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Review

Ecological effects of alternative fuel-reduction treatments: highlights of the National Fire and Fire Surrogate study (FFS)

James D. McIver[A,T], *Scott L. Stephens*[B], *James K. Agee*[C], *Jamie Barbour*[D], *Ralph E. J. Boerner*[E], *Carl B. Edminster*[F], *Karen L. Erickson*[A], *Kerry L. Farris*[G], *Christopher J. Fettig*[H], *Carl E. Fiedler*[I], *Sally Haase*[J], *Stephen C. Hart*[K], *Jon E. Keeley*[L], *Eric E. Knapp*[M], *John F. Lehmkuhl*[N], *Jason J. Moghaddas*[B], *William Otrosina*[O], *Kenneth W. Outcalt*[O], *Dylan W. Schwilk*[P], *Carl N. Skinner*[M], *Thomas A. Waldrop*[Q], *C. Phillip Weatherspoon*[U], *Daniel A. Yaussy*[R], *Andrew Youngblood*[S] and *Steve Zack*[G]

[A]Eastern Oregon Agricultural Research Center, Oregon State University, PO Box E, Union, OR 97883, USA.
[B]Department of Environmental Science, Policy, and Management, University of California, Berkeley, 137 Mulford Hall, Berkeley, CA 94720, USA.
[C]School of Environmental and Forest Sciences, Box 352100, University of Washington, Seattle, WA 98195, USA.
[D]Pacific Northwest Research Station, USDA Forest Service, 333 SW 1st Avenue, Portland, OR 97204, USA.
[E]Department of Evolution, Ecology, and Organismal Biology, 280 Aronoff Laboratory, Ohio State University, Columbus, OH 43210, USA.
[F]Rocky Mountain Research Station, USDA Forest Service, 2500 S Pine Knoll Drive, Flagstaff, AZ 86001, USA.
[G]Wildlife Conservation Society, North America Program, 718 Southwest Alder Street, Portland, OR 97205, USA.
[H]Pacific Southwest Research Station, USDA Forest Service, 1731 Research Park Drive, Davis, CA 95618, USA.
[I]University of Montana, College of Forestry and Conservation, 32 Campus Drive, Missoula, MT 59812, USA.
[J]Pacific Southwest Research Station, USDA Forest Service, 4955 Canyon Crest Drive, Riverside, CA 92507, USA.
[K]School of Natural Sciences and Sierra Nevada Research Institute, University of California, 5200 North Lake Road, Merced, CA 95343, USA.
[L]US Geological Survey, Western Regional Research Center, Sequoia and Kings Canyon Field Station, 47050 Generals Highway #4, Three Rivers, CA 93271, USA.
[M]Pacific Southwest Research Station, USDA Forest Service, 3644 Avtech Parkway, Redding, CA 96002, USA.
[N]Pacific Northwest Research Station, USDA Forest Service, 1133 N Western Avenue, Wenatchee, WA 98801, USA.
[O]Southern Research Station, USDA Forest Service, 320 Green Street, Athens, GA 30602, USA.
[P]Department of Biological Sciences, Box 43131, Texas Tech University, Lubbock, TX 79409, USA.
[Q]Southern Research Station, USDA Forest Service, 233 Lehotsky Hall, Clemson University, Clemson, SC 29634, USA.
[R]Forestry Science Laboratory, Northern Research Station, USDA Forest Service, 359 Main Road, Delaware, OH 43015, USA.
[S]Pacific Northwest Research Station, USDA Forest Service, 1401 Gekeler Lane, La Grande, OR 97850, USA.
[T]Corresponding author. Email: james.mciver@oregonstate.edu
[U]Retired.

Abstract. The 12-site National Fire and Fire Surrogate study (FFS) was a multivariate experiment that evaluated ecological consequences of alternative fuel-reduction treatments in seasonally dry forests of the US. Each site was a replicated experiment with a common design that compared an un-manipulated control, prescribed fire, mechanical and mechanical + fire treatments. Variables within the vegetation, fuelbed, forest floor and soil, bark beetles, tree diseases and wildlife were measured in 10-ha stands, and ecological response was compared among treatments at the site level, and across sites, to better understand the influence of differential site conditions. For most sites, treated stands were predicted to be more resilient to wildfire if it occurred shortly after treatment, but for most ecological variables, short-term response to treatments was subtle and transient. Strong site-specificity was observed in the response of most ecosystem variables, suggesting that practitioners employ adaptive management at the local scale. Because ecosystem components were tightly linked, adaptive management would need to include monitoring of a carefully chosen set of key variables. Mechanical treatments did not serve as surrogates for fire for most variables, suggesting that fire be maintained whenever possible. Restoration to pre-settlement conditions will require repeated treatments over time, with eastern forests requiring more frequent applications.

Additional keywords: dry forest management, forest thinning, frequent fire regimes, mechanical treatment, oak, pine, prescribed fire, seasonally dry forests.

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Introduction

Prescribed fire and mechanical treatments have been the most common fuel-reduction practices used in seasonally dry forests of the US since the 1970s (Agee and Skinner 2005). These practices are popular because forest managers realise that frequent disturbance is necessary to maintain stand structure in oak (*Quercus* spp.)- and pine (*Pinus* spp.)-dominated forests of eastern and western North America (Weaver 1943; Van Lear and Waldrop 1989; Hutchinson *et al.* 2008*[A]). Prior to settlement by Euro–Americans, low to moderate intensity surface fires burned frequently in these forests, and tended to reduce the quantity of fuels, break up their continuity and discourage the establishment of shrubs and fire-intolerant tree species, leading eventually to stands dominated by larger diameter fire-tolerant tree species (Youngblood *et al.* 2004; North *et al.* 2007; Hutchinson *et al.* 2008*; Collins *et al.* 2011). Yet fire suppression, preferential harvest of large diameter trees and livestock grazing over the past 100–150 years have converted stands to fire-intolerant species and shifted fuelbed conditions over millions of hectares in the East and in the Interior West (Parsons and DeBenedetti 1979; Stephens and Ruth 2005). As a result, recent wildfires in seasonally dry forests have tended to be larger and more severe, even in areas that might rarely have experienced stand-replacement fires (Parsons and DeBenedetti 1979; Hessburg and Agee 2003; Knapp *et al.* 2005*). This scenario explains why prescribed fire and mechanical treatments are commonly used by managers in oak- and pine-dominated forests that once burned frequently, in an effort to change the only factor in the fire formula they can: the quantity and continuity of fuel (Agee and Skinner 2005).

Prescribed fire has been the most attractive fuel-reduction practice for forest managers, for the obvious reason that it is most likely to emulate the natural process that it is designed to replace (McRae *et al.* 2001). Unfortunately, when forest managers attempt to apply prescribed fire, they are often constrained by social, economic and administrative issues, such that the window of opportunity for its application is often narrowed or eliminated (Winter *et al.* 2002; Brunson and Shindler 2004). In addition, prescribed fire after long periods of fire suppression differs from fire at historically frequent intervals and may lead to undesirable ecological effects. As a result, fuel-reduction surrogates such as forest thinning or mastication have become more attractive (Crow and Perera 2004). The assumption is that if managers can use mechanical treatments to reduce fuels, and accomplish the same stand-structure goals as those obtained by prescribed fire, the constraints and risks posed by the application of fire can be avoided. The only problem with this idea is that we know little about how mechanical treatments compare with prescribed fire, particularly in terms of ecological effects and their interactions (McIver *et al.* 2001*). Furthermore, because few multi-site studies have been conducted, we have little confidence in how the comparison between alternative fuel-reduction methods might play out when repeated in different forests having different conditions (Waldrop and McIver 2006*). These considerations provided the incentive behind the genesis and development of the National Fire and Fire Surrogate study (FFS) (McIver and Weatherspoon 2010*).

The FFS was designed to evaluate how alternative fuel-reduction treatments influence a multitude of ecological variables at 12 seasonally dry sites nationwide (forests that experience at least one dry season per year) (Fig. 1; McIver and Weatherspoon 2010*). Short-term results of this study have been disseminated in a variety of media over the years (Youngblood *et al.* 2007*), and have been published in more than 170 technical papers (http://frames.nbii.gov, accessed 22 September 2012), including collections in four journals (*Forest Ecology and Management*, McIver *et al.* 2008*; *Ecological Applications*, McIver *et al.* 2009*; *Forest Science*, McIver and Fettig 2010*; *Open Environmental Sciences*, Robinson 2010*). Detailed findings for each publication can be found on the website of the Joint Fire Science Program (http://www.frames.gov/FFS, accessed 21 September 2012), and have been recently published as a US Forest Service General Technical Report

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[A] Citations marked with asterisk refer to papers published as part of the National Fire and Fire Surrogate Study.

