Post-fire Burn Severity and Vegetation Response Following Eight Large Wildfires Across the Western US

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ABSTRACT

Vegetation response and burn severity were examined following eight large wildfires that burned in 2003 and 2004: two wildfires in California chaparral, two each in dry and moist mixed-conifer forests in Montana, and two in boreal forests in interior Alaska. Our research objectives were 1) to characterize one-year post-fire vegetation species richness and percent canopy cover, and 2) to use remotely-sensed measures of burn severity to describe landscape-level fire effects. We correlated one-year post-fire plant species richness and percent canopy cover to burn severity and to soil surface cover immediately after the fires. For all eight wildfires, plant canopy cover and species richness were low and highly variable one year post-burn. We found a greater number of forbs when compared to other plant life forms, independent of burn severity. Plant cover was dominated by grasses in chaparral systems, by forbs in mixed-conifer forests, and by shrubs in boreal forests. Variation among sites, fine-scale variability in post-fire effects on soils, and diversity of prefire vegetation likely explain the high variation observed in post-fire vegetation responses across sites and burn severities. On most low and moderate burn severity sites, >30% of the soil surface was covered with organic material immediately post-fire, and one year later, the canopy cover of understory vegetation averaged 10% or more, suggesting low risk to post-fire erosion. In CA, MT-NW and MT-W, 5% or less burned with high severity, while in AK, 58% was mapped as high burn severity. All fires had a mosaic of different burn severities (as indicated by delta Normalized Burn Ratio, dNBR) with highly variable patch size (mean 1.3 to 14.4 ha, range from <1 to over 100,000 ha).

KEYWORDS: Fire effects, delta Normalized Burn Ratio, dNBR, species richness, species diversity

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INTRODUCTION

Ecologists have long recognized the enormous variability in fire effects and vegetation response that results from large wildfires. Burn severity (Lentile *et al.* 2006, Jain *et al.* 2004, Ryan and Noste 1985) classifications are used to infer fire effects on soil and vegetation, potential successional trajectories, and rates of ecosystem recovery. Because large fires are heterogeneous in their effects across the landscape, such events provide ideal opportunities for characterizing initial fire effects and vegetation recovery across the range of burn severities. It is the inherent variation following disturbance that challenges fire ecologists to identify unifying trends in burn severity and post-fire soil and vegetation response, without losing the fine-scale and localized information that land managers need to support post-fire decisions.

This study was part of a rapid response research (Lentile *et al.* in press*)* project designed to address how fire effects on soil and vegetation differ with burn severity, and to identify measures of immediate post-fire effects that indicate the degree of fire effects on soil and the vegetation response over time. Our research team sampled eight large wildfires, all selected for extended burning over several days to weeks across a diversity of vegetation, soils, and topographic conditions and where satellite images were available for the burned landscape. With the help of the fire incident management teams, we identified locations where we could safely establish research plots to sample within a few weeks post-fire (also see Hudak *et al.* this issue, Lewis *et al.* this issue), and we sampled the same sites again one year later.

The specific objectives of the research reported here were 1) to characterize one year post-fire vegetation recovery, and 2) to use remotely-sensed measures of burn severity to describe landscape-level fire effects. We sought to characterize understory plant vegetation response in areas of different burn severity and to determine which immediate post-fire effects on the soil surface serve as good indicators of one year post-fire soil and vegetation response (and thus, ultimately longer-term post-fire ecosystem recovery). Many fire ecology studies must rely on retrospective reconstruction of immediate post-fire condition. This study is unique for examining vegetation response relative to burn severity using consistent methods across eight large wildfires.

BACKGROUND

Burn severity influences injury and mortality of plants and the rate of reestablishment of resprouting species (Lyon and Stickney 1976; Ryan and Noste 1985; Morgan and Neuenschwander 1988; DeBano *et al.* 1998). Whether the removal of some vegetation and altered soil surface conditions is favorable to vegetation depends upon the characteristics of the plant species on the site, their susceptibility to fire, and the means by which they recover after fire (Mutch 1970; Lyon and Stickney 1976; Anderson and Romme 1991; Turner *et al.* 1998). Alterations to light and nutrient regimes following fires may have major implications for understory plant and seedling recovery in burned stands. We expected greater reductions in understory plant species richness and cover in areas burned more severely, and resprouting to dominate one-year vegetation response.

Plant regeneration may occur from on-site seeds, from off-site seed sources, or from resprouting from deeply buried root and stem structures (Lyon and Stickney 1976). Seed production, and therefore, understory plant community composition and abundance are temporally and spatially variable, and likely influenced by site conditions, the pre-fire plant community, and the post-fire climate (Whelan 1995). Relative to high burn severity, we expected quicker recovery of plant cover in low and moderately burned areas due to on-site sources for plant regrowth (sprouts) and establishment (seeds) after fire. Post-fire forest floor conditions are an important determinant of post-fire vegetation recovery, as this determines the amount of bare soil. Litter accumulation may be higher in areas of greatest crown scorch, but lowest where needles were consumed. Scorched needles help to reduce post-fire erosion rates when they blanket the soil surface (Pannkuk and Robichaud 2003). Similarly, the recovery of vegetation is likely to differ by plant functional groups (e.g., moss, grass, forb, or shrubs) (Rowe and Scotter 1973). Lower plant species richness was correlated with significant duff consumption in recent wildfires in ponderosa pine forests (Laughlin *et al.* 2004). Thus, we expected plant species richness and abundance to be lowest where litter and duff were consumed.

Identification of indicators of burn severity, and thus potential ecosystem recovery, could prove useful to post-fire planners tasked with strategically rehabilitating areas likely to recover slowly or in undesirable ways. Remotely-sensed data provide one means by which managers can quickly and consistently evaluate burned areas and identify areas in need of rehabilitation treatment to prevent erosion and weed establishment (Lentile *et al.* 2006). In general, remotely sensed data more accurately depict post-fire changes in overstory tree canopy than understory or forest floor changes (Hudak *et al.* this issue).

METHODS

Study Sites

We sampled two wildfires in each of four different geographic areas. For a map of site locations, see Hudak *et al.* (this issue).

