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The influence of experimental wind disturbance on forest fuels and fire characteristics

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ABSTRACT

Current theory in disturbance ecology predicts that extreme disturbances in rapid succession can lead to dramatic changes in species composition or ecosystem processes due to interactions among disturbances. However, the extent to which less catastrophic, yet chronic, disturbances such as wind damage and fire interact is not well studied. In this study, we simulated wind-caused gaps in a *Pinus taeda* forest in the Piedmont of north-central Georgia using static winching of trees to examine how wind damage may alter fuel characteristics and the behavior of subsequent prescribed fire. We found that experimental wind disturbance increased levels of fine and coarse woody fuels (but not leaf litter), increased spatial heterogeneity of fuels, and led to more complete consumption of leaf litter. These patterns led to changes in fire combustion characteristics in experimental gap plots within areas of downed tree crowns where we observed a large increase in fire radiative flux density (kW m^{-2}) and its time integral, fire radiative energy density (MJ m^{-2}). These results suggest that wind disturbance may interact with fire not only through addition of fuel, but also through more subtle changes in fuel composition, consumption, and arrangement. More broadly, this study shows that disturbances can influence one another via a variety of mechanisms not all of which are immediately obvious. Understanding disturbance interactions can allow forest managers to make more informed decisions about how wind disturbance influences fuel heterogeneity, and how management processes, such as prescribed fire can interact with other prior wind disturbances to interactively shape plant communities.

1. Introduction

1.1. Disturbance interactions

Disturbances are important drivers of ecological change in many ecosystems. Consequently, their effects have been frequently examined. However, when ecosystems are subjected to multiple disturbances in rapid succession, current theory predicts that unanticipated "ecological surprises" such as non-linear changes in species composition may occur (Paine et al., 1998; Frelich and Reich, 1999; Scheffer et al., 2001). Paine et al. (1998) suggest that the ecological effect of disturbances in rapid succession may be multiplicative rather than additive. As an example, moderate severity forest disturbances that cause damage to either the overstory or understory can maintain pre-disturbance composition. However, when a more severe disturbance or disturbance combination affects both the understory and overstory, dramatic changes in forest composition occur (Frelich and Reich, 1999). Even so, most disturbances are not rare or catastrophic. In fact, there is a continuum of disturbance severity in most ecosystems; yet the interactions among these disturbances remain poorly understood (Turner, 2010). Here we investigate how two chronic and integral disturbances—wind disturbance and wildland prescribed fire—interact.

Prescribed burning is a commonly implemented forest management tool throughout the United States (e.g., 3.8 million hectares of forest treated in 2011; Melvin, 2012), and wind damage from hurricanes, tornados, and other events is a particularly common forest disturbance, affecting a combined 1.65 million hectares in the U.S. annually (Dale et al., 2001). Understanding how these common and chronic disturbances interact can advance ecological understanding of disturbance interactions and inform forest management practices where wind disturbance and fire co-occur.

The most straightforward hypothesis of wind–fire interaction posits that wind disturbance to forests increases fuel loading, in

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turn increasing the likelihood or intensity of fire (Webb, 1958; Myers and van Lear, 1998). Paleoecological studies corroborate the view that historically, fires frequently followed severe hurricane disturbance (Liu et al., 2008; Urquhart, 2009). Thus, wind disturbance such as hurricanes can increase the probability or extent of wildfire—likely due to increased surface fuel loads across large areas—but the interaction between wind and fire at the forest gap level is less understood. Smaller scale wind disturbance may affect fuel characteristics and the intensity and behavior of fire, which has a direct influence on individual plant mortality and regeneration (Whelan, 1995). In this study, we examine how wind disturbance at the gap level alters fuel availability and heterogeneity, and how these factors in turn influence fire combustion characteristics.

1.2. Effect of wind disturbance on fuels and fire behavior

While fuel type, moisture, and wind speed all affect fire behavior, the amount of available fuel is a consistent determinant of fire intensity (Byram, 1959; Alexander, 1982; Whelan, 1995), and fire parameters such as radiative energy density increase with fuel consumption (Kremens et al., 2012). While it is known that small-scale changes in woody fuel such as downed tree branches can increase fuel loading and fire intensity, it is not known how larger-scale disturbances (such as multiple tree blowdown gaps) alters available fuels and fire behavior. Previous studies of blowdowns shed light on how wind disturbance may alter fuels such as woody debris and leaf litter. Studies in tropical, temperate, and boreal forests following wind disturbance have found marked increases in coarse woody debris, fine woody debris, and leaf litter, though these studies were not explicitly studying forest fuels (Whigham et al., 1991; Harmon et al., 1995; Busing et al., 2009; Bradford et al., 2012). Although wind disturbance can clearly increase woody fuels, it should also be noted that natural canopy gaps reduce leaf litter abundance, decreasing fuel availability and continuity for subsequent fires (O'Brien et al., 2008).

Fuels such as leaf litter, grass, and woody debris present on the forest floor are known to create fine-scale variation in fire behavior (Hiers et al., 2009; Mitchell et al., 2009; Thaxton and Platt, 2006; Loudermilk et al., 2012), including changes in radiant heat flux, fire intensity, rate of spread, and fire effects on vegetation recovery. Variation in fire intensity can in turn change the relative abundance of species and alter floristic composition during recovery (e.g., Morrison, 2002; Wiggers et al., 2013). Determining the extent to which wind disturbance alters fire behavior is important for understanding how forests disturbed by wind and fire will recover from coupled disturbances. In this study, we examine how experimental wind disturbance can influence fuel characteristics and change aspects of fire combustion characteristics.