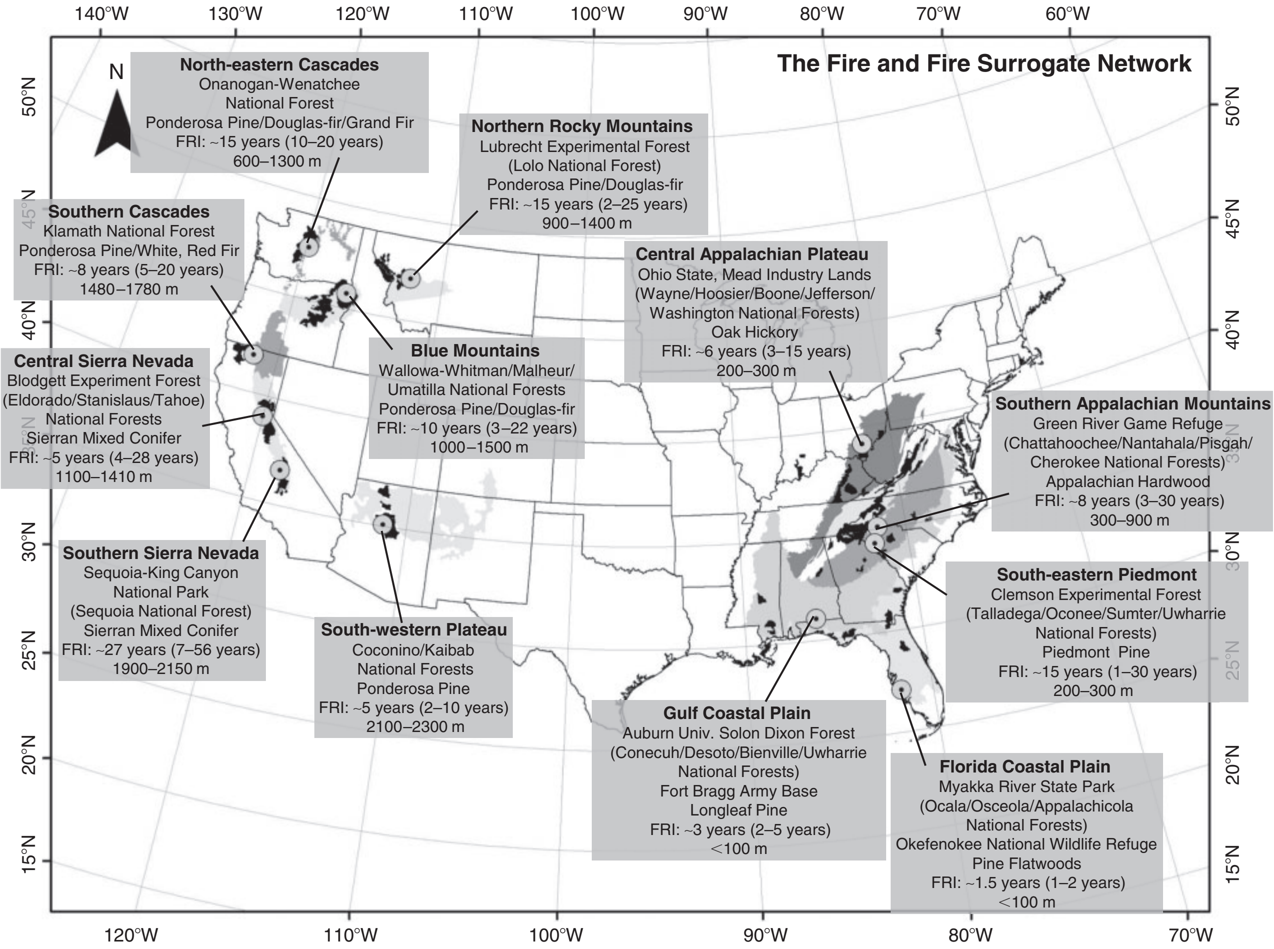

Fig. 1. Name and location of the 12 National Fire and Fire Surrogate (FFS) sites, showing relevant national forests (black-shaded areas), forest type, fire return interval (FRI) and elevation range (m). Lighter shading indicates 'representative land base', or the area to which FFS results can be most directly applied for each site. Representative land bases are derived from EPA Type III Ecoregions: www.epa.gov/wed/pages/ecoregions/level_iii.htm, accessed 21 September 2012. Scientific names for tree species in Fig. 1, but not mentioned in text: Douglas-fir (*Pseudotsuga menziesii*), grand fir (*Abies grandis*), white fir (*Abies concolor*) and red fir (*Abies magnifica*).

(McIver *et al.* 2012*). In the current paper, we summarise the published findings of the FFS study, and interpret them in the context of key literature. We first describe the experiment and report on the effectiveness of the implemented treatments. A summary of experimental results is then presented and interpreted from the perspective of key management 'themes' the study was designed to address, including the magnitude and duration of effects, the issue of fuel-reduction surrogates, key management tradeoffs, habitat effects on flora and fauna and restoration of seasonally dry forest ecosystems.

FFS study design

The FFS study was conducted in seasonally dry forests administered by the US Forest Service, National Park Service, state parks, universities and private industry at 12 sites across the United States: five in the East and seven in the Interior West (Fig. 1). Fuel-reduction treatments were applied between 1998 and 2006 at all 12 sites (Table 1). Eleven sites received four treatments: un-manipulated control, prescribed fire only, mechanical treatment only and mechanical + fire. At the Southern Sierra Nevada site (NPS land, prescribed fire the primary treatment option) the two active treatments were early and late season burns. Each treatment was replicated at all 12 sites three or four times at the stand level, and most analyses were conducted at this scale. Each stand was at least 10 ha in size, with the perimeter surrounded by a buffer at least 50 m wide that received the same treatment. All pre- and post-treatment measurements were taken within a set of plots established on a 40–60-m grid in the interior of each stand.

Detailed prescriptions for prescribed fire and mechanical treatment were unique to each site (Table 1), but the common objective for all treatments was to achieve stand and fuel conditions such that, if subjected to a head fire under the 80th percentile weather conditions, at least 80% of the basal area of the dominant and co-dominant trees would survive (80/80 rule). Clearly, because the alternative fuel-reduction treatments would be expected to influence stands and fuelbeds in fundamentally

Table 1. Past management history and treatment information for the 12 Fire and Fire Surrogate sites
Citations marked with asterisk refer to papers published as part of the National Fire and Fire Surrogate Study

Site name and location	Past management history	Treatment: type and year
North-eastern Cascades, Okanogan–Wenatchee National Forest, central WA (Dodson *et al.* 2008*; Agee and Lehmkuhl 2009*)	Logging in the 1930s and pre-commercial thin in 1970s; fire exclusion since early 1900s; heavy grazing in early 20th century.	Mechanical (2001): fell, limb and buck with chainsaws; yard with helicopter; residue left on site. Burn (2004): spring underburn using combination of backing and strip head fires
Blue Mountains, Wallowa–Whitman National Forest, north-eastern OR (Youngblood *et al.* 2006*)	Harvesting in early 20th century and as recently as 1986; fire exclusion since early 1900s; grazing; most trees 60–90 years old	Mechanical (1998): fell, limb and buck with tracked single-grip harvesters; yard with forwarders; residue left on site Burn (2000): autumn underburn, strip head fire
Northern Rocky Mountains, University of Montana, Lubrecht Experimental Forest, western MT (Metlen and Fiedler 2006*)	Logging in early 20th century and fire suppression resulting in 80–90 year old stand; Grazing over last 100 years	Mechanical (2002): fell, limb and buck with tracked single-grip harvesters; yard with forwarders; residue left on site Burn (2002): spring underburn, strip head fire
Southern Cascades, Klamath National Forest, north-eastern CA (Ritchie 2005)	Railroad logging in 1920s – various sanitation and salvage since.	Mechanical (2001): fell with feller-buncher; yard whole trees with rubber-tired or tracked skidders Burn (2001): autumn underburn, strip head fire
Central Sierra Nevada, University of California, Blodgett Forest Experimental Station, central CA (Stephens and Moghaddas 2005*a**, 2005*b**)	Railroad logging in early 20th century; sanitation salvage mid 1970s; commercial harvest using various methods to present	Mechanical (2002): fell, limb and buck trees >25-cm diameter at breast height (DBH) with chainsaws; lop and scatter tops and limbs; yard with skidders; post-harvest masticate 70% of trees <25-cm DBH Burn (2002): autumn underburn using a combination of backing and strip head fires
Southern Sierra Nevada, Sequoia National Park, south-central CA (Knapp *et al.* 2005*)	Fire suppression since early 20th century	Mechanical: none Burn (2002, 2003): autumn and spring underburn, using strip head fires
South-western Plateau, Kaibab and Coconino National Forests, northern AZ (Converse *et al.* 2006*b**)	Past harvesting; grazing; limited low thinning in early 1990s	Mechanical (2003): fell, limb, and buck trees >13-cm DBH with chainsaws; fell and lop trees <13 cm to waste with chainsaws Burn (2003): autumn underburns conducted as both backing and strip head fires
Central Appalachian Plateau, Mead Corporation, Ohio State Lands, southern OH (Waldrop *et al.* 2008*)	Forests largely cut over during 1800s; human ignited fires common before early 1880s; fire suppression since early 1900s	Mechanical (2001): fell, limb, buck trees >15-cm DBH with chainsaws; leave 18-m^2 ha^{-1} basal area Burn (2001): spring underburns conducted as strip head fires.
Southern Appalachian Mountains Green River Wildlife Conservation Lands, western NC (Waldrop *et al.* 2008*)	Forests largely cut over during 1800s; human ignited fires common before early 1880s; fire suppression since early 1900s	Mechanical (late 2001–early 2002): chainsaw felling all tree stems >1.8-m height and <10.2-cm DBH as well as all shrubs, regardless of size. Burn (2003, 2006): winter ground fires ignited by hand and by helicopter using strip head fire and spot fire.
South-eastern Piedmont, University of Clemson Experimental Forest, western SC (Phillips and Waldrop 2008*)	Row-cropping prevalent 1800–1930; reforestation 1930–1950, now second-growth loblolly and shortleaf, pines and mixed pine-hardwood stands.	Mechanical (late 2000–early 2001): fell with feller buncher, yard whole trees with rubber-tyre skidders, slash distributed across the site. Burn (burn only 2001 and 2004, mechanical + burn 2002 and 2005): winter ground fires ignited by hand using strip head fire.
Gulf Coastal Plain, Auburn University of Solon Dixon Experimental Forest, southern AL (Outcalt 2005*)	Naturally regenerated longleaf pine. Managed for timber and naval stores by private family 1880s to 1981. Sporadic burning	Mechanical (2002): fell with feller-buncher; chainsaw limb, yard trees length with rubber-tired skidders. Burn (2002): spring underburn, strip head fire
Florida Coastal Plain, Myakka River State Park, west-central FL (Outcalt and Foltz 2004*)	Sparse slash and longleaf pine overstorey with saw palmetto understorey. Periodic prescribed burns for last 15 years.	Mechanical (2002): chop with marden aerator pulled by 4-wheel drive rubber tired tractor. Burn (2000, 2001): spring underburn, strip head fire