Our California (CA) sites were dominated by chaparral vegetation and included the Simi (34° 16' 56" N, 118° 49' 56" W, centroid; elevation 46 to 1118 m) and Old fires (34° 11' 37" N, 117° 15' 17" W, centroid; elevation 396 to 2030 m) that burned in southern California during the fall of 2003. The Simi Fire began on 25 October 2003 and burned 43,800 ha in Ventura and Los Angeles Counties, while the Old Fire began on 28 October 2003 and burned 23,300 ha north of San Bernadino, California. The Simi Fire burned in a mix of vegetation types including chaparral, coastal sage scrub, and annual grasslands across a diversity of topographic conditions including rolling hills and very steep, rocky terrain, where annual precipitation is variable, but generally less than 50 cm. The Old Fire burned in chaparral mixed with interior woodlands, also on rough terrain.

Chaparral is a shrubby, sclerophyllous vegetation type that is common in middle elevations throughout much of California (Barro and Conard 1991). Chaparral vegetation is highly adapted to stand-replacing fires that were historically common in this ecosystem (Hanes 1977; Keeley 2006b). Common chaparral trees and shrub genera include *Adenostoma, Arctostaphylos, Ceanothus, Cercocarpus, Prunus, Quercus*, and *Rhamnus.* Ground cover is relatively sparse when shrubs are dominant, and forb (e.g., *Phacelia, Penstomen, Mimulus* species) and grass species are common in these ecosystems following fire. The presence of native forbs and grasses tend to be ephemeral (<2 years), although non-native post-fire invaders, including *Bromus diandrus*, *Bromus tectorum*, *Centaurea solstitialis*, *Erodium* species, and *Trifolium hirtum,* may persist longer (Keeley 2006b). Chaparral plant adaptations to fire include post-fire root sprouting, prolific seeding, seed banking, fire-related germination cues, and allelopathy (Hanes 1977; Keeley 2006b). The combined effects of frequent human and natural ignitions, hot dry summers, rainfall limited to mostly the winter, and the high flammability of chaparral vegetation due to volatile compounds and seasonally low fuel moisture (Roberts *et al.* 2006) make these ecosystems susceptible to intense fires (Barro and Conard 1991; Keeley 2000; Keeley and Fotheringham 2001).

Our western Montana (MT-W) sites were dominated by dry forests and included the Black Mountain II (46° 50' 29" N, 114° 10' 41" W, centroid; elevation 1072 to 1743 m) and Cooney Ridge fires (46° 40' 10" N, 113° 49' 27" W, centroid; elevation 1247 to 2167 m) that burned in western Montana during the fall of 2003. The Black Mountain II fire began on 8 August 2003 and burned 2,854 ha. The Cooney Ridge fire began on 8 August 2003 and burned 8,589 ha. The Black Mountain II and Cooney Ridge fires burned in mixed-conifer forests of *Larix occidentalis, Pinus contorta, Abies lasiocarpa, Pseudotsuga menziesii*, and *Pinus ponderosa* with understories of *Xerophyllum tenax, Physocarpus malvaceus,* and other species. These lower subalpine forests are generally located on sites with average July temperatures ~ 17 ° C, and mean annual precipitation ranges from 50 to 125 cm with much falling as snow (Cooper *et al.* 1991). In general, mixed-conifer forest sites like these were historically burned by mixed-severity fires. Here and in the other sites, fire frequency and severity are related to climatic and topographic effects such as wind, temperature, humidity, elevation, and aspect (Fischer and Bradley 1987, Agee 1993), as well as to fire suppression and past land uses.

Our northwestern Montana (MT-NW) sites were dominated by moist forests and included the Robert (48° 31' 14" N, 114° 2' 49" W, centroid; elevation 975 to 1961 m) and Wedge Canyon fires (48° 54' 22" N, 114° 24' 14" W, centroid; elevation 1141 to 2414 m). The Robert fire began on 23 July 2003 and burned 23,297 ha, while the Wedge Canyon fire began on 18 July 2003 and burned 21,519 ha. Both fires burned in Flathead County on private and state lands and on federal lands managed by the Flathead National Forest and Glacier National Park. The Robert and Wedge Canyon fires burned in mid-elevation, moist, mixed-conifer forests of *Tsuga heterophylla, Thuja plicata, Larix occidentalis, Abies lasiocarpa, Pseudotsuga menziesii, Pinus monticola, Pinus contorta*, and *Picea engelmannii* with understories of *Vaccinium species, Xerophyllum tenax, Chimaphila umbellate,* and other species. Sites sampled in these forests are relatively moist, receiving 50 to 80 cm of mean annual precipitation. The relatively deep soils with higher moisture holding capacity make these sites effectively more mesic than the MT-W sites. Fire regimes for these forests are described as moderate frequency (fire return interval of 78 years (Fischer and Bradley 1987)) and mixed-severity. Mixed-severity regimes may include individual fires that create variable fire effects in a fine-scale mosaic of stand-replacing and surface fire (Agee 1998, 2005; Arno *et al.* 2000).

Our Alaska (AK) sites included the Porcupine and Chicken fires that burned in boreal forests. The Porcupine and Chicken fires (AK) burned and eventually merged, along with the Billy Creek and Gardiner Creek fires, to form the Taylor Complex (478,274 ha) (63° 43' 28" N, 142° 50' 36" W, centroid; elevation 424 to 1529 m) in interior Alaska during the summer and fall of 2004. The Porcupine fire began on 21 June 2004 and burned 115,171 ha. The Chicken fire began on 15 June 2004 and burned 173,651 ha. The Porcupine and Chicken fires burned in interior moist forests of *Picea glauca*, *Picea mariana*, *Populus tremuloides*, *Betula papyrifera*, *Salix* species, and *Alnus* species with deep mats of *Hylocomium splendens* (feather moss) and other mosses. Historically, wildland fires in the boreal forest tended to burn infrequently, as conditions were commonly too wet to burn. These fires tended to burn slowly, over long periods of time, and to create a patchy mosaic of fire effects that are generally stand-replacing in black spruce forests and non-lethal in hardwood forests (Foote 1983). Recent fires have severely burned large expanses of land and, in some cases, exposed permafrost and consumed future seed sources.