1.3. Research questions and hypotheses

We conducted a large-scale field experiment where we combined experimental wind disturbance with prescribed fire. We addressed the following research questions. (1) Does wind disturbance alter the forest fuel composition and distribution? (2) Do prescribed fire combustion characteristics differ between wind damaged and undamaged plots? We expected simulated wind gaps to increase the amount of fuel after the first year following disturbance. We also expected gaps to alter fuel composition such as an increase in woody fuels and herb-layer vegetation—particularly grasses. Conversely, we expected leaf litter mass to be lower due to decreased overstory inputs. Furthermore, we expected changes in spatial distribution of fuel loads across treatments. Finally, due to changes in fuel loading, composition, and aggregation, we hypothesized that fire radiation characteristics would be amplified in gaps, especially in areas of increased fuel load such as in tangles of downed tree crowns.

2. Methods

2.1. Study site

The experiment was conducted at Piedmont National Wildlife Refuge (PNWR) in central Georgia. PNWR is composed of Piedmont forest burned approximately every three years, dominated by 80+ year old *Pinus taeda* trees with a mixed-hardwood sapling understory. For this experiment, we established six 1250 m^2 plots (Fig. 1) in a forest stand that had received prescribed fires in 2004, 2006, and 2009 (Carl Schmidt, US Fish and Wildlife Service, personal communication). The selected plots had a standing tree (>10 cm dbh) basal area of 17–27 $m^2\ ha^{-1}$ and stand tree densities ranged from 140 to 570 stems ha^{-1}. Three plots were treated with simulated wind disturbance (Fig. 2) and three were undamaged controls. In April 2013, one year following wind disturbance, all plots received a cool season prescribed fire.

2.2. Experimental wind disturbance and prescribed fire

We simulated wind damage gaps in three of the six plots (Fig. 2) using static winching to manually pull down trees. Tension was applied to the target tree using nylon straps, a snatch block pulley, and a steel cable until the tree snapped or uprooted (see Peterson and Claassen, 2013 for details). The winching gaps were designed to mimic a tornado gap by imposing realistic changes in forest structure and light levels. The largest trees were removed first until 80% of the basal area was removed. We winched the trees to fall northward—typical of tornado disturbance (Peterson, 2007), and we winched between March and May—a time when significant tornado disturbance occurs in the area (Peterson, 2000). Though on the lower end of typical gap sizes created by moderate severity windstorms (e.g., McNab et al., 2004), we chose to create 40 m diameter gaps (1250 m^2) as this was the maximum size we could create with replication within the given size of the study area. Although we took care to mimic many aspects of a natural windstorm, some events such as heavy rain and stripping of leaves by wind cannot be adequately simulated (Cooper-Ellis et al., 1999).

Approximately one year after winching, on 9 April 2013, the PNWR staff and US Forest Service volunteers implemented an experimental fire across the study area. Ambient air temperatures during the burn ranged from 26 to 27 °C; relative humidity decreased from 52% to 40% over the course of the fire. Flame lengths ranged from less than 0.5 m for backing fires to 2.5–3.5 m for heading fires.

2.3. Measuring available fuel and residual fuel

To examine how wind disturbance altered available fuel composition, we collected fuel samples from plots just prior to the prescribed burn. Within each plot, we sampled fuel from randomly placed 0.25 m^2 fuel sampling quadrats placed within each plot. We established 25 quadrats in each gap plot and 15 quadrats in each intact plot, because we expected more fuel variability in gap plots. Within each quadrat, we collected and sorted all leaf litter, grass, and cones, as well as woody debris, which was sorted according to fuel diameter—a proxy for drying time. The fuel classes included were 1-h (0–0.6 cm), 10-h (0.6–2.5 cm), and 100-h (2.5–7.6 cm; Fosberg, 1970). We included living vegetation <0.6 cm in 1-h fuels. We did not sample any living vegetation $\geqslant$0.6 cm (10-h) or any woody debris >7.6 cm (1000-h) because they were not expected to combust in the prescribed fire.