different ways, we did not expect post-treatment stands to look the same for all treatments and for all sites. Rather, the 80/80 rule served to guide fire-management officers and silviculturists so that they could better envision the kinds of treatments we wanted (Stephens *et al.* 2009*). For mechanical treatments, managers at each site used a biomass or sawlog removal system that was locally applicable to that site, but always with the 80/80 rule in mind. Burning was conducted following common local practices: in the late spring or early autumn at all western sites, in spring at the Central Appalachian Plateau and both Coastal Plain sites, and in the winter at the South-eastern Piedmont and Southern Appalachian Mountain sites. The mechanical + fire treatment typically required that we wait at least a full season for mechanically treated fuels to cure before burning at each site.

Table 2. List of ecosystem components studied, including information on measurement scale, measurement intervals, and sites at which indicated variables were measured

Component	Variable group	Measurement scale	Measurement intervals	Sites
Site characterisation	Slope, aspect, global position, topographic position, elevation	Unit	Pre-treatment	All
Weather	Precipitation, temperature	Control core plots	Throughout study	All
Vegetation	Trees, shrubs, grasses, forbs, density, cover, richness	Plot within unit	Pre-, several post-treatment	All
Fuels	Litter, duff, shrub biomass, woody fuel	Transects on grid within unit	Pre-, several post-treatment	All
Soils, forest floor, dead wood	Characterisation (depth, texture, type)	Unit	Pre-treatment	All
	Carbon and nitrogen dynamics cation exchange soil bulk density	Plots within unit	Pre-, several post-treatment	All
Vertebrates	Songbird density, richness, nest density	Unit	Pre-, several post-treatment	All
	Small mammal density, richness	Unit	Pre-, several post-treatment	Western sites; Southern Appalachian Mountains
Invertebrates	Relative abundance, guild composition, richness	Unit	Pre-, several post-treatment	South and Central Sierra; South-eastern Piedmont; Southern Appalachian Mountains
Bark beetles	Activity in pine trees	Unit	Pre-, several post-treatment	Pine sites
Diseases, fungi	Root disease, mistletoe	Unit	Pre-, several post-treatment	All

Although the method of application of prescribed fire was fairly uniform throughout the 12 sites (Table 1), the mechanical treatments were more variable. At the Central Sierra Nevada site trees smaller than 25-cm diameter at breast height (DBH) were masticated to compact the fuelbed; at the Florida Coastal Plain site the saw palmetto understorey was masticated, leaving the sparse overstorey untouched; and at the Southern Appalachian Mountain site all tree stems >1.8-m height and <10.2-cm DBH were felled, as well as all shrubs, regardless of size. All other sites applied the mechanical treatment to thin trees in the overstorey.

Ecological variables were interpreted within six ecosystem components (Table 2): (1) vegetation, including trees, shrubs, forbs and grasses; (2) the relevant fuelbed, comprised of the forest floor, woody fuels and live fuels; (3) soils and the forest floor, with a focus on carbon, nitrogen, exchangeable ions, soil exposure and bulk density; (4) fauna, including small mammals, birds, herpetofauna (reptiles, amphibians) and macroinvertebrates; (5) bark beetles (on pine-dominated sites) and (6) root diseases and dwarf mistletoe (*Arceuthobium* sp.). Most variables were measured the year before sites were treated, the year after treatment and for up to 4 years post-treatment. Several statistical methods were used for analysis, including general linear models for univariate analyses, structural equation modelling for multivariate questions, and meta-analyses for multi-site comparisons.

Treatment validation

When applied as distinct treatments, both prescribed fire and mechanical treatments had consistent short-term effects on stand structure and fuels across the FFS network (Schwilk *et al.* 2009*; Stephens *et al.* 2012*a**). Although prescribed fire alone influenced live stand structure at the two Sierra Nevada sites, neither basal area nor tree density were greatly affected at most sites. Prescribed fire also tended to decrease the mass of woody fuels, particularly for the western sites (Table 3). Mechanical treatment had nearly opposite effects on stand structure and fuels, resulting in lower live-tree density and basal area. It either did not influence, or increased, woody fuel mass. The only exception to these patterns was at the Florida Coastal Plain site, where fuel treatments were designed to target the understorey.

A somewhat less consistent picture emerges when we examine short-term effects of treatments when applied in combination (first mechanical, then prescribed fire). Although the mechanical + fire treatment affected live tree parameters in almost the same way as for the mechanical treatment (Table 3), there were distinct differences between western and most eastern FFS sites in effects on total fuel mass. Whereas the mechanical + fire treatment decreased woody fuel mass at nearly every western site, in the east it was only at the Gulf Coastal Plain site (longleaf pine, *Pinus palustris*) that the combined treatment had this effect. Interestingly, in terms of treatment effectiveness, the south-eastern longleaf pine site tended to sort best with the western sites, whereas the other eastern sites were more variable.

In terms of predicted post-treatment fire behaviour, fire performance analyses conducted at six western sites (excluding North-eastern Cascades) (Stephens *et al.* 2009*), and at the Southern Appalachian Mountain site (Waldrop *et al.* 2010*) indicated that the mechanical + fire treatment was the most effective treatment in these dry forest systems. This is consistent with actual observations on post-wildfire effects after fuel-reduction treatments (Prichard *et al.* 2010) and with a recent meta-analysis of western ponderosa pine (*Pinus ponderosa*) forests by Fulé *et al.* (2012). These results are not surprising, because for most sites only the mechanical + fire treatment resulted in short-term stand structure and fuelbed conditions – reduced live-tree density, live basal area and fuel mass – that

Table 3. Treatment validation

Immediate effect of treatments on live-tree density, basal area and total woody-fuel mass for 12 FFS sites for burn (B), mechanical (M), and mechanical + burn (MB) treatments. ↑, increase; ↓, decrease; 0, no trend change for indicated variable, with trend indicated by non-overlapping standard errors. Southern Cascades site had no pre-treatment data, so effect trends are estimated with the use of control units; Southern Sierra site (Sequoia National Park) did not implement mechanical treatment – trajectories below combine spring + autumn burns

	Live-tree density			Basal area			Total woody-fuel mass		
Western sites	B	M	MB	B	M	MB	B	M	MB
North-eastern Cascades	0	↓	↓	0	↓	↓	↓	↑	0
Blue Mountains	0	↓	↓	0	↓	↓	↓	0	↓
Northern Rocky Mountains	0	↓	↓	0	↓	↓	↓	↑	0
Southern Cascades	0	↓	↓	0	↓	↓	↓	↑	↓
Central Sierra Nevada	0	↓	↓	0	↓	↓	↓	0	↓
Southern Sierra Nevada	↓	NA	NA	↓	NA	NA	↓	NA	NA
South-western Plateau	0	↓	↓	0	↓	↓	↓	↑	↓
Eastern sites	B	M	MB	B	M	MB	B	M	MB
Central Appalachian Plateau	0	↓	↓	0	↓	↓	0	↑	↑
Southern Appalachian Mountains	0	0	↓	0	0	0	0	0	0
South-eastern Piedmont	0	↓	↓	0	0	↓	↓	0	0
Gulf Coastal Plain	0	↓	↓	0	↓	↓	0	↑	0
Florida Coastal Plain	0	0	0	0	0	↑	0	0	0

would be expected substantially to influence future fire behaviour. In contrast, at two other eastern sites at which potential fire behaviour analyses were conducted – (Central Appalachian Plateau, Iverson *et al.* 2003*; South-eastern Piedmont, Mohr and Waldrop 2006*) – the most effective treatment was prescribed fire alone, probably because slash produced by the mechanical treatment had not dried sufficiently by the time prescribed fire was applied, and was thus not consumed. In terms of fuel-treatment effectiveness therefore, the mechanical + fire treatment most closely resembled the mechanical-only treatment for these two eastern sites. These patterns of treatment effectiveness will now serve as the context for analysis and interpretation of the influence of FFS treatments on other components of the ecosystem, for the key themes the study was designed to address.