Vegetation response field data

Preliminary Burn Area Reflectance Classification (BARC) maps were used as guides to identify potential field sites. Field sites were classified as low, moderate, or high severity if tree crowns were predominantly green, brown, or black, respectively, as called in the field. Sites were selected within areas large enough to include many 30-m Landsat satellite image pixels and be broadly representative of the range of post-fire conditions occurring across the post-fire landscape. Field site centers were placed a random distance away from and on a compass bearing perpendicular to nearby access roads.

Forty-six sites (Table 1) were established immediately post-fire across the full range of burn severities. Our design was unbalanced, as we purposefully sampled more sites in low and moderate severity because we expected the fire effects and vegetation response to be more heterogeneous for these classes than for high burn severity.

Sites consisted of nine plots systematically arranged to span a 130 m x 130 m area, with plots composed of fifteen 1 m x 1 m subplots sampling a 9 m x 9 m area. Sites were oriented according to slope direction. Surface cover fractions of charred organic material (litter, duff, and dead wood), total organic material (charred and uncharred litter duff, and dead wood, but not green vegetation which was estimated separately), bare mineral soil and ash were ocularly estimated at all 135 subplots as soon as possible following fire. One year post-fire, understory species composition and cover were inventoried in four subplots per site. Site locations and the systematic plot/subplot layout are described in more detail by Hudak *et al.* (this issue).

Landscape patterns of burn severity

Landsat data were used to calculate the delta Normalized Burn Ratio (dNBR) (Key and Benson 2002) on images taken one year before fire and immediately post-fire. All the images were provided by either USFS Remote Sensing Application Center (Montana and California fires) or USGS (Alaska fires). Each image was already rectified geometrically and radiometrically, and calibrated to top-of-atmosphere reflectance, following accepted preprocessing procedures (http://landcover.usgs.gov/pdf/image_preprocessing.pdf).Values were classified according to unburned, low, moderate, and high burn severity thresholds established by Key and Benson (2002). An edge-smoothing utility was applied to smooth class boundaries defined by the dNBR classification and basic patch metrics were generated using ArcGIS (ESRI, Redlands, CA). Size distributions for patches of different burn severity were compared with a nonparametric multi-response permutation test (Mielke and Berry 2001). Multiple comparisons for the multi-response permutation tests were based on Peritz closure (Petrondas and Gabriel 1983) and tested for significance at the 95% confidence level.

RESULTS

Vegetation response

On all eight wildfires, post-fire vegetation responded quickly. However, understory plant canopy cover was low one-year post-burn (Figures 1 and 2). Total species richness was high in each of the four ecosystems with 10 to 50 different species (Figure 1). The variability in species richness was so high that the differences were not significantly different ($p>0.05$). Most plant species found on burned sites in CA were non-native, whereas few non-native species were observed on plots in other sites.

Grasses, forbs and shrubs established soon after the fire (Figure 2). In sites burned with low burn severity, one year post-fire, grass cover was important in the chaparral (CA) and dry forests (MT-W), while forb cover was most prevalent in the moist forests (MT-NW). Lichen and moss were abundant in the boreal forests of Alaska (AK). In sites burned with moderate severity, forbs were important in both dry (MT-W) and moist forests (MT-NW), with high percent canopy cover of grasses in CA and shrubs and lichens in AK. Species composition was dominated by forbs independent of burn severity on sites in CA, MT-W and MT-NW, while shrub species were more common on burned sites in AK. Lichen and moss species were also important on AK sites, and, to a lesser degree, on the MT-NW sites.

Post-fire, significantly less litter remained on high burn severity sites than on low or moderate burn severity sites ($p<0.05$, Figure 3). The percent cover of surface organic material differed ($p<0.05$) among burn severity classes (Figure 3), and differed more for low and moderate burn severity classes than did depth of litter, except in Alaska, where surface organic cover was highest on moderate burn severity sites. The ocular estimates of surface organic cover did not include green vegetation, which was an important cover fraction on low burn severity sites in Alaska but much less so in the other regions. The deep organic mats in Alaska also caused less soil to be exposed compared to the other regions, across all burn severity classes (Figure 3). The amount of bare soil is another good indicator of burn severity, and varied as expected between burn severity classes across all four regions (Figure 3). The presence of unburned and charred organic matter as well as bare mineral soil likely provides a variety of microsites for plants to survive and recover post-fire (Figure 3) .

Several species were common in terms of presence and cover contribution across the range of burn severities and across sites within a geographic region. In CA, grass species commonly observed in all burn severities were non-native *Bromus* species (particularly *B. diandrus*), forb species were the non-native *Brassica nigra*, the native *Calystegia macrostegia cyclostegia*, and both native and non-native *Cirsium* species, and the native shrub species included *Adenostoma fasciculatum, Arctostaphylos species*, and *Ceanothus species* In MT-W, forb species *Epilobium angustifolium* and *Xerophyllum tenax* and shrub species *Spiraea betulifolia, Vaccinium globulare,* and *Amelanchier alnifolia* were commonly found across burned sites. In MT-NW, forb species, including *Epilobium angustifolium*, *Xerophyllum tenax,* and *Arnica cordifolia,* and shrub species, such as Spiraea *betulifolia* and *Pachistima myrsinites,* were common across burn severities. In Alaska, the sedge species, *Carex rossii*, the forb species *Epilobium angustifolium,* and the shrub species *Vaccinium vitis-idaea* and *Ledum groenlandicum* were found in all burn severities.

Landscape patterns of burn severity

The burn severity interpreted from dNBR varied among and within a given fire (Table 2, Figure 4). In the California and Montana fires, less than 5% of the area within the fire perimeter burned at high burn severity, while in Alaska more than 50% burned with high severity (Table 2 and Figure 4). In the California and Montana fires, from 14 to 43% was unburned (Table 2), while 7% of the Alaska fires was unburned.

The proportion and size of patches burned in different burn severities were dissimilar between regions (Table 2 and Figure 4). Patch size was significantly different in low, moderate, and high burn severity in individual fires and across all fires ($p < 0.05$). With the exception of MT-W, unburned patches were the smallest in size. The mean size of low severity patches was consistent across all regions, while the mean size of moderate severity patches in Alaska was anomalously lower than in the other regions. Conversely, the largest high severity patches were much larger in Alaska than in the other three regions ($p < 0.05$) (Table 2).