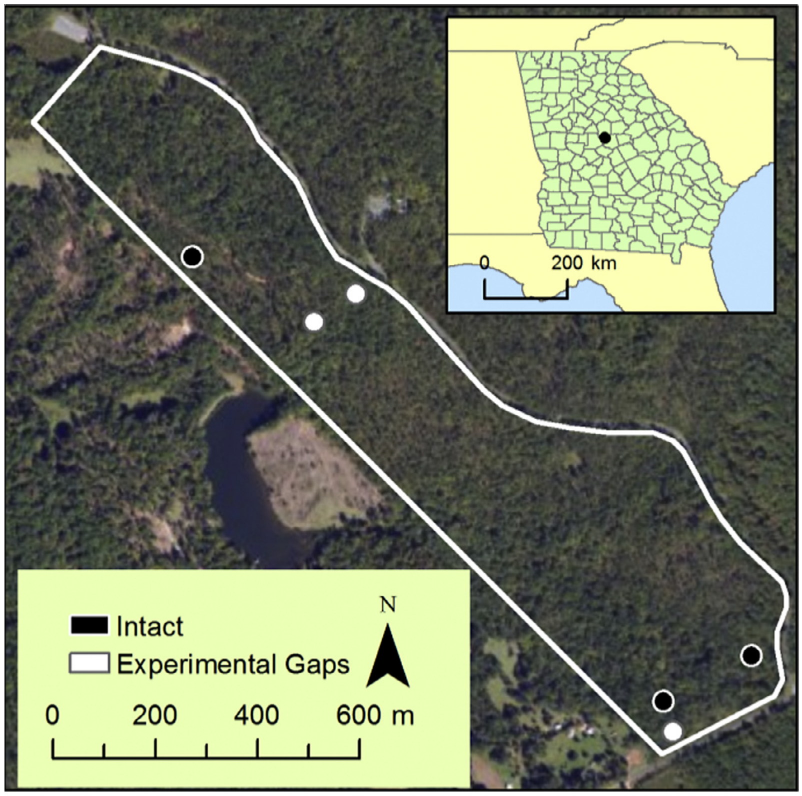

Fig. 1. Map of study area within the Piedmont National Wildlife Refuge illustrating locations of six 1250 m^2 plots treated with experimental gaps (white circles) or undamaged controls (black circles).

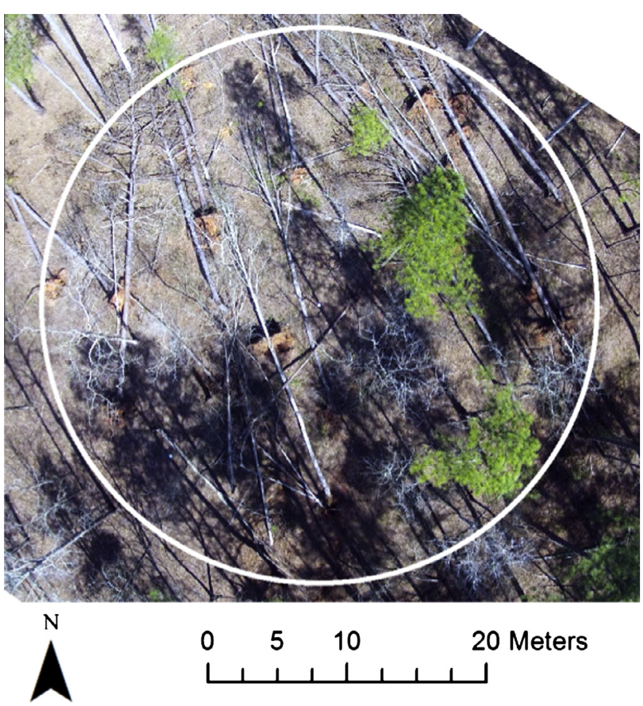

Fig. 2. Aerial photograph of a plot that has received experimental wind gaps. This plot is the northeastern most depicted in Fig. 1. Photo courtesy of USDA Forest Service, Southern Research Station, Center for Forest Disturbance Science.

This expectation was supported from post-burn observations. The sampled fuel was oven-dried at 70 °C for 48 h and weighed to the nearest 0.1 g. We measured residual fuels immediately following the prescribed burn in the same manner as pre-burn sampling in order to make inferences regarding the type and amount of fuel consumed.

2.4. Measuring fire radiation characteristics

Measurements from dual-band radiometers allowed us to focus on differences in combustion characteristics at the scale of tree crowns. We report average and peak fire radiated flux density (FRFD, kW m^{-2}) and fire radiative energy density (FRED, kJ m^{-2}). FRFD is known to be linearly related to the rate of fuel consumption (Wooster et al., 2005; Freeborn et al., 2008), thus mean FRFD is linked to the mean rate of fuel consumption, peak FRFD is known to be linearly related to peak fuel consumption rate and Byram's fire intensity (W m^{-1}, Kremens et al., 2012), and FRED is known to be linearly related to fuel consumption (Wooster et al., 2005; Freeborn et al., 2008; Kremens et al., 2012). Each radiometer included two sensors with different band passes for which the ratio of outputs, through calibration against laboratory blackbody temperatures, determines FRFD (see Kremens et al., 2010 for analysis details). FRFD is an average for the fractional area of the pixel that is above background levels (known as fire fractional area). FRFD measurements decline with height of deployment (because fire fractional area declines) and, thus, can only be compared among deployments that utilize the same sensor height. In contrast, time-integrated FRFD (i.e., FRED) is not dependent on height of deployment as long as the integral spans the period from before fire arrival to the time at which radiation from the burned-over plot reaches an asymptote near background levels.

The radiometers included a midwave infrared (MW) and a longwave (LW) sensor. The MW sensor was built by Dexter Research (detector DR 2 M) and has a calcium fluoride window with nominal bandpass of 0.15–12.5 μm and spectral transmission described by

DC-6100-CaF2-U8. The LW sensor was built by Perkin Elmer (detector TPS334) and has a silica window with a nominal bandpass of 5–20 μm and spectral transmission described by DC-6188 5LWPSi – L1 (characterized by Dexter Research).

