cooperating scientists at the FFS sites for field, laboratory, and statistical assistance: Ken Outcalt and Graham Lockaby (AL, FL), Steve Overby and Carl Edminster (AZ), Emily Moghaddas and Scott Stephens (CA-C), Carl Skinner and Celeste Abbott (CA-N), Sarah Hamman and Eric Knapp (CA-S), Tom DeLuca and Carl Fiedler (MT), Tom Waldrop and Ross Phillips (SC, NC), Dan Yaussy (OH), Andy Youngblood and Jim McIver (OR), and Jim Agee and Darlene Zabowski (WA). We also thank Jennifer Brinkman, Carla Giai, Jessica Miesel, Phil Ruse, and Megan Cartwright for assistance in the lab.

Literature Cited

Agee, J. K. 1993. Fire ecology of Pacific Northwest forests. Island Press, Washington, D.C., USA.

Berger, A. L., K. J. Puettmann, and G. E. Host. 2004. Harvesting impacts on soil and understory vegetation: the influence of season of harvest and within-site disturbance patterns on clear-cut aspen stands in Minnesota. Canadian Journal of Forest Research 34:2159–2168.

Bethlalmy, N. 1974. Water supply as affected by micro- and macro-watershed management decisions on forest lands. Northwest Science 48:1–8.

Boerner, R. E. J. 2006. Earth, wind, water, and fire: how the elements conspire in the forest context. Pages 104–122 *in* M. B. Dickinson, editor. Fire in eastern oak forests: delivering science to land managers, Proceedings of a conference, 15–17 November 2005, Columbus, Ohio. General Technical Report NRS-P-1. USDA Forest Service, Northern Research Station, Newtown Square, Pennsylvania, USA.

Boerner, R. E. J., J. A. Brinkman, and E. K. Sutherland. 2004. Effect of fire at two frequencies on forest soils in a nitrogen-enriched landscape. Canadian Journal of Forest Research 34: 609–618.

Boerner, R. E. J., C. Giai, J. Huang, and J. R. Miesel. 2008*a*. Fire and mechanical thinning effects on soil enzyme activity and nitrogen transformations in eight North American forest ecosystems. Soil Biology and Biochemistry 40:3076–3085.

Boerner, R. E. J., J. Huang, and S. C. Hart. 2008*b*. Fire, thinning, and the carbon economy: effects of the FFS treatments on carbon storage and sequestration rate. Forest Ecology and Management 255:3081–3097.

Boerner, R. E. J., E. K. Sutherland, S. J. Morris, and T. F. Hutchinson. 2000. Spatial variations in the effect of prescribed fire on N dynamics in a forested landscape. Landscape Ecology 15:425–439.

Boyle, S. I., S. C. Hart, J. P. Kaye, and M. P. Waldrop. 2005. Restoration and canopy type influence soil microflora in a ponderosa pine forest. Soil Science Society of America Journal 69:1627–1638.

Carter, R. E., Jr., N. J. Myers, V. B. Shelburne, and S. M. Jones. 2000. Ecological land classification in the high rainfall belt of the southern Appalachian Mountains. Castanea 65: 258–272.

Certini, G. 2005. Effects of fire on properties of forest soils: a review. Oecologia 143:1–10.

Covington, W. W., L. F. DeBano, and T. G. Huntsberger. 1991. Soil nitrogen changes associated with slash pile burning in pinyon–juniper woodlands. Forest Science 37:347–355.

Covington, W. W., and S. S. Sackett. 1992. Soil mineral nitrogen changes following prescribed burning in ponderosa pine. Forest Ecology and Management 54:347–355.

Dyrness, C. T., and C. T. Youngberg. 1957. The effect of logging and slash burning on soil structure. Soil Science Society of America Proceedings 21:444–447.

Eivasi, F., and M. R. Bayan. 1996. Effects of long-term prescribed burning on the activity of selected soil enzymes in an oak–hickory forest. Canadian Journal of Forest Research 26:1799–1804.

Gurevitch, J., and L. V. Hedges. 1993. Meta-analysis: combining the results of independent experiments. Pages 378–389 *in* S. M. Scheiner and J. Gurevitch, editors. Design and analysis of ecological experiments. Chapman and Hall, New York, New York, USA.

Hart, S. C., T. H. DeLuca, G. S. Newman, D. M. MacKenzie, and S. I. Boyle. 2005. Post-fire vegetative dynamics as drivers of microbial community structure and function in forest soils. Forest Ecology and Management 220:166–184.

Hubbard, R. M., J. M. Vose, B. D. Clinton, K. J. Elliot, and J. D. Knoepp. 2003. Stand restoration burning in oak–pine forests in the southern Appalachians: effects on aboveground biomass and carbon and nitrogen cycling. Forest Ecology and Management 190:311–321.