DISCUSSION

Understory vegetation response was highly variable

The high variability in vegetation response following eight large wildfires is not surprising as heterogeneous effects have been documented following other large wildfires (Lyon and Stickney 1974; Whelan 1995; DeBano et al 1998; Turner *et al.* 1994; Turner and Romme 1994; Turner *et al.* 1997, 1998; Graham 2003; USDA 2003, 2004). Variability in understory plant response was highest for low severity burns, and lowest for high severity burns. On all sites, the coefficient of variation of understory plant canopy cover was well over 30% (Figures 1 and 2).

Site conditions, prefire vegetation composition, and the life-history strategies of individual plant species most likely explain the high variation we observed in post-fire response across sites and burn severities. Especially on low and moderate burn severity sites, the variety of microsites, including some unburned, some with charred organic cover on the soil, and some with bare soil, likely create conditions for many different plant species to survive, regrow or establish from seed. In general, high severity burn sites have significantly ($p<0.05$) more exposed soil and less surface organic matter on the surface than less severely burned sites (Figure 3). Other factors also contribute. Hudak (*et al.* this issue) found that fire effects on the soil surface may vary at finer scales than fire effects on the tree overstory. Thus, even within areas with relatively uniform fire effects on the overstory (e.g. across a patch we classified as moderate severity) the highly variable post-burn soil surface likely contributes to the high variation in vegetation response. Similarly, Turner *et al.* (1994) found that smaller patches, those less than < 1250 ha in area, were often quite heterogeneous in fire effects on the soil surface. There is also high variability in vegetation present before the burn which would have affected post-fire vegetation response.

In general, sites in CA and MT-W were drier and less productive. No doubt this contributed to the overall lower amount of total organic material and plant cover we measured there in comparison to the moist forests of MT-NW and the boreal forests of AK (Figures 1 and 2).

The post-fire vegetation composition is influenced by what vegetation is there before the fire to serve as the source of resprouting grasses, shrubs and forbs and of seed stored in the soil. Unburned islands of vegetation are also an important source of seed for vegetation that establishes post-fire. In all burn severities, but especially in areas burned with low severity in MT-NW and MT-W, shrubs such as *Acer glabrum*, *Holodiscus discolor*, and *Amelanchier alnifolia* sprouted following topkill from fire. In moderately burned sites in interior AK, scorched *Hylocomium splendens* and other mosses, *Cladina* species, *Picea mariana* seedlings, *Carex* species, and sprouts of *Alnus* species, and *Betula* species were commonly observed. The plots in high severity burns in chaparral were dominated by burned shrub skeletons and rocky soil immediately after the fire, and *Adenostoma* species and *Ceanothus* species shrubs had prolifically sprouted within one growing season after the fire, as had *Delphinium cardinale* and many other forbs that flower following fire. Many of the plant species in the ecosystems we sampled were well-adapted to fire as they exhibited multiple life strategies such as seed-banking and sprouting that ensured successful post-fire regeneration. As we expected, resprouting was important, especially in areas severely burned. Post-fire responses depend upon the characteristics of the plant species on the site, their susceptibility to fire, and the means by which they recover after fire (DeBano *et al.* 1998). Many herbaceous and shrub species can regenerate from seed and from rootstock (Lyon and Stickney 1976, Stickney 1986, Anderson and Romme 1991). Lyon and Stickney (1976) found that 86% of individuals dominant in lodgepole pine stands in the first few years after fire were present before the fire, and 75% resprouted. Anderson and Romme (1991) found that 67% of post-fire species survived and that all resprouted after the 1988 Yellowstone fires in lodgepole pine forests. Plant survival and post-fire resprouting has been related to differences in depth distribution of rhizomes in soil (Granstrom and Schimmel 1993; Turner *et al.* 1997). Surviving vegetation may also produce seeds and facilitate germination or, alternatively, exert a competitive influence.

Burn severity was heterogeneous across the landscape

Spatial patterns have important implications for post-fire recovery. Patch size and arrangement can strongly influence the kinds and number of seeds that are dispersed into a burned area (Turner *et al.* 1994). Mean patch sizes for all eight wildfires are small though highly variable (Table 2), suggesting that seed sources are available for those trees and understory plant species dependent on seed availability from unburned forest. Burn severity and patch size exert an important influence on plant succession following fire. While large patches of high burn severity will have resprouting species and seeds in the soil seedbank post-fire, the vegetation response is likely to be affected by the relatively harsh post-fire environment that is likely in these large patches (Turner *et al.* 1994; Graham 2003).

In comparison, patch sizes were large (mean of about 3500 ha) following the Yellowstone fires, where crown fires burned 31% of the area (Turner *et al.* 1997). In both the Rodeo-Chedeski fire that burned >185,000 ha of dry mixed conifer forests in Arizona in 2002 and in the Biscuit that burned more >200,000 ha in both dry and mesic forests in California and Oregon in 2002, fires burned in mosaics of burn severity (USDA 2003, 2004). Of the national forest lands burned in the Rodeo-Chedeski fire, ~54% burned at moderate or high severity, creating patches greater than several hundred meters across that will presumably take several centuries to re-establish forest cover (USDA 2003). In the Biscuit fire ~20% of the area burned lightly, with less than 25% of the vegetation killed, while another 50% of the area burned with high severity, with more than 75% of the vegetation killed (USDA 2004). Patch sizes were also large in the Hayman fire, where ~50% (~28,000 ha) of the forest was described as burned with high severity, and a single large patch of high burn severity spanned almost 3500 ha (Graham 2003). The proportion and mean patch sizes of high burn severity were much smaller in the fires we sampled, although there were some very large patches in all fires, especially in AK (Table 2 and Figure 4). In most cases, we found a matrix of surviving vegetation interspersed with patches of high burn severity on the landscape. Similarly, following a large fire (~34,000 ha) in ponderosa pine forests of the South Dakota Black Hills, large patches were often more heterogeneous in fire effects and less severely burned. Low and moderate severity patches averaged ~10 and 24 ha in size and were within 10 m of a green edge, while high severity patches were small, averaging ~8 ha in mean size, and 55% of the area that burned under high severity was within 30 m of a potential tree seed source in adjacent low or moderate severity patches (Lentile et al. 2005). In AK, even the largest patches of high burn severity included small islands of less severely burned or unburned vegetation. Odion et al. (2004) documented similarly variable mosaics of burn severities for large fires (> 1500 ha) burning from 1977 to 2002 on the Klamath National Forest, including 20-82% low, 5-50% moderate and 5-45%.