Ecological consequences

The unique design of the FFS study permits organisation of findings into five key themes meaningful to managers. The study was experimental and followed treatment effects through at least 4 years at some sites, and thus we could examine short-term *effect size* and *duration*. Because the study applied both prescribed fire and mechanical treatments at the same time and in the same place, we could compare ecological effects of prescribed fire with those of its principle mechanical *surrogates*. The study was multivariate, and thus we could examine *trade-offs* among variables for the various treatments, and could also evaluate how stand structural changes influenced *habitat* of plants, invertebrates and vertebrates. Finally, the measurement of both 'target' variables (stand structure, fuelbed), and 'effects' variables (soils, fauna, understorey) for at least 4 years post-treatment for many sites, provides the opportunity to predict how treatments designed to reduce fuels in the short term may play out for *restoration* of dry forest ecosystems in the longer term.

Effect size and duration

Results from the extensive analytical work of Ralph Boerner and colleagues best illustrate the modest and transient response to treatment of the great majority of ecological variables we measured (Fig. 2). Short-term response to treatment was modest for carbon pools, nitrogen storage, soil chemical properties, nitrogen turnover and microbial activity (Boerner *et al.* 2008*a**, 2008*b**). Although all treatments decreased forest floor C : N ratio in the short-term, the relative difference between treatment and control averaged just 8% (Boerner *et al.* 2008*c**). Similarly, no treatment affected ecosystem nitrogen levels by more than 15% at any site (Boerner *et al.* 2008*a**, 2008*b**). Whereas mechanical and burning treatments modestly decreased carbon mass in the vegetation and forest floor respectively, there were few significant treatment effects on either dead wood carbon or soil carbon (Boerner *et al.* 2008*b**). Although burning did cause persistent increases in mineral-soil exposure, most other soil properties were either unaffected by treatment or experienced very modest short-term effects (Boerner *et al.* 2009*). Certainly, variation among sites in how measurements were taken and treatment-induced spatial heterogeneity both contributed to the lack of statistically significant response in many ecological variables (Boerner *et al.* 2009*). For the most part however, surface fires and mechanical treatments used by land managers to reduce fuel and to restore more fire-resilient stand structure generally contributed only a small fraction of the variation in measured properties within the larger context of variation that arose from topographic, edaphic and historical factors, or from interannual variation in climate and organism activity (Boerner 2006*).

The relatively light touch of fuel-reduction treatments on soils and the forest floor was consistent with the modest response observed for most vertebrate fauna. For example, little or no response was detected for avian daily survival rates (Gaines *et al.* 2010*, North-eastern Cascades), avian

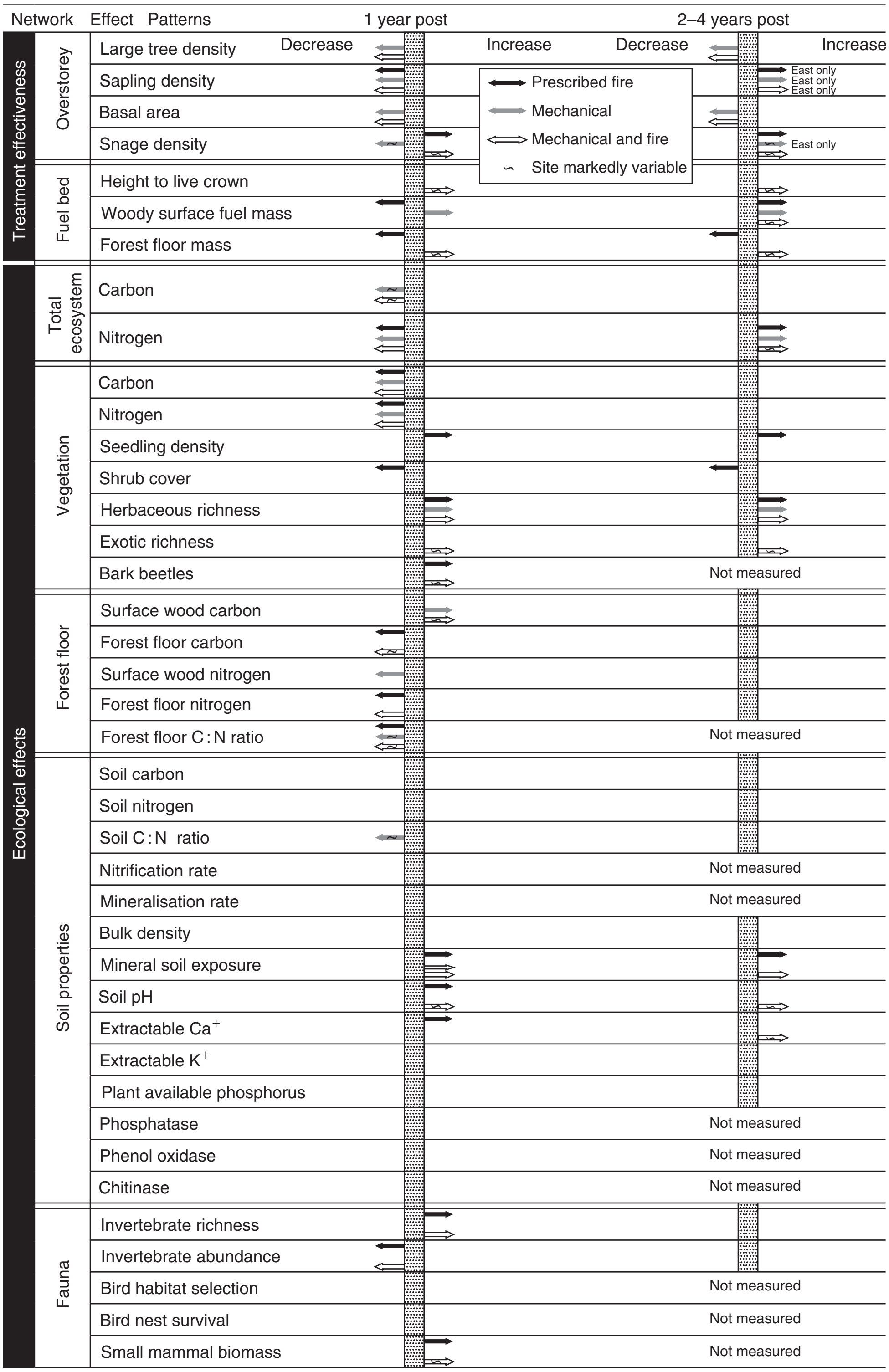

Fig. 2. Patterns of network-level directional response to fuel-reduction treatments of 40 principle variables immediately (<1 year), and 2–4 years, after application. Variables lacking directional arrow did not respond to treatment.

community structure (Woolf 2003*, Northern Rocky Mountains; Zebehazy *et al.* 2004*, South-eastern Piedmont), avian nest survival (Farris *et al.* 2010*a**, multi-site), small mammal abundance (Amacher *et al.* 2008*, Central Sierra Nevada; Greenberg *et al.* 2006*, Southern Appalachian Mountains), small mammal biomass (Converse *et al.* 2006*a**) or breeding bird, shrew or herpetofauna abundance (Greenberg *et al.* 2007*a**, 2007*b**; Greenberg and Waldrop 2008*, Southern

Appalachian Mountains). For the most part, vertebrates evaluated in this study were native species adapted to forests with frequent, low-intensity, patchy disturbance. Adaptations like dormancy and dispersal allow many species to avoid direct effects of disturbance, particularly at the time of year the treatments are typically applied. In addition, the patchy nature of fire provides spatial refuges within which species are shielded from direct effects, and from which species can recolonise after disturbance. Thus, measurements of flora and fauna response averaged to the stand scale will tend to mask lethal effects observed at much smaller scales. Finally, for many larger bodied or more mobile species like birds, experimental units were not large enough to capture meaningful population responses (Robinson 2010*), and this probably obscured many effects that might have emerged if treatments had been applied at larger scales. These considerations aside, across a broad spectrum of the ecosystem, treatment response tended to be subtle or non-existent, suggesting that a single entry of prescribed fire, mechanical treatment or mechanical + fire is unlikely to cause major or persistent changes in most ecosystem properties (Stephens *et al.* 2012*a**).