Specifically, our radiometer measurements allowed us to compare fire radiation characteristics within downed tree crowns in experimental gaps with radiation in both non-crown areas within experimental gaps and areas outside of gaps. Prior to burning, we deployed three radiometers in each plot (three gap and three intact plots). Each radiometer was mounted on 5.5 m posts to provide a nadir perspective with an approximate field of view of 47° (full angle) resulting in a field of view on the ground of approximately 18 m^2. In each intact plot, we suspended radiometers in randomly selected locations. In each gap plot, we suspended one radiometer over a randomly chosen downed tree crown and suspended two radiometers in randomly selected areas outside of a downed tree crown.

2.5. Statistical analyses

Analysis of fuel data required special consideration because total fuel data was not normally distributed and required log-transformations in all tests of total fuel loading. However, analysis of individual fuel components (grasses, cones, etc.) required rank-based tests since these data contained many zeroes. To test whether winching increased total fuel, we used a one-tailed Welch *t*-test of log-transformed pre-burn total fuel data, as there was unequal sub-sampling in winched and control plots. To determine how winching altered pre-burn fuel composition, we used one-tailed Wilcoxon rank sum tests comparing amounts of individual fuel components in winched and control plots. To test whether more fuel was consumed in gap plots than in intact plots, we used two-way ANOVAs on the log-transformed total fuel data. We included treatment (gap, intact) and burn (before, after) as factors. A significant interaction would indicate differences in fuel consumption between treatments. Similarly, to evaluate whether consumption differed between various individual fuel components, we used two-way ANOVA followed by Tukey's HSD tests on ranked data because the fuel components data included many zeroes.

A simpler, more intuitive description of fuel composition (either before or after fire) is possible by adopting multivariate ordination techniques. While multivariate ordination is often used in ecology for the analysis of vegetation (McCune and Grace, 2002), it has also been adopted for other diverse purposes (e.g., analysis of the microhabitats of fish; Grossman and Freeman, 1987). We suggest that multivariate ordination such as Principal Components Analysis (PCA) could be used to describe changes in fuel composition. This approach is analogous to familiar vegetation ordination, but abundances of fuel components (expressed as Mg ha^{-1}) are substituted for plant species abundances. To introduce this application, we performed PCA ordination of fuels before and after fires. We performed PCA using the "princomp" function for R version 3.0.0 (R Core Team, 2013). Fuel data was normalized using a *z*-transformation on each fuel type. The ordination was in two dimensions. After ordination, we calculated central ellipses representing the mean and standard deviation in 2-dimensional PCA space for each treatment combination.

To assess whether wind disturbance treatments or microsites (downed crown versus non-crown) had an effect on fire radiation characteristics, we used one-way ANOVAs to test for differences in average FRFD, peak FRFD, and FRED of each winching treatment and microsite combination, for a total of three levels: gap crowns, gap non-crowns, and intact non-crowns. The "crown" microsite was only located in gap plots and is represented by three replicates. The "non-crown" microsites were located in both gap and intact plots and are represented by four and seven replicates respectively, due to five radiometers failing to record data. We used Tukey's HSD tests to evaluate significant differences between treatment combinations.

2.6. Spatial autocorrelation analysis of fuels

We measured the magnitude and significance of spatial autocorrelation or "clumping" of fuel loading using Moran's *I* analysis with the "spdep" package (Bivand, 2013) in R. We used total available fuels (excluding 100-h fuels) and incorporated inverse distance weighting between fuel samples. To assess the range of spatial correlation and magnitude of spatial variability between treatments, we modeled the semivariance (spatial autocorrelation function) within treatments using Stanford Geostatistical Modeling Software (SGeMS v2.5b, Advanced Resources and Risk Technology, LLC, Stanford, CA; Remy et al., 2009). For each treatment, an isotropic exponential autocorrelation function (Goovaerts, 1997) was fit to the empirical semivariance using appropriate lag, nugget, sill, and range parameters (Table A1–Appendix). Semivariograms were created for three of the four time × treatment combinations (pre- and post-burn gap plots and post-burn intact plots), as no significant spatial autocorrelation was found in the pre-burn intact plots (see Moran's *I* in Results below).

3. Results

3.1. Effects of wind disturbance on fuel composition and consumption

We found that total fuel loading was higher in gap plots than in intact plots (16.75 Mg ha^{-1} versus 14.15 Mg ha^{-1}, $t_{115.116} = 1.808$, $P = 0.037$). As the largest class of fuel (100-h) showed no statistical or observational evidence of consumption, a characteristic of prescribed fires in the region, we omitted this fuel component in analyses of total fuels and included only the combustible fuels. Cones and 10-h fuel also showed no significant consumption, but we included these fuels because both field observations as well as a consumption trend suggested some degree of consumption (see below). When unburned fuels (100-h) were excluded, the trend towards greater amount of fuel in the gap plots was not significant (14.51 Mg ha^{-1} versus 13.49 Mg ha^{-1}, $t_{107.830} = 0.880$, $P = 0.190$).

Although total available fuel did not differ between treatments, experimental gaps affected individual fuel components (Fig. 3). Several fuel types were significantly higher in gap plots compared to intact plots, including grass ($W = 2067$, $P = 0.019$), 1-h fuels ($W = 2176$, $P = 0.004$), and 100-h fuels ($W = 1943$, $P = 0.036$). Woody fuel in the 10-h class was marginally higher in gap plots compared to intact controls ($W = 1983$, $P = 0.053$). The amount of leaf litter and pine cones did not differ between gap and intact plots ($W = 1525$, $P = 0.189$ and $W = 1714$, $P = 0.563$, respectively).