The heterogeneity of fire effects and distance from living vegetation affect vegetation recovery and influences successional trajectories (Pickett and White 1985; Turner et al.1997). Species richness was lower in larger and more severely burned patches in the cold forests in Yellowstone after the 1988 fires (Turner *et al.* 1997). Turner *et al.* (1994) found that smaller patches were often more variable in fire effects and less severely burned, and larger patches were more likely to be less variable in effects and burned with high severity. In Yellowstone, 25% of the area burned by crown fire was greater than 200 m from unburned or lightly burned areas (Turner *et al.* 1994). The juxtaposition of low, moderate, and high burn severity patches will likely mitigate the effects of high burn severity by providing nearby herbaceous and tree seed sources and likely increase rates of plant recovery. Even in the very large patches of high burn severity fires we sampled in boreal forests of Alaska, understory plants were resprouting and seedlings of the serotinous black spruce were established one-year post-fire.

The severity classes upon which our vegetation results are based were consistently identified in the field based on the predominance of green, scorched (brown), or charred (black) vegetation. Our landscape analyses of burn severity classes and patch metrics were based on one set of dNBR thresholds among unburned, low, moderate and high burn severity classes for all sites. We used dNBR thresholds developed in northwestern Montana (Key and Benson 2002). The threshold for dNBR between moderate and high burn severity in particular may be ill-suited for AK boreal forests, where it appears to result in a higher percent of high burn severity than ecologists find on the ground (Murphy *et al.* In Review). Land managers in AK (Karen Murphy, pers. comm.) have suggested that a different threshold for high burn severity may be more ecologically appropriate in these boreal forests, which would effectively decrease the area and mean patch size of high severity in our AK dataset. This may explain why the largest high burn severity patches we found across all sites were on the Alaska (AK) fires. On the other hand, both the number and size of fires are predicted to increase in Alaska due to climate change and this must not be discounted as an explanation (Rupp *et al.* 2000). In ecosystems where stand-replacing fires were common historically, it is unlikely that the patches we called high burn severity are uncharacteristic, but that is beyond the scope of this study to determine.

Ecological Implications

Vegetation responded quickly post-fire. When we sampled within the first few days or weeks post-burn, many plants were already resprouting and establishing from seed. Most of the species present post-burn were present pre-burn as evidenced by comparing plant communities in burned areas to those in nearby unburned patches. The term burn severity can be misleading given that vegetation responds quickly post-fire even in large, severely burned patches. Fire may result in very different ecological responses depending on location (climate and topography), pre-fire vegetation and spatial patterns. Of all the fires we sampled, the vegetation cover one-year post-fire was lowest in the Alaskan boreal forest, but even there, many plants were resprouting within days after sites burned. Post-fire vegetation cover and species richness was lowest in the chaparral and dry forests, and highest in the moist forests of northwestern Montana (MT-NW), relative to wildfires burned in the other three ecosystems we sampled.

On low burn severity and most moderate burn severity sites we sampled, well over 30% of the ground surface was covered with organic material immediately after the fire (Figure 3). One-year later, the canopy cover of understory vegetation averaged nearly 10% and in most areas far more, though the cover was highly variable (Figures 1 and 2). Pankukk and Robichaud (2003) found that when fallen Douglas-fir needles covered 50% of the soil surface, soil erosion in rills was reduced by 20% and in interrills by 80%. Robichaud and Brown (2000) correlated lower post-fire erosion rates with pre-fire conditions (e.g., mesic sites where survival of lichens and moss was high, sites where a diversity of grasses, forbs, and shrubs were present before the fire and available to revegetate burned sites), and less steep slopes. The timing and intensity of post-fire rainfall, presence of water-repellent soils, and soil texture also influence the likelihood that significant post-fire soil erosion will occur. It is likely that the vegetation cover will continue to increase quickly, thus providing some soil surface protection as the organic matter remaining post-fire decomposes.

For those ecological effects of fire that depend on the soil, mapping using dNBR is likely most effective at detecting large patches that are severely burned. In areas burned severely, the overstory canopy is largely removed immediately post-fire, and therefore surface reflectance dominates. The fine-scale variation in fire effects on soils and surface organic materials is less detectable on moderate or especially low severity sites where substantial overstory canopy remains after the fire.

BAER teams target areas for post-fire rehabilitation based on burn severity classification maps derived from dNBR values. These maps have been shown to be more influenced by the presence (or lack) of green vegetation than by the amount of surface organic or inorganic cover (Hudak *et al.* this issue). The unusually high proportion of the high severity class in Alaska is not evidence that dNBR is an unsuitable metric, though the threshold between classes may need to be adjusted (Murphy *et al.* In Review). Whether absolute thresholds have utility across the widely different ecosystems sampled in this study, or the many other ecosystems to which they might be applied in North America and elsewhere, is debatable (Miller and Thode In Press). For the purpose of this study primarily concerned with post-fire vegetation response, the use of dNBR to characterize fire effects on vegetation is well supported (Hudak *et al.* this issue) and justifies using dNBR to understand landscape patterns in burn severity.

The scale and homogeneity of fire effects is important ecologically. Often larger fires and large patches within fires are dominated by high burn severity (Turner *et al.* 1994; Graham 2003). Turner *et al.* (1994) found that large burned patches (~ 500 to 3700 ha) tended to have a greater percentage of crown fire and smaller percentages of light surface burns. Such severely burned areas may be more vulnerable to invasive species and soil erosion and may not return to pre-fire conditions for extended time periods.