Even when significant treatment-induced changes were detected, more often than not conditions returned to pre-treatment levels in 1 to 3 years, indicating that most responses were not only subtle, but transient as well (Coates *et al.* 2008*; Boerner *et al.* 2009*). Thus, of 40 key variables measured immediately after treatment, 19 (47%) showed significant change after prescribed fire alone, 14 (35%) after mechanical treatment alone, and 22 (55%) after the mechanical + fire treatment (Fig. 2). Yet of the 30 key variables measured a second time at least 2 years following the first measurement, only eight (27%) were significant after fire alone, just five (17%) after mechanical alone, and only 12 after mechanical + fire treatment (40%). These results indicate that if managers want to elicit substantive change in dry forest ecosystems, they will have to apply treatments repeatedly at a high enough frequency to prevent rebound from the few subtle short-term changes that do occur.

Most available literature supports the FFS finding that standard fuel-reduction treatments generally cause modest effects on most components of dry forest ecosystems, that intensity of treatment correlates well with magnitude of effect and that variables that do respond tend to recover quickly to previous levels. For example, both Fulé *et al.* (2001) and Abella and Covington (2004) recorded very minor understorey effects of fuel-reduction treatments in northern Arizona ponderosa pine, with the former paper suggesting that drought or herbivory could have been responsible for observed changes. Similarly, Wilson *et al.* (2002), working in longleaf pine, suggested that landscape position explained more variation in soil carbon than did restoration treatments, concurring with the general finding that even repeated prescribed fire has little effect on this important variable (Moehring *et al.* 1966; McKee 1982; Richter *et al.* 1982). In fact, most studies in eastern deciduous forests have shown that forest floor variables generally respond little to fuel-reduction treatments (Wells 1971; Knoepp and Swank 1993; Johnson and Curtis 2001), with litter showing relatively more response than duff (Elliott and Vose 2005). Available literature on wildlife demonstrates similar patterns of response, with many studies finding that the most common factors explaining variation in response among treatments are site, interannual variation in population numbers, or heterogeneity in pre-treatment conditions (Kennedy and Fontaine 2009*). Of course, in the case of vertebrate species, which typically have relatively large home ranges, study plot size is a major contributing factor that constrains our ability to detect differences among treatments (Robinson 2010*; Robinson and Rompre 2010*).

The magnitude of measured response also tends to correlate well with the intensity of treatment. In a thorough meta-analysis, Wan *et al.* (2001) mention that fire severity is a major factor in explaining variation in soil chemical effects. Similarly, Crawford *et al.* (2001), Griffis *et al.* (2001) and Passovoy and Fulé (2006) suggest that responses of the understorey to prescribed fire treatments are likely to be much more subtle than those observed after wildfire. The same correlation has been observed for mechanical treatments, with Zenner *et al.* (2006) suggesting that much more intensive harvesting may be necessary to cause marked changes in the understorey, especially in forb and grass components. In terms of soil chemistry, the only study we could find that reported short-term losses of soil organic carbon examined effects after clearcutting (Carter *et al.* 2002), and estimates of nitrogen loss in vegetation at FFS sites were ~30–50% of those reported after clearcutting in western conifer forests (Mann *et al.* 1988) or in eastern deciduous forests (Clinton *et al.* 1996). Additionally, the very low soil compaction effects of mechanical treatments were somewhat lower than that reported in other studies (Rummer *et al.* 1997; Klepac *et al.* 1999), probably because FFS thinning was generally from below (small trees removed) and heavy machines visited only a fraction of the ground area. Finally, mechanical treatment had very little effect on invertebrates at any site, which contrasts with the nearly complete turnover in species composition of litter-inhabiting spiders after clearcutting in a western Oregon conifer ecosystem (McIver *et al.* 1992). Clearly, treatment intensity drives magnitude of response, and for the most part, fuel-reduction treatments applied a light touch to dry forest ecosystems, even for FFS sites (e.g. Southern Sierra Nevada) that experienced relatively intense prescribed fires.

Reports from other studies on effect duration were also consistent with FFS findings. Schoenagel *et al.* (2004) and MacKenzie *et al.* (2004) reported but short-lived shrub response to fire in other dry forests, and Harvey *et al.* (1980) showed rapid recovery of the understorey in giant sequoia (*Sequoiadendron giganteum*) groves. Findings from eastern forests are particularly telling, with rapid recovery commonly observed after treatment in the forest floor, the understorey (Wade *et al.* 1989), the fuelbed and in both vertebrate and invertebrate fauna. Clearly, it will require repeated application of both fire and mechanical treatment in most dry forest systems to maintain ecosystem trajectories that approach long-term restoration goals (Boerner *et al.* 2008*d**).

Fire surrogates

Mechanical treatment did not typically serve as a complete surrogate for fire for most ecological variables, across the spectrum of ecosystem components that were studied (Fig. 2).

This is largely because fire has unique effects on ecosystems and these effects cannot be simulated by changing forest structure in any other way (Hart *et al.* 2005*). This is clearly illustrated in an analysis of fuel treatment effects on carbon loss at six western USA FFS sites, in which mechanical-only treatments typically left higher levels of carbon in the fuelbed (forest floor and downed wood), compared with prescribed fire-only and the mechanical + fire treatments (Stephens *et al.* 2012*b**). Fire was also much more effective in killing small-diameter trees through direct effects (Kobziar *et al.* 2006*) and through the activities of bark beetles, which were preferentially attracted to burnt trees (Schwilk *et al.* 2006*; Youngblood *et al.* 2009*; Fettig *et al.* 2010*; Hessburg *et al.* 2010*). Enhanced bark beetle numbers in burned stands attracted bark-foraging birds, especially woodpeckers of the genus *Picoides* (Farris et al. 2010*b**). Prescribed fire exposed patches of mineral soil (Agee and Lolley 2006*; Boerner *et al.* 2009*) and increased light penetration to the forest floor, which altered habitat for ectomycorrhizal fungi (Smith *et al.* 2005*) and understorey plants (Metlen *et al.* 2004*; Phillips *et al.* 2004*; Albrecht and McCarthy 2006*; Collins *et al.* 2007*; Phillips and Waldrop 2008*), favouring species that preferred drier conditions. Fire caused differences in microbial functional diversity, with bacterial and fungal assemblages in burnt stands becoming respectively N- and C-limited, the opposite of thinned stands (Giai and Boerner 2007*). Fire created greater spatial heterogeneity within stands (Gundale *et al.* 2006*; Boerner *et al.* 2008*c**), due to capricious patterns of fire behaviour, patchiness of trees and surface fuels, variation in fuel moisture and percent bare ground and variation in fuelbed structure among tree species (Agee and Lolley 2006*; Knapp and Keeley 2006*). Fire had unique effects on soil and forest-floor nitrogen dynamics (Gundale *et al.* 2005*), and created patchiness in total inorganic nitrogen (TIN), which in turn led to increased within-stand plant species diversity (Gundale *et al.* 2006*). Heterogeneity in fire effects also enhanced habitat complexity for arthropods, resulting in higher species diversity, favouring species adapted to more xeric conditions (Apigian *et al.* 2006*a**; Ferrenberg *et al.* 2006*). In general, for the great majority of ecological variables, the mechanical + fire treatment tended to sort with the burn-only treatment, whereas the mechanical-only treatment tended to sort more with the un-manipulated control. The one exception to this general pattern was reported in a meta-analysis conducted on birds, in which 81% of the 31 species evaluated showed the same directional response to thinning *v.* low–moderate-severity prescribed fire (Fontaine and Kennedy 2012*). Although the studies evaluated were short term (<4 years) and small scale (stand-level), this analysis suggests that thinning may under certain conditions mimic habitat conditions created by prescribed fire.

Fire is well known to have unique affects on ecosystems that cannot be emulated with any other management action, including effects on soil and forest floor chemistry, exposure of bare mineral soil and creation of substantial within-stand heterogeneity (Kaufmann *et al.* 2000; Beaty and Taylor 2001; Hart *et al.* 2005*). In particular, several studies have demonstrated that available nitrogen generally increases immediately after prescribed fire, and that mechanical treatments have no such effect, except when stands are clearcut (Hart and Firestone 1989). Consumption of forest-floor layers increases the percentage of bare mineral soil, which offers necessary germination conditions for a wide variety of plant species, and creates more xeric habitat conditions for invertebrate and vertebrate fauna. The capricious nature of fire makes it difficult to fully control, but also results in much enhanced within-stand heterogeneity, which often leads to increases in richness of both plant and animal species. This is because many invertebrates (and presumably understorey plants as well) have populations that are structured on a relatively fine spatial scale, on the order of just 10–15 m (Niemela *et al.* 1996; Apigian *et al.* 2006*b**), which is similar to the scale of patchiness that fire generally creates (Knapp and Keeley 2006*). The link between plant species richness and total inorganic nitrogen has not been previously demonstrated (see Baer *et al.* 2004) but several studies have shown that composition of plant (Fitter 1982; Tilman and Pacala 1993; Reynolds *et al.* 1997) and animal communities (Sulkava and Huhta 1998) varies among resource patches at smaller scales, thus leading to higher diversity at the landscape scale. Similarly, the distinct differences in species composition produced by fire *v.* its mechanical surrogates can lead to higher landscape species richness (Metlen and Fiedler 2006*), if alternate treatments are applied in adjacent stands.