Ice, G. G., D. G. Neary, and P. W. Adams. 2004. Effects of wildfires on soils and watershed processes. Journal of Forestry 102:16–20.

Iverson, L. R., M. E. Dale, C. T. Scott, and A. Prasad. 1997. A GIS-derived integrated moisture index to predict forest composition and productivity of Ohio forests (U.S.A.). Landscape Ecology 12:331–348.

Johnson, D. W., and P. S. Curtis. 2001. Effects of forest management on soil C and N storage: meta analysis. Forest Ecology and Management 140:227–238.

Keeney, D. R., and D. W. Nelson. 1982. Nitrogen: inorganic forms. Pages 643–698 *in* A. L. Page, editor. Methods of soil analysis: part 2, chemical and microbiological properties. Second edition. American Society of Agronomy, Madison, Wisconsin, USA.

Klepac, J., S. E. Reutebuch, and R. B. Rummer. 1999. An assessment of soil disturbance from five harvesting intensities. ASAE 1999 Meeting Presentation Paper 99-5052. American Society of Agricultural Engineers, St. Joseph, Michigan, USA.

Knoepp, J. D., J. M. Vose, and W. T. Swank. 2004. Long-term soil responses to site preparation burning in the southern Appalachians. Forest Science 90:540–550.

Matson, P. A., and P. M. Vitousek. 1981. Nitrogen mineralization and nitrification potentials following clearcutting in the Hoosier National Forest. Forest Science 27:781–791.

McIver, J. M. 2001. FFS Network Study Plan. ⟨http://frames.nbii.gov/portal/server.pt?open=512&objID=367&&PageID=1570&mode=2&in_hi_userid=382&cached=true⟩

Moehring, D. M., C. X. Grano, and J. R. Bassett. 1966. Properties of forested loess soils after repeated prescribed burning. Research Note SO-40. USDA Forest Service, Southern Forest Experiment Station, New Orleans, Louisiana, USA.

Moghaddas, E. E. Y., and S. L. Stephens. 2008. Mechanized fuel treatment effects on soil compaction in Sierra Nevada mixed-conifer stands. Forest Ecology and Management 255: 3098–3106.

Neary, D. G., K. C. Ryan, and L. E. DeBano, editors. 2004. Fire effects on soil and water. General Technical Report RMRS-42. Volume 4. USDA Forest Service, Rocky Mountain Research Station, Fort Collins, Colorado, USA.

Olsen, S. R., and L. E. Sommers. 1982. Phosphorus. Pages 403–430 *in* A. L. Page, editor. Methods of soil analysis: part 2, chemical and microbiological properties. Second edition. American Society of Agronomy, Madison, Wisconsin, USA.

Raison, P. J. 1979. Modification of the soil environment by vegetation fires, with particular reference to nitrogen transformations: a review. Plant and Soil 51:73–108.

Raudenbush, S. W. 1994. Random effects models. Pages 301–321 *in* H. Cooper and L. V. Hedges, editors. The handbook of research synthesis. Russell Sage Foundation, New York, New York, USA.

Rosenberg, M. S., D. C. Adams, and J. Gurevitch. 2000. MetaWin: statistical software for meta-analysis. Version 2.0. Sinauer, Sunderland, Massachusetts, USA.

Rummer, B., E. Carter, B. Stokes, and J. Klepac. 1997. Strips, clearcuts, and deferment cuts: harvest costs and site impacts for alternative prescriptions in upland hardwoods. Pages 103–112 *in* D. A. Meyer, editor. Proceedings of the 25th annual hardwood symposium. National Hardwood Lumber Association, Memphis, Tennessee, USA.

Walstad, J. D., S. R. Radosevich, and D. V. Sandberg, editors. 1990. Natural and prescribed fire in the Pacific Northwest. Oregon State University Press, Corvallis, Oregon, USA.

Wan, S., D. Hui, and Y. Luo. 2001. Fire effects on nitrogen pools and dynamics in terrestrial ecosystems: a meta-analysis. Ecological Applications 11:1349–1365.

APPENDIX A

Publications from the Fire and Fire Surrogate Network that focus on effects on soil biological, physical, and chemical properties as of 15 April 2008 (*Ecological Archives* A019-014-A1).

APPENDIX B

Pretreatment soil conditions at the Fire and Fire Surrogate Network (FFS) scale and in the 12 individual FFS study sites (*Ecological Archives* A019-014-A2).

APPENDIX C

First year posttreatment soil conditions at the Fire and Fire Surrogate Network (FFS) scale and in the 12 individual FFS study sites (*Ecological Archives* A019-014-A3).

APPENDIX D

Second or third year posttreatment soil conditions at the Fire and Fire Surrogate Network (FFS) scale and in the 12 individual FFS study sites (*Ecological Archives* A019-014-A4).