Conclusions

Comparing burn severity conditions across large wildfires burning in different vegetation types allows us to describe important general patterns. First, vegetation responds quickly. Many plants are well adapted to regrow and establish following fires, even when those fires create large patches burned with high severity. Second, vegetation species richness and percent canopy cover are highly variable among patches burned with low, moderate and high severity. While this is likely the result of the wide variation in prefire vegetation and other site conditions, it also reflects the fine-scale heterogeneity in fire effects on soils within patches that are mapped using dNBR and satellite imagery. Thus, areas mapped as having low and moderate severity encompass microsites that vary from unburned to low, moderate and high severity effects. Third, for this and other reasons, dNBR is a reasonable but imperfect indicator of post-burn fire effects. Although the immediate post-fire effects on the soil surface did differ with dNBR, one-year post-fire vegetation response was so highly variable that there were no significant differences with burn severity mapped with dNBR. It is possible that longer-term fire effects will differ more. Fourth, extensive areas within even large wildfires that burned intensely have sufficient organic material covering the soil and vegetation that responds quickly to reduce the risks to soil erosion. Further, large wildfires leave a mosaic of unburned vegetation interspersed with areas of low, moderate, and high burn severity. Our data support the approach used by many BAER teams to strategically target post-fire rehabilitation treatments on large, severely burned patches while considering other factors, such as vegetation response, slope, soil texture and resources at risk.

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Table 1. Number of sites sampled in each of four different geographic regions by low, moderate and high burn severity classes.

	Low	Moderate	High	Total
CA	3	6	3	12
MT-W	5	3	2	10
MT-NW	5	4	3	12
AK	4	5	3	12
Total	17	18	11	46

Table 2. Proportional area burned, mean patch size, and range of patch sizes classified as unburned or as low, moderate, or high burn severity, averaged across two large wildfires in each of four geographic regions. Values in parentheses are standard errors.

	Unburned			Low Severity			Moderate Severity			High Severity		
Location	Area (%)	Mean patch size (ha)	Range in patch size (ha)	Area (%)	Mean patch size (ha)	Range in patch size (ha)	Area (%)	Mean patch size (ha)	Range in patch size (ha)	Area (%)	Mean patch size (ha)	Range in patch size (ha)
CA	33%	3.1 (4.4)	<1 to 10,444	28%	3.7 (0.9)	<1 to 8,270	35%	10.2 (5.1)	<1 to 10,410	4%	7.1 (1.1)	<1 to 385
MT-W	43%	21.1 (11.1)	<1 to 4,893	9%	3.3 (2.5)	<1 to 759	45%	13.8 (11.8)	<1 to 2,900	4%	10.9 (4.1)	<1 to 253
MT-NW	14%	1.3 (0.6)	<1 to 1,876	38%	4.4 (1.8)	<1 to 3,703	43%	16.6 (5.8)	<1 to 2,637	5%	10.0 (5.0)	<1 to 129
AK	7%	2.7 (0.4)	<1to 3,899	5%	3.9 (0.2)	<1to 488	30%	7.15 (0.7)	<1 to 6,212	58%	14.4 (7.3)	1 to 128,510

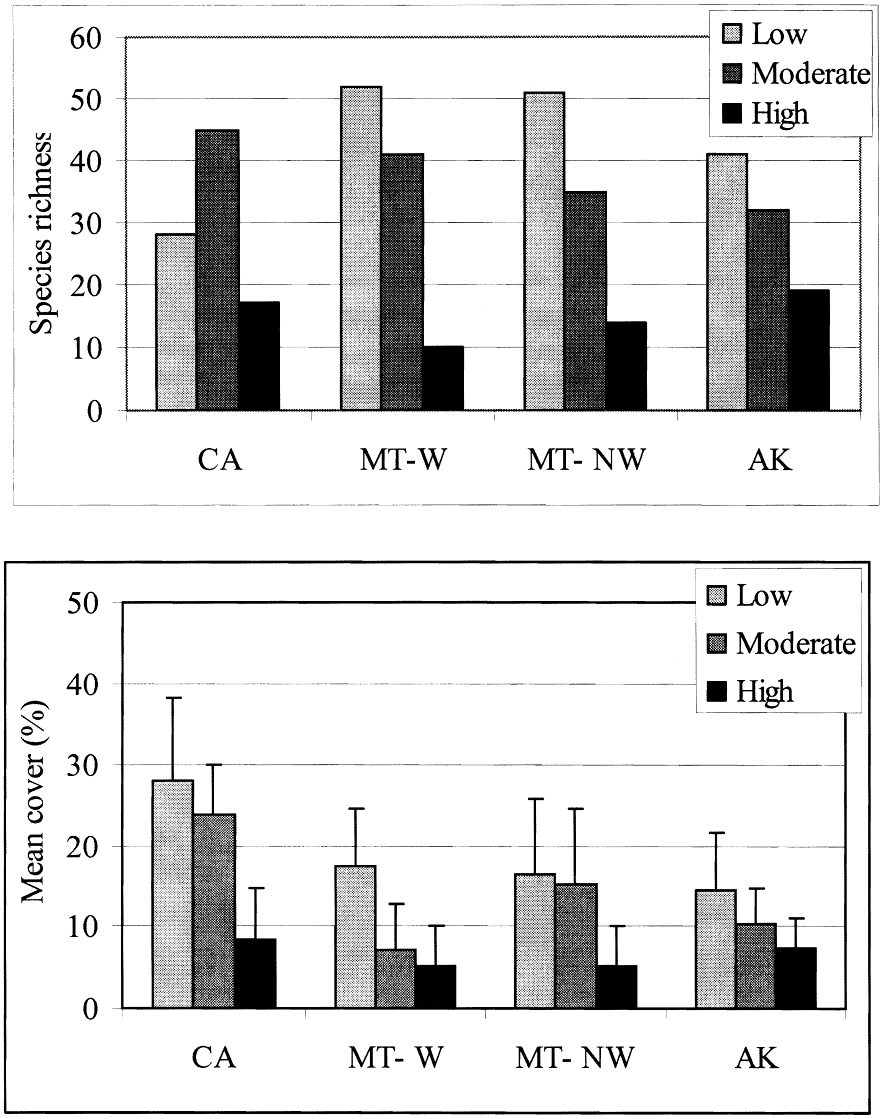

Figure 1. One year post-fire, total plant species richness (top) and mean canopy cover (bottom) compared for areas of low, moderate and high burn severity in two fires in each of four geographic regions. Vertical bars are standard errors (see text for n, which varied with site and burn severity). Standard errors were not calculated for species richness since this represents total number of species across vegetation plots within a site.