Tradeoffs

The multivariate design of the FFS study, in which several key ecosystem variables were measured simultaneously in the same plots, allowed us to assess potential tradeoffs that managers may want to consider when choosing among alternate fuel-reduction strategies. It is clear from multivariate work that components within dry forest ecosystems are in some cases tightly linked, through physical and chemical processes, and through biological interactions. We should therefore expect to identify management tradeoffs at times, because by chance alone we should observe 'desirable' outcomes at odds with undesirable ones, represented as they are by the variables we measure. We identified three such potential tradeoffs in which the short-term benefits of fuel reduction conflicted with other key issues: (1) although the application of prescribed fire is necessary to reduce surface fuels, this treatment also tends to reduce coarse woody debris resources, including snags and large diameter logs; (2) the intensity of treatment-induced disturbance is related to the cover and richness of exotic plant species and (3) prescribed fire has the potential to weaken high-value trees, and simultaneously attract bark beetles, which in some cases killed weakened trees.

At some sites prescribed fire, alone or in combination with the mechanical treatment, resulted in a loss of dead wood, specifically snags and coarse woody debris (e.g. Stephens and Moghaddas 2005*b**; Youngblood *et al.* 2008*; Hessburg *et al.* 2010*). Large diameter logs, both sound and rotten, serve as important critical habitat for ants, beetles and other invertebrates, which in turn provide food for a variety of vertebrate species (Bull 2002). In addition, large diameter snags are a critical resource for cavity-nesting birds and mammals (Harmon *et al.* 1986) and, together with other large woody resources, can serve as important general habitat for small mammal species (Kalies *et al.* 2012). It is for this reason that some authors have questioned the wisdom of applying prescribed fire across broad landscapes of the Interior West (Tiedemann *et al.* 2000), especially in forests with mixed fire-return intervals. It is likely however, that frequent-fire forests may never have supported high levels of snags or large down woody debris under more natural fire regimes. Evidence for this supposition stems from surveys of down woody material in pine forests that have maintained a more natural fire regime over time (Stephens *et al.* 2007). Also, because even very low-intensity prescribed fires tend to consume snags and large logs (Covington and Sackett 1984; Stephens and Finney 2002; Torgersen 2002), and because these kinds of fires are thought to have occurred frequently in seasonally dry forests, it is logical to assume that large-diameter woody resources would have been limited in the pre-settlement world. This is especially true for more decomposed log resources, because these are more completely consumed by low-intensity surface fires (Uzoh and Skinner 2009). Also, because fire effects tend to be spatially heterogeneous, at least some large-diameter woody material may remain in patches within most stands immediately after treatment, thus leaving some habitat for species that require the unique conditions offered by this resource. In any case, managers may want to consider how to balance the need for rapid fuel reduction with the consequences of decreased quality of faunal habitat, especially when there are threatened, endangered or sensitive species involved.

Although the mechanical + fire treatment provided the most rapid progress towards stand-structural goals, disturbance intensity associated with this treatment also caused the greatest increase in cover of exotic plant species (Dodson and Fiedler 2006*; Collins *et al.* 2007*; Dodson *et al.* 2007*; Bartuszevige and Kennedy 2009*; Schwilk *et al.* 2009*). Exotic plants can be ‘transformative’ and therefore capable of altering environmental conditions for other species (Dodson and Fiedler 2006*). Several studies have demonstrated increases in exotic plant cover or diversity after prescribed fire, in ponderosa pine forests of northern Arizona (Griffis *et al.* 2001; Fulé *et al.* 2005), the Black Hills of South Dakota (Wienk *et al.* 2004), in the Sierra Nevada (Kane *et al.* 2010), in coastal conifer forests of the Pacific Northwest (Thysell and Carey 2001) and in southern Canada boreal forests (Haeussler *et al.* 2002). Other studies however, have reported no differences in exotic plants before and after prescribed fire (Fornwalt *et al.* 2003; Wayman and North 2007), suggesting that mitigating factors may explain variation in response. These include pre-existing levels of exotic plant species in areas to be burned, or differences in prescribed fire intensity. Certainly, disturbance intensity can have marked effects on levels of exotic plant infestations, as indicated repeatedly in the FFS study with the mechanical + fire treatment, and in other studies with or without fire (Battles *et al.* 2001). Because exotic plant species can persist at sites for many years (Keeley *et al.* 2003), managers in weed-prone areas will want to consider the landscape context of the treated area, such as nearby roads, wildland–urban interface and previous exotic plant invasions (Bartuszevige and Kennedy 2009*), in order to mitigate introduction and spread of exotic plants.

At the five western FFS sites that experienced significant levels of bark beetle-caused tree mortality, the great majority of trees killed were small diameter (Stephens *et al.* 2012*a**), which is consistent with the management target for restoration (Six and Skov 2009*; Fettig *et al.* 2010*). However, large-diameter trees were occasionally killed by bark beetles as illustrated with a structural equation model developed by Youngblood *et al.* (2009)*, working at the Blue Mountains site. The model examined how treatment-induced changes in the fuelbed influenced ponderosa pine mortality as caused by bark beetles. In particular, the mechanical portion of the mechanical + fire treatment increased the mass of both 100-h and 1000-h fuel, and later burning of these fuels resulted in higher mean fire temperatures, more severe bole charring of trees and higher mortality of both large and small trees due to bark beetles (Fig. 3). Interestingly, tree mortality was primarily attributed to wood borers, which are not typically known to be mortality agents of ponderosa pine. In general, whenever fire is reintroduced into dry forest stands after a long absence, large-diameter trees may be lost, because accumulated duff at the base of trees may support smouldering combustion, which may in turn kill fine roots and predispose trees to subsequent attack by bark beetles (McHugh and Kolb 2003; Parker *et al.* 2006). Although we saw no evidence of smouldering duff combustion contributing to bark beetle-caused tree mortality of large trees, managers may want to consider protecting large trees in high value areas like campgrounds or historical old-growth stands, especially if there is evidence of high levels of slash or deep layers of duff at the base of these trees. Finally, although bark beetles contribute to short-term increases in levels of tree mortality, they can be regarded as keystone species from an ecosystem perspective. For example, bark beetle populations attract woodpeckers that in turn create cavities for other wildlife species, disperse wood-decaying fungi, and thereby help accelerate decomposition of snags (Farris *et al.* 2004).

Habitat effects

Any significant management action is likely to favour some species over others, mostly through changes in habitat brought about by manipulation of stand structure, the fuelbed and the forest floor. For the most part, species responded to fuel-reduction treatments in a manner consistent with their life history characteristics, demonstrating adaptation to frequent, low-intensity fire (Metlen *et al.* 2004*). The conditions created by fire, such as increased light and heat at the forest floor (Huang *et al.* 2007*; Joesting *et al.* 2007*), exposed bare mineral soil (Boerner *et al.* 2009*), decreased shrub cover but increased grass cover (Collins *et al.* 2007*; Sharp *et al.* 2009*) and increased within-stand heterogeneity (Gundale *et al.* 2006*; Knapp and Keeley 2006*), favoured species that can thrive under drier microhabitat conditions (Metlen *et al.* 2004*; Boerner 2006*; Greenberg *et al.* 2007*a**; Phillips and Waldrop 2008*; Kilpatrick *et al.* 2010*).