The prescribed fire consumed approximately 64% of the available fuel. Average available fuel decreased from 14.13 Mg ha^{-1} before the prescribed burn to 5.12 Mg ha^{-1} remaining after the burn ($F_{1,236} = 330.276$, $P \ll 0.001$). However we did not detect a difference in overall fuel consumption between treatments ($F_{1,236} = 0.023$, $P = 0.880$), and there was no treatment × burn interaction ($F_{1,236} = 0.904$, $P = 0.343$), indicating that the overall pattern of fuel consumption did not differ between gap and intact plots.

Because the analysis of fuel totals can mask changes in individual fuel components, we also examined consumption patterns of component fuels. Several fuels showed a significant reduction after burning including leaf litter ($F_{1,236} = 521.003$, $P < 0.001$), grass ($F_{1,236} = 120.839$, $P < 0.001$), and 1-h fuels ($F_{1,236} = 111.692$, $P < 0.001$. It should be noted that grass was a small fraction of total fuel (1–2%). Other fuels showed no significant decrease after burning cones ($F_{1,236} = 0.551$, $P = 0.459$), 10-h ($F_{1,236} = 1.570$, $P = 0.211$),

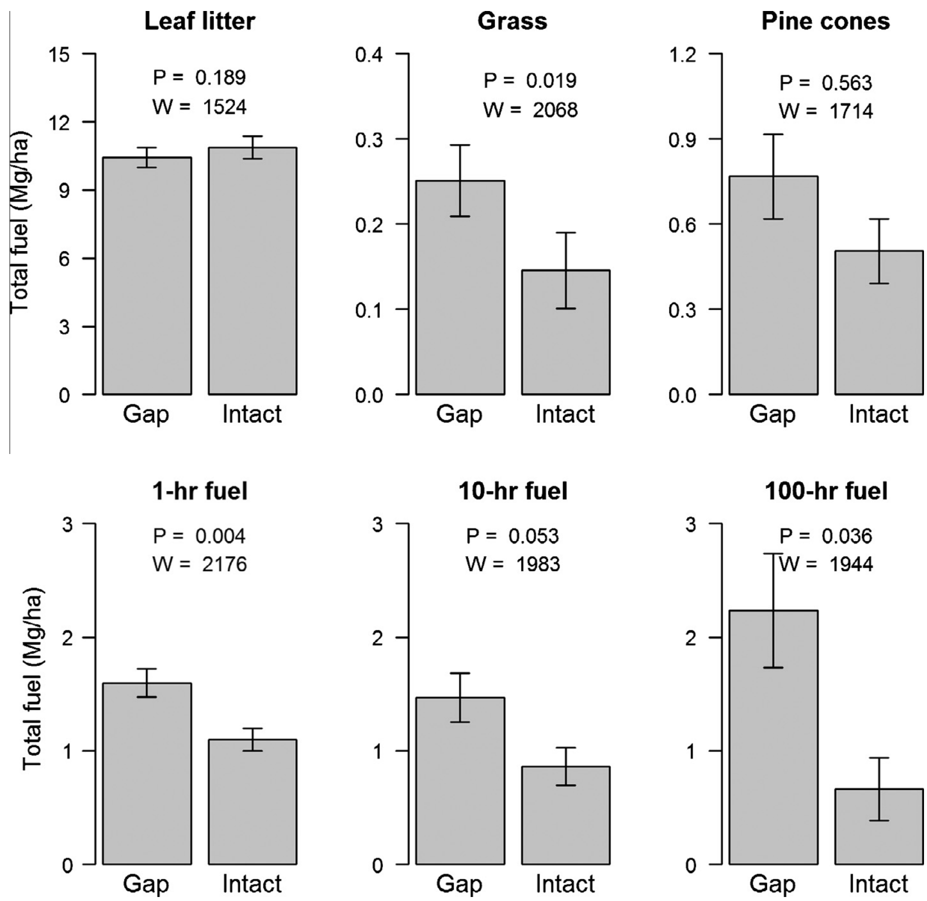

Fig. 3. Mean mass of forest floor fuels. *P*-values represent the result of one-tailed Mann–Whitney *U*-tests comparing fuel mass in experimental gap (G) and intact (I) plots. Error bars represent one standard deviation of the mean fuel loading.

or 100-h fuels ($F_{1,236} = 0.846$, $P = 0.846$). The two-way ANOVAs showed no significant interactions.

Using Tukey's HSD test, we found that although the amount of leaf litter was similar in gap and intact plots before the fire, leaf litter was lower in the gap plots after the fire (Fig. 4A). This pattern indicates that more litter was consumed in the gap plots than in intact plots. Conversely, consumption of 1-h fuels was higher in the intact plots (Fig. 4D). These results indicate that leaf litter burned more completely in gap plots while 1-h fuel burned more completely in intact plots.

The first two axes in the PCA explained 58.5% of the fitted variation in fuel abundances (37.6% and 20.9%, respectively). The two-axis ordination (Fig. 5) gives an overview of overall changes in fuel composition, and plainly illustrates several important points. First, the large scatter present in pre-burn plots compared to post-burn plots demonstrates the reduction in fuel variability after fire in both treatments. Second, the larger scatter in gap plots both before and after fire relative to intact plots illustrates the greater variability of fuel composition in gap plots. Third, the pre-burn plots are shifted to the right along the *x*-axis relative to post-burn plots. Because this axis is strongly correlated to leaf litter and 1-h fuels, this indicates that fine fuels such as litter and 1-h fuels exhibited the greatest reduction during burning, and are likely responsible for fire continuity.