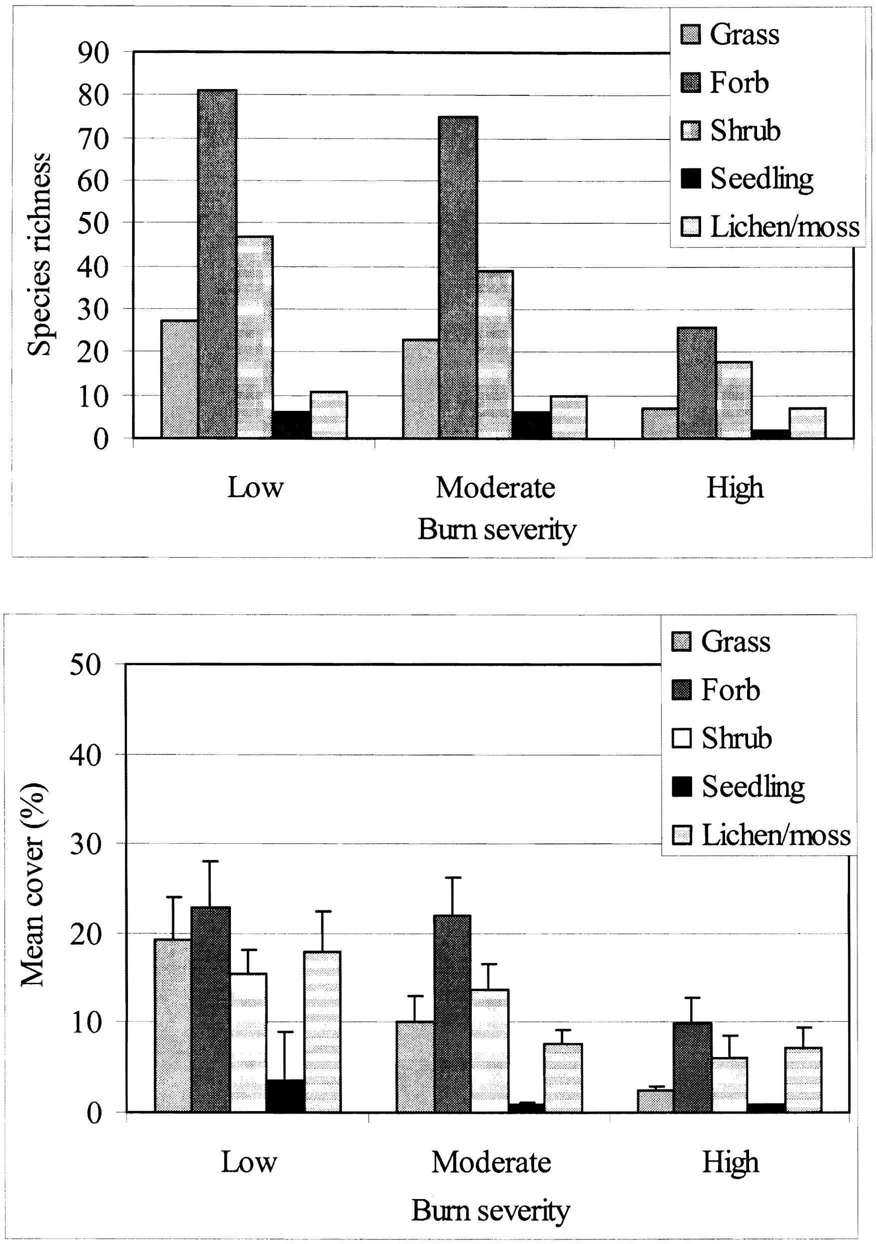

Figure 2. Plant growth form and burn severity for eight wildfires. One-year post-fire total species richness (top) and mean percent canopy cover by plant growth form (bottom). Vertical bars are standard errors (see text for the number of sites sampled in each burn severity class). Standard errors were not calculated for the species richness because these represent total number of species across vegetation plots within a burn severity class.