Changed conditions within stands can influence species composition and diversity for a wide spectrum of organisms, including plants, invertebrates and vertebrates. For example, working at the North-eastern Cascades site, Dodson and Peterson (2010)* reported that all active treatments, especially those including fire, tended to increase plant species diversity, through enhanced colonisation of disturbance-adapted species, and reduced abundance (but not extirpation) of extant species that

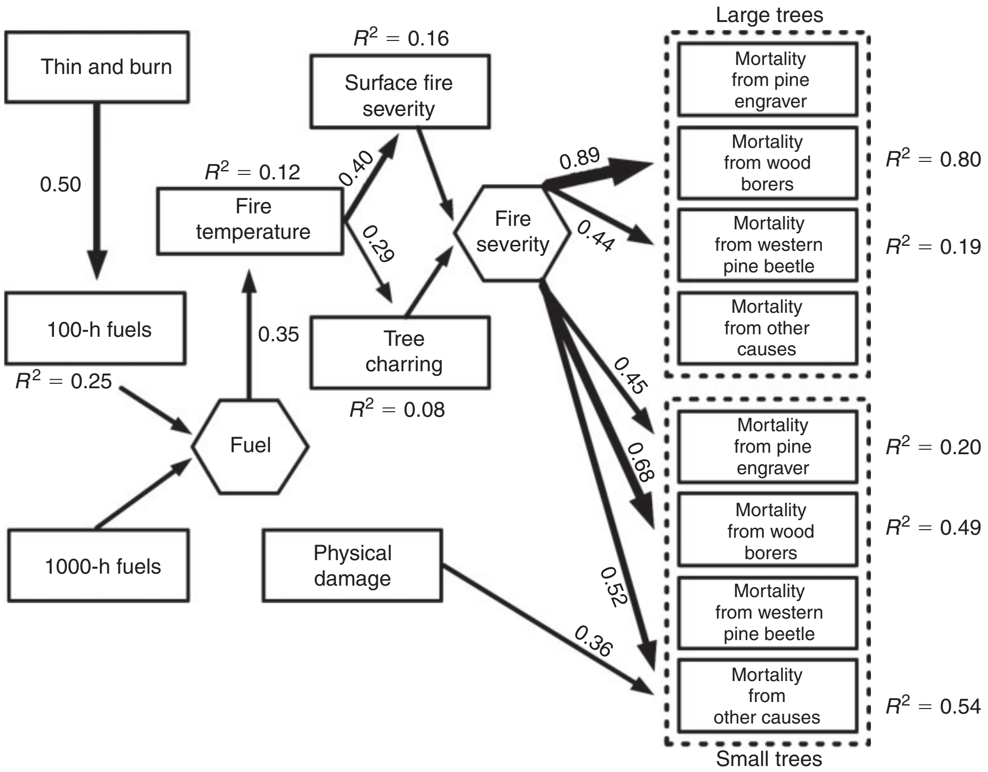

Fig. 3. Structural equation model results for large and small ponderosa pine mortality. Overall model Chi-square = 7.86 with $P = 0.10$, indicating no major deviations between data and model. Rectangles represent observed variables, whereas hexagons represent composites summarising the effects of multiple predictors on individual responses. Only significant pathways are shown. Path coefficients presented are standardised values. Observed variables with pseudo-R^2 values are response variables for mortality.

favoured more mesic conditions. At the Central Appalachian Plateau site, Joesting *et al.* (2007)* demonstrated that chestnut (*Castanea* sp.) seedlings responded favourably to the increased light conditions of the mechanical-only treatment, by increasing their net rate of photosynthesis. At the Northern Rocky Mountain site, Dodson *et al.* (2007)* demonstrated that although overall native plant species diversity was generally enhanced by all treatments, burning in particular increased the prevalence of short-lived species, which depend on disturbed conditions on the forest floor (exposed mineral soil; light and heat penetration) to persist in stands that harbor more competitively dominant species (Steele and Geier–Hayes 1987). At the Central Sierra Nevada site, burning increased patchiness of mineral soil within stands, which was sufficient to favour leaf litter arthropod species that prefer more xeric conditions (Apigian *et al.* 2006*a**). Similarly, treatments that reduce leaf-litter depth and shade can reduce relative abundances of vertebrates like shrews and salamanders in the short term (Greenberg *et al.* 2007*a**; Matthews *et al.* 2009*, 2010*), probably because these conditions offer fewer refuges from predation and present significant osmoregulatory challenges to smaller individuals. In contrast, the same treatments can provide thermoregulatory opportunities for vertebrates like lizards, who rely on basking to elevate body heat for efficient foraging (Matthews *et al.* 2010*). Burning-induced changes in the distribution of vegetation and other structural elements of stands can also shift the relative proportion of bird nesting guilds, from a predominance of canopy, shrub and ground nesting guilds in thinned or control stands (Zebehazy *et al.* 2004*) to cavity-nesting species in burned stands (Lyons *et al.* 2008*; Farris *et al.* 2010*b**). The fact that uncommon, disturbance-dependent species were often favoured by the application of fire (Apigian *et al.* 2006*a**; Dodson *et al.* 2007*; Sharp *et al.* 2009*) suggests that over the years lack of fire had allowed these systems to shift considerably towards more mesic conditions, thus favouring species that thrive in disturbance-free environments. Presumably, repeated application of prescribed fire over time will lead to a more balanced community structure for most organism groups, including species that thrive in disturbance-free patches and those that depend on the conditions created by disturbance, a group that includes many threatened, endangered and sensitive species (Satterthwaite *et al.* 2002; Norden and Kirkman 2004; Menges *et al.* 2006). A good example of this was reported by Campbell *et al.* (2007)*, who observed that the rare Diana Fritillary (*Speyeria diana*) seems to favour stands treated both mechanically and by burning, which suggests that widespread application of fuel-reduction treatments may help restore healthier populations of rare species that have declined in the era of fire suppression.

Most available literature supports the FFS conclusion that fuel-reduction treatments tend to initially favour plant species that are adapted to low intensity disturbance, through complex changes in the canopy, the understorey, the forest floor and the soil. Mechanical treatments tend to reduce overstorey cover, which increases light penetration to the forest floor and opens up resources for competing plant species. Understorey plant species that can better tolerate increased light and heat, and can opportunistically seize suddenly available resources tend to be favoured, particularly short-lived (Merrill *et al.* 1980; Laughlin *et al.* 2004; Fulé *et al.* 2005) and early successional species (Jenkins and Parker 1998). Disturbances can also favour short-lived, opportunistic species by decreasing or extirpating late successional species (Halpern and Spies 1995; Battles *et al.* 2001; Grant and Loneragan 2001). Finally, after observing that fuel-reduction treatments favour pioneer bryophyte species, Hardman and McCune (2010) suggest that these kinds of species perform a valuable ecosystem service of stabilising the soil surface immediately after disturbance, thereby reducing its vulnerability to erosion.

Exactly how structural changes in different layers of the forest might influence animal species can be difficult to determine. This is partly because habitat requirements for most species are poorly known, but also because treatments can have both direct, immediate effects and indirect, lagged effects. For example, opening the canopy by overstorey thinning is a direct way to immediately increase light penetration to the forest floor (Wilson *et al.* 1995; Conner *et al.* 2002; Wood *et al.* 2004) but an indirect result of this is that forest floor herbaceous cover can increase shortly thereafter (Riegel *et al.* 1995; Wayman and North 2007). Thus, as long as mechanical treatment leaves the forest floor intact, species like south-eastern shrews (*Sorex longirostris*) and most salamanders will tend to be favoured by this practice, even if more light reaches their habitat (Pough *et al.* 1987; Petranka *et al.* 1993). In addition, species like certain butterflies will also tend to be favoured to the extent that increased herbaceous vegetation provides greater nectar resource (Thill *et al.* 2004; Campbell *et al.* 2007*).

Burning, in contrast, tends to remove both the understorey and the forest floor in the short term, which tends to favour ground-dwelling species like lizards and snakes (Zug 1993; Perison *et al.* 1997; Matthews *et al.* 2010*), which prefer bare mineral soil for basking and to facilitate movement (Renken 2006). In contrast, species that require high levels of ground-level moisture, such as shrews and salamanders, may decline in the short term (Matthews *et al.* 2009*, 2010*). However, over time, regrowth of the understorey and accumulation of litter will shift the balance back towards more mesic habitat conditions even for treatments that cause the greatest initial disturbance (i.e. thinning + burning; Matthews *et al.* 2009*). This dynamism is the principle reason why time since treatment is such a critical variable when sampling animal populations – most native species will not only tend to rebound quickly after treatment (e.g. Vickers 2003*) but species mixes will be in constant flux due to shifting habitat conditions over time.

In dry forest systems in which fire has been excluded for several cycles, species richness of both plants and animals tends to increase with fuel-reduction treatment, because higher quality habitat for disturbance-adapted species suddenly becomes available (Fiedler *et al.* 1992; White and Jentsch 2001). In particular, uncommon species tend to increase in abundance because disturbance re-establishes conditions and processes that are critical features of their evolutionary history (Dodson *et al.* 2007*). In fact, fire exclusion has been implicated as a major factor in reduced understory species richness in frequent-fire forests of the western US (ponderosa pine, northern Arizona, Covington and Moore 1994; Fulé *et al.* 1997; ponderosa pine, Black Hills, South Dakota, Laughlin *et al.* 2004; Wienk *et al.* 2004). This same pattern has been observed for invertebrates, with most increases in species number occurring within the subset of species that favour higher levels of disturbance (Apigian *et al.* 2006*a**). Findings from the FFS study and the supporting literature are therefore consistent in concluding that reintroduction of fire into dry forest systems will result in habitat shifts and enhanced heterogeneity that will likely result in more balanced species compositions of both plants and animals.