3.2. Spatial structure of fuel loading

Fuel loadings showed significant spatial autocorrelation within the gap plots both before (Moran's $I = 0.075$, $P = 0.002$) and after burning (Moran's $I = 0.076$, $P = 0.002$). No significant spatial structure was found in intact plots before burning (Moran's $I = 0.022$, $P = 0.183$), but there was significant spatial structure in the post-burn intact plots (Moran's $I = 0.313$, $P < 0.001$). Furthermore, Moran's *I* values for the post-burn control plots were closer to zero than any treatment plots, illustrating a more even distribution of fuel loads in control plots. The semivariance was smaller after the fire (post-burn treatments) simply because of the reduction in fuel loads after the fire. The range (distance) of spatial variability was similar (8–11 m) between the three treatments.

3.3. Fire radiation characteristics

In general, FRFD and FRED were greater in crown microsites and lowest in non-crown microsites in gap plots. Furthermore, intact plots generally showed intermediate levels of the three measured radiation characteristics (Fig. 6). Mean FRFD (related to mean rate of fuel consumption; Wooster et al., 2005; Freeborn et al., 2008) differed significantly between treatment combinations ($F_{2,10} = 8.929$, $P = 0.006$). Mean FRFD was greatest in crown microsites of gap plots (8.2 kW m^{-2}), lowest in non-crown microsites of gap plots (3.5 kW m^{-2}), and intermediate in intact plots (5.9 kW m^{-2}; Fig. 6A). Tukey's HSD test indicated that crown microsites had higher mean FRFD relative to non-crown microsites in gap plots ($P_{adj} = 0.005$), but intact plots were not significantly different from either crown or non-crown microsites in gap plots ($P_{adj} = 0.094$ and $P_{adj} = 0.058$, respectively).

In the same fashion, peak FRFD (proportional to peak fuel consumption rate and fire intensity; Kremens et al., 2012) differed

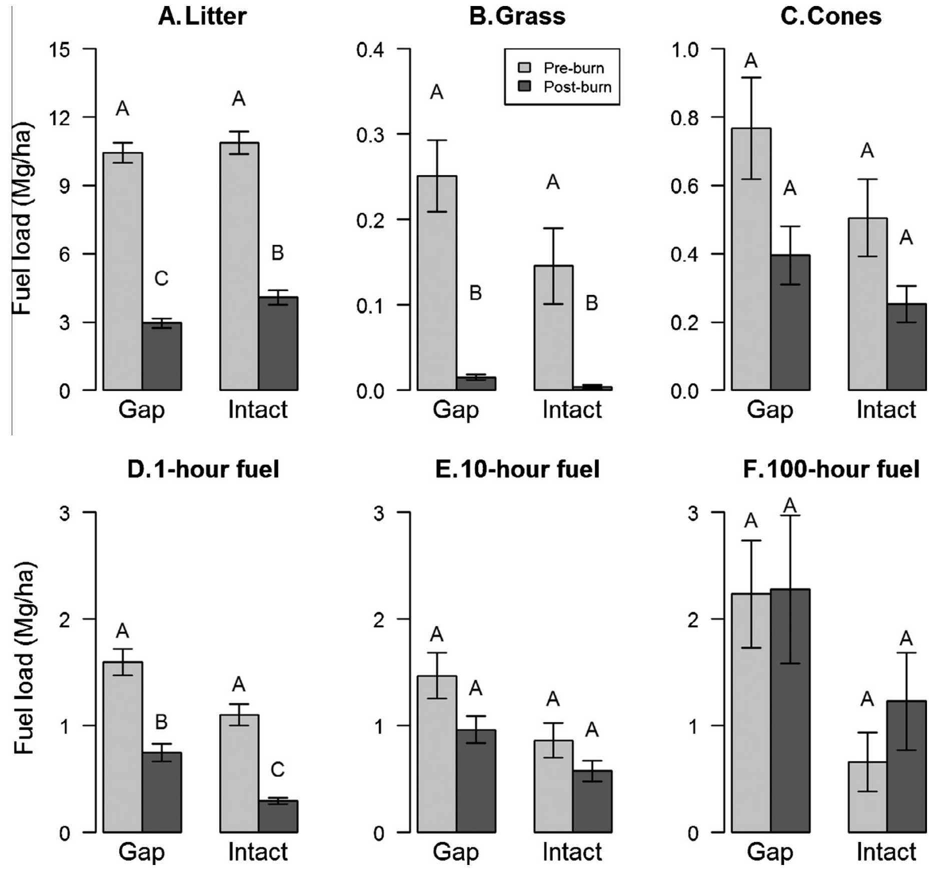

Fig. 4. Mean mass of forest floor fuels comparing experimental gap (G) and intact (I) plots before and after burning. Within each graph, means sharing the same letter are not significantly different (Tukey's HSD, $P_{adj} < 0.05$.) Error bars represent one standard error of the mean.