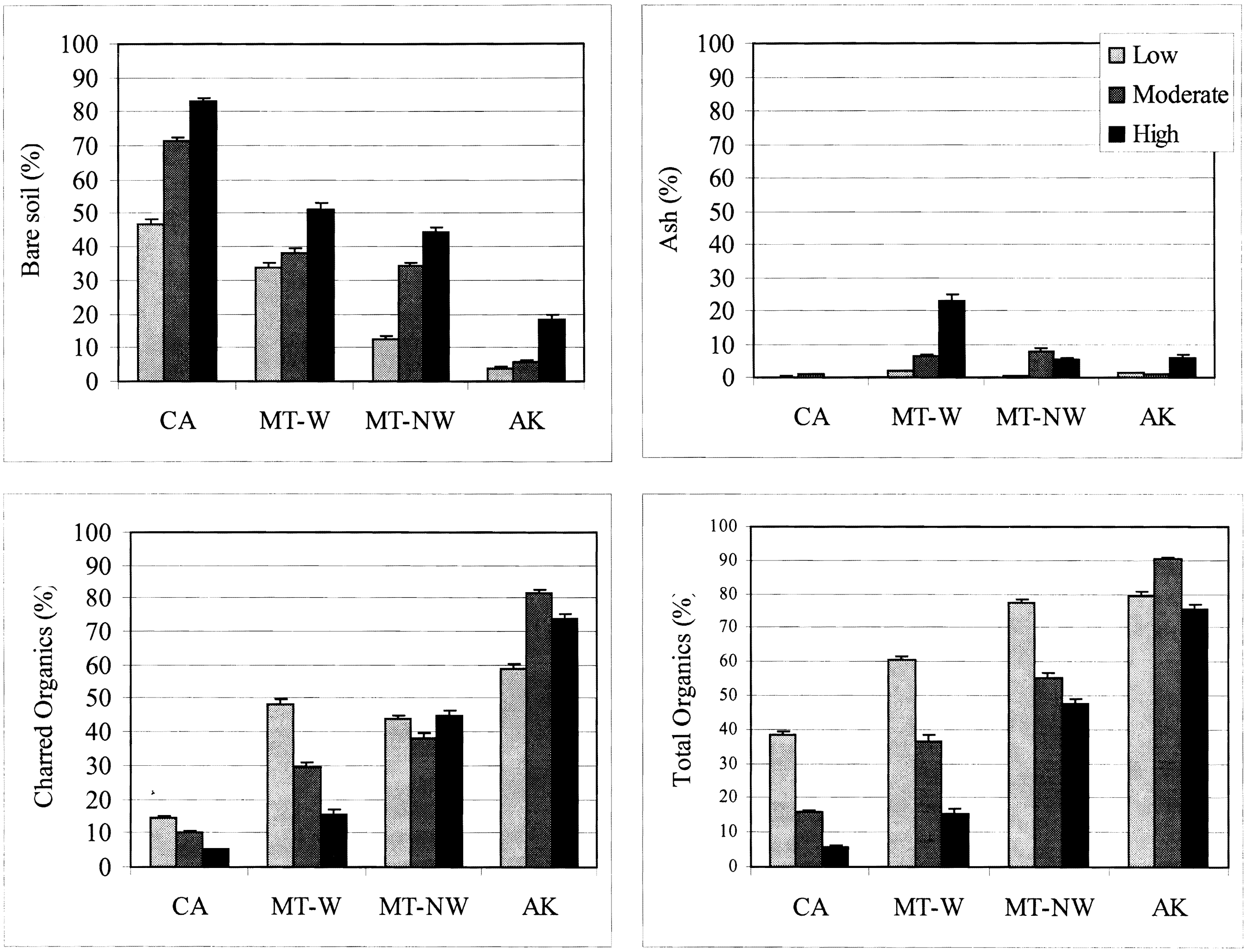

Figure 3. Percent cover of bare soil (top left), ash (top right), charred organic matter (lower left), and total organic material, including both charred and uncharred (lower right). These data were collected soon after and in the same season as fires occurred. Data shown are means and standard errors calculated for all of the 135 subplots on each of the sites sampled within each of two fires in each study region.

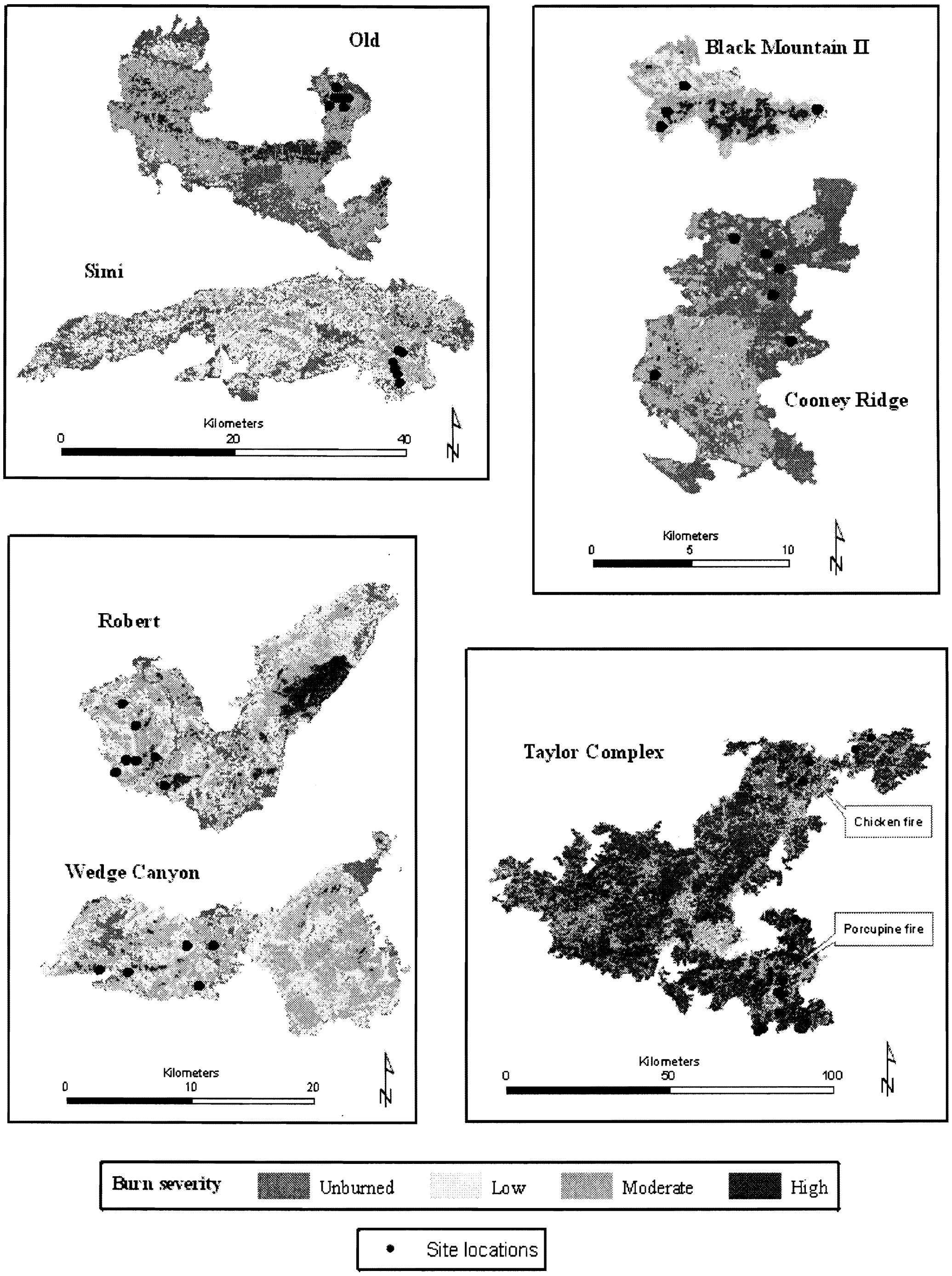

Figure 4. Maps of the burn severity (classified dNBR) for the eight wildfires sampled, two each in four geographic regions. These images show effects of the fires immediately after the fires burned. Note that the extent and therefore the scale varies greatly.