Restoration

To date, the FFS study has measured only short-term effects of alternative fuel-reduction treatments, with insufficient time having elapsed since treatment to assess long-term progress toward restoration goals (McIver and Weatherspoon 2010*). Nevertheless, measurements taken up to 4 years after treatment are sufficient to make four distinct predictions on what might happen if managers embark on long-term restoration plans in dry forest systems: (1) Restoration of conditions similar to those thought to have prevailed before settlement will require persistent management, featuring repeat entries of both mechanical treatment and prescribed fire; (2) eastern forests will require much more frequent applications of both mechanical treatment and fire, due to their greater productivity and the need to control a more diverse set of competing plant species; (3) application of mechanical treatments alone may gradually cause dry forest systems to diverge from states maintained by fire alone, despite the observation of generally subtle effects of both treatments in the short term and (4) long-term monitoring of key ecosystem components needs to accompany persistent management, in order to gauge whether or not projected goals are met, and to make course corrections if needed.

Overall, FFS findings indicate that meaningful progress towards long-term restoration goals will benefit from a management scenario that features repeat entries of both prescribed fire and mechanical treatments over time (Boerner *et al.* 2008*d**; Iverson *et al.* 2008*). It is clear that unless prescribed fire can be applied frequently enough and with a high enough intensity to remove vegetation that has encroached with fire suppression, mechanical treatments will at least occasionally be needed to maintain overstorey density and basal area at desirable levels (Fiedler *et al.* 2010*; Youngblood 2010*). Prescribed fire needs to be applied more frequently because this practice influences components (fuels) that have a higher turnover rate than those influenced by mechanical treatment (overstorey). This finding stems from the consistent observation that even the most aggressive fuel-reduction treatments have subtle and transient effects on most key ecosystem variables (Fig. 2). Several understorey studies support this finding, indicating that multiple entries are needed to restore systems to within the historical range of variability (Harrington and Edwards 1999; Metlen and Fiedler 2006*; Iverson *et al.* 2008*; Waldrop *et al.* 2008*). For example, Laughlin *et al.* (2008) reported that it took 11 years of multiple prescribed fires to restore historical understorey community structure in a ponderosa pine-bunchgrass system. Similarly, Dey and Hartman (2005) noted that multiple fires were necessary in younger dry oak forests in the Missouri Ozarks to favour oak and hickory (*Carya* sp.) relative to their competitors. In some cases however, restoration goals may be even more difficult to achieve: Waldrop *et al.* (1992) reported that 43 years of frequent burning (3–5-year intervals) in pine forests of the southern coastal plain did little to change understorey plant species composition.

Seasonally dry forests of the eastern US differ from western forests in many ways, but most importantly, they tend to be more productive and diverse. Greater productivity means that eastern forests rebound more quickly after disturbance, and therefore require much more frequent application of restoration treatments. In particular, high decomposition rates in hardwood forests can return fine-fuel mass to initial conditions within a few years (Graham and McCarthy 2006*) and rapid sprouting and growth of undesirable species can quickly return stands to initial conditions (Waldrop *et al.* 2008*; Outcalt and Brockway 2010). In fact, during the FFS study period, four of the five eastern sites required at least two prescribed fires (Table 1), whereas none of the seven western sites demonstrated rebound from disturbance that was significant enough to require re-entry by the end of the study period (2008).

Although it is true that even fairly aggressive mechanical or burning treatments caused subtle and transient effects for most variables, it is also true that mechanical treatments were not surrogates for fire in many cases. Therefore, if two equivalent stands received persistent application of either mechanical treatment or burning at a high enough frequency to prevent rebound, the two stands would diverge from one another within two or three treatment cycles. It is for this reason that restoration towards conditions thought to prevail before European settlement will only occur with both burning and mechanical treatments applied in tandem: burning because fire is such a unique process and cannot be emulated in any other way (Weaver 1943), and mechanical treatment because overstorey adjustments will occasionally need to be made due to constraints placed on the intensity of prescribed fire. Of course, if current constraints on prescribed fire operations were relaxed such that summer burns were possible, burning by itself could probably be used in some cases to maintain stand structure over time.

Evidence from the short-term measurements of the FFS identifies the need for repeat entries over time, in order to achieve long-term restoration goals. But it would be unwise simply to extrapolate observed short-term responses over longer periods of time, because trajectories of many variables may be non-linear. For example, in a study of oak flatwoods that had been burned every 3–4 years for 30 years, Vance and Henderson (1984) measured reduced nitrogen mineralisation rates and attributed these to slow but persistent changes in the *quality* of organic matter, possibly through conversion of carbon into more recalcitrant forms (like charcoal) over time (Ponomarenko and Anderson 2001). Another reason why short-term results may not scale to the long term is that weather patterns observed in a short-term study may turn out to be a primary factor in explaining results. A possible example of this is the contrasting results on long-term understorey response to treatment, in which Busse *et al.* (2000) and Laughlin *et al.* (2008) found significant and lasting effects, whereas Fulé *et al.* (2002) did not, and attributed lack of response to a prolonged drought in northern Arizona during the study period. In any case, to the extent that repeat entries cause changes in the quality of other variables as well, the subtle and transient short-term effects measured in the FFS study will not necessarily scale linearly over longer periods of time. Only long-term monitoring will provide meaningful, reliable information on the effects of land-management scenarios that are implemented for the long term (Boerner *et al.* 2008*c**; McIver and Weatherspoon 2010*).

Conclusion

Current conditions of many seasonally dry forests in the US leave them uncharacteristically susceptible to high-severity wildfire. Alternative fuel-reduction treatments have been used for decades to mitigate fire hazard in these forests. The National Fire and Fire Surrogate study was designed to bolster information on how these practices influence whole ecosystems.

When applied under prescription, both surface fire and its mechanical surrogates are generally successful in meeting short-term fuel-reduction objectives, changing stand structure and fuelbeds such that treated stands are potentially more resilient to moderate-intensity wildfire. Mechanical treatment followed by prescribed fire is most effective in altering stand structure, reducing fuels and lowering fire hazard, but both mechanical treatment and prescribed fire alone can reduce potential fire intensity in some cases.

Most available evidence suggests that these desirable objectives are typically accomplished with few unintended consequences, as most ecosystem components exhibit very subtle effects, or no measurable effects at all. Significant effects are more prevalent and lasting in the vegetation, followed by the forest floor, dead wood and soils. Whereas exotic plants tend to increase with levels of treatment disturbance, overall understorey species richness also increases, especially fire-adapted plants and those plants that are favoured by more open, xeric forest floor conditions. Though mineral soil exposure, pH, exchangeable cations and total inorganic nitrogen respond to treatment in the short term, initial changes tend to disappear or diminish after only a few years. Other soil variables including bulk density, soil carbon, dead wood carbon and soil nitrogen exhibit extremely subtle response to treatment. Bird species show subtle response as well, but bark-foraging and cavity-nesting birds tend to be more attracted to stands that received a burning treatment. Invertebrate communities also exhibit subtle short-term response, but fire tends to cause distinctly different effects compared with mechanical treatment, primarily because fire creates much more patchy forest-floor conditions. Although bark beetles often take advantage of fire-weakened trees, and can therefore cause additional tree mortality, the percentage of trees killed by beetles is usually very low and tends to be limited to smaller-diameter trees.

Desired treatment effects on stand structure and fuels tend to be transient, just like effects on most other ecosystem variables, indicating that once fuel-reduction management starts managers need to be persistent with repeat entries into the future, especially in the faster-growing eastern forests. For most variables, mechanical treatments are not surrogates for fire, and so if mechanical treatments are consistently applied alone, stands may diverge considerably over time compared with stands that receive at least occasional prescribed fire.

In general, results of the multisite, multivariate National Fire and Fire Surrogate study indicate that although certain treatment-related tradeoffs within ecosystems are inevitable (e.g. treatment intensity *v.* exotic plant species or coarse woody material) land managers can move forward with fuel-reduction work, confident that these practices will be unlikely to cause substantial unintended consequences in seasonally dry forest ecosystems in the short term. Because mechanical treatments are not complete surrogates for fire, however, and because most effects tend to be transient, repeat treatments that include at least occasional prescribed fire will be necessary to restore dry forest systems in the long run.

Finally, it is important to note that because dry forest ecosystems are so idiosyncratic, and because the exact pattern of weather before and after treatment will likely influence details of treatment response, it will always be difficult to predict exactly what will happen when alternative fuel-reduction treatments are applied. Fortunately, we already have a tool that allows managers to adjust prescriptions through time, based on what they see after prior treatments. Adaptive management, applied with a blend of scientific rigor and management practicality, can lead managers through the long process of restoration even in systems that are complex and dynamic. Variables chosen to measure need not be extensive but would probably need to include variables that validate treatments, variables that reflect damage to the soil resource, and variables that monitor key species such as invasive plants and TES species.

The analyses conducted by FFS researchers were extensive and deep for most sites and for most ecosystem components. Nonetheless, numerous opportunities are available for further analysis with the existing dataset, particularly in the realm of multivariate studies that would likely be successful in identifying and elucidating relationships among variables within and among ecosystem components. Consequently, the entire FFS database, complete with explanatory meta-data, is now available at the US Forest Service Data Repository (http://www.fs.usda.gov/rds/archive/, accessed 21 September 2012).

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