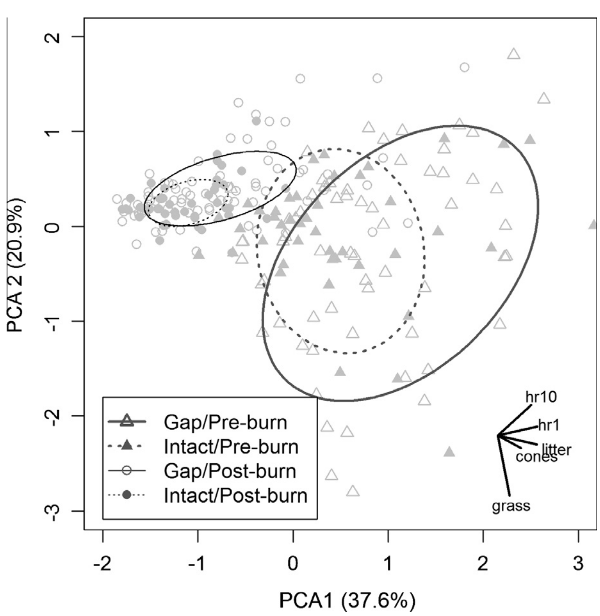

Fig. 5. Principal Components Analysis ordination of fuel composition of experimental gap treatment and intact control plots before and after prescribed burning. Ellipses represent the standard deviation of the mean axis scores for each treatment combination. Inset arrows represent partial correlation vectors, which are proportional in length to the partial correlation of the associated fuel component with each axis.

significantly between treatment combinations ($F_{2,10} = 5.864$, $P = 0.021$). Peak FRFD was greatest in crown microsites of gap plots (48.6 kW m^{-2}), lowest in non-crown microsites of gap plots (13.5 kW m^{-2}), and intermediate in intact plots (24.9 kW m^{-2}; Fig. 6B). Tukey's HSD test indicated that crown microsites had higher peak FRFD relative to non-crown microsites in gap plots ($P_{adj} = 0.019$), but intact plots were not significantly different from either crown or non-crown microsites in gap plots ($P_{adj} = 0.059$ and $P_{adj} = 0.436$, respectively).

Lastly, FRED (related to fuel consumption; Wooster et al., 2005; Freeborn et al., 2008; Kremens et al., 2012) differed significantly between treatment combinations ($F_{2,10} = 9.187$, $P = 0.005$). As with the other combustion characteristics, FRED was greatest in crown microsites of gap plots (8.9 MJ m^{-2}), lowest in non-crown microsites of gap plots (1.2 MJ m^{-2}), and intermediate in intact plots (2.0 MJ m^{-2}; Fig. 6C). Tukey's HSD test indicated that crown microsites had higher FRED relative to both non-crown microsites in gap plots ($P_{adj} = 0.010$) and in intact plots ($P_{adj} = 0.007$). However, FRED did not differ significantly between non-crown gap plots and intact plots ($P_{adj} = 0.900$).

4. Discussion

The results of this study indicate that small-scale wind disturbance may alter aspects of gap-level fire characteristics. Our results suggest that the mechanism by which wind disturbance alters fire combustion characteristics is more nuanced than a simple addition of fuel (e.g., Myers and van Lear, 1998). We found that plots receiving experimental wind disturbance had altered fuel composition and spatial distribution without a corresponding increase in available fuels compared to controls. These changes in fuel

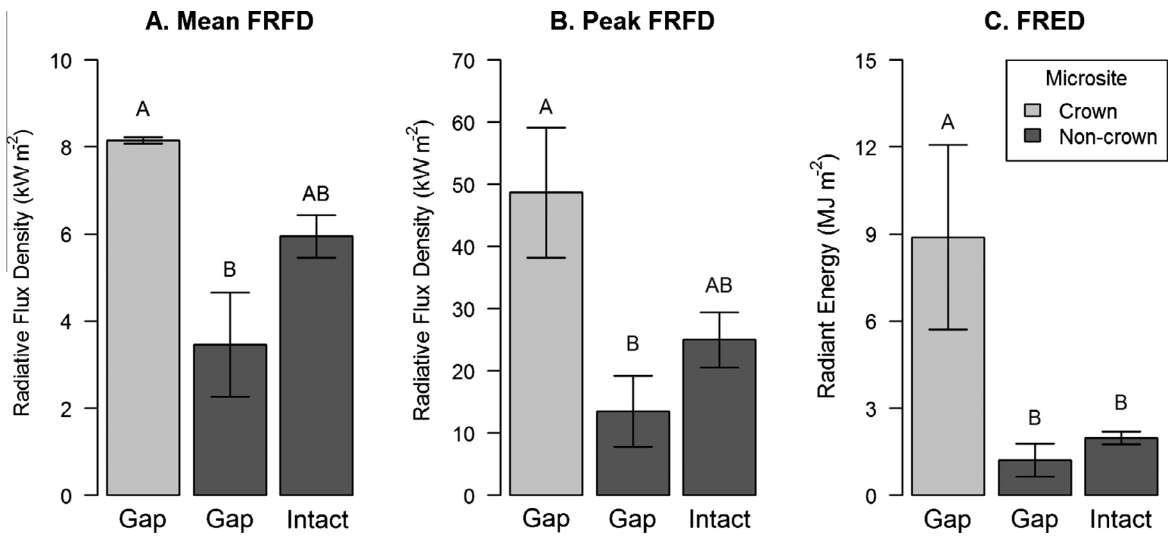

Fig. 6. Measures of fire radiation characteristics including (A) mean fire radiative flux density (FRFD; kW m^{-2}), (B) peak fire radiative flux density (FRFD; kW m^{-2}), and (C) fire radiative energy density (FRED; MJ m^{-2}) in both gap and intact plots. Gap plots contain both crown and non-crown microsites. Error bars represent ± one standard error of the mean. Within each graph, means sharing the same letter are not significantly different (Tukey's HSD, $P_{adj} < 0.05$.).

characteristics led to fires with higher energy released and altered fuel consumption patterns in treatment plots.

4.1. Fuel loading, composition, and consumption

The increase in fuel loading caused by winching in our study was not surprising. Several studies have documented increased fuel loading after hurricane or windthrow (Whigham et al., 1991; Harmon et al., 1995; Busing et al., 2009; Bradford et al., 2012). In our study, simulated wind disturbance substantially increased coarse woody fuels such as 100-h fuels (Fig. 3). Although unmeasured, 1000-h fuels (>7.6 cm diameter) such as downed tree boles dramatically increased after winching (Fig. 2).

Despite increases in 100- and 1000-h fuels, the prescribed fire did not consume these large fuels, likely due to the low intensity of the prescribed fire. Among finer fuels, loading was similar between gap and intact plots. Thus, the observed changes in fire characteristics in gap plots cannot be explained by a simple increase in fuel loading. It appears that more subtle changes in fuel characteristics such as changes in the composition, consumption, and physical arrangement of the fuel may have led to changes in combustion patterns in gap plots. In this study, we found that loading of available fuels was unchanged from winching treatments. While the longest time lag fuels (100- and 1000-h) were not consumed during this prescribed burn, we expect that these larger fuels could combust during a wildfire that occurred after sufficient drying such as during a drought (Fosberg et al., 1981). We hypothesize that in conditions which lead to combustion of these larger fuels, the patterns we have shown here would be accentuated.

Although we found no differences in available fuel loading, the composition of fuel differed between simulated gap openings and the intact forest. Gap openings created by winching had increased representation of grasses, as well as increases in woody fuels (including 1- and 100-h fuels and a marginal increase in 10-h fuels; Fig. 3). Analysis of residual fuels indicated that leaf litter was more thoroughly consumed in gaps while grasses and 1-h fuels were more thoroughly consumed in intact plots (Fig. 4). The PCA ordination comparing fuel composition of treated plots before and after experimental wind disturbance (Fig. 5) illustrated several important changes in fuel characteristics such as differences in variability between gap and intact plots as well as changes in fuel composition before and after burning.

4.2. Spatial structure of fuel loading

The spatial analysis of fuel loads illustrated how wind disturbance can create a more clumped distribution of fuel loadings across an area, even if fuel loads are similar. This discrepancy in spatial structure of fuel loads between treatments may explain differences in consumption of particular fuel types (e.g., litter, grasses). More heterogeneous fuel loadings were likely created by the concentration of fuels in areas such as within downed tree crowns.

Fuels were spatially heterogeneous after burns in both gap and intact plots. This patchy burn structure has been found within similar southeastern ecosystems where fuels and fire behavior vary at very fine-scales (within just a few meters) and throughout the forest matrix with various disturbance patterns (Hiers et al., 2009; Loudermilk et al., 2012; Thaxton and Platt, 2006). The downed trees in gap plots created more spatial variability in consumption, however, than the intact forest, likely a product of less fuel continuity and fire spread potential. Ultimately, spatial connectivity of various fuel characteristics affects fire behavior and consumption patterns at various scales and is not necessarily driven by overall fuel loadings.

4.3. Combustion characteristics

Closely linked to the spatial structure of fuels, we found that fire radiation characteristics were greatly altered in gap plots compared to intact plots. We found that each of the three measured radiation characteristics (mean FRFD, peak FRFD, and FRED) was higher within downed crowns in gap plots and consistently lower in gap plots outside of tree crowns. When comparing the non-crown portions of gap with intact plots, we found no significant differences though non-crown portions of gap plots had significantly lower measures of all three combustion characteristics. These results make clear that extreme fire behavior is localized within downed crowns where fuels are aggregated. Furthermore, we found consistent (though not significant) reductions in fire radiation in non-crown microsites of gap plots. These results suggest that although wind disturbance likely amplifies fire intensity within downed crowns, wind disturbance may lead to somewhat muted fire behavior outside of downed crowns. Thus, to understand how wind disturbance influences fire behavior, it is important to consider the spatial structure of fuels created by wind disturbance which can be influenced by factors such as forest density, wind disturbance severity, as well as the size and degree of overlap of downed tree crowns.

One criticism of our approach of measuring combustion characteristics using radiometers is that the measured radiative energy is a small fraction of the total combustion energy density released from fire—the largest fraction actually coming from convective heat which is difficult to measure. An integrated heat budget (Kremens et al., 2012) and measurements of stationary (Wooster et al., 2005; Freeborn et al., 2008) and spreading flames (Kremens et al., 2012) suggests that radiation from flame fronts accounts for a fraction of total heat dissipation from combustion on the order of 15% as measured from the nadir perspective. Recent laboratory measurements suggest that fire radiated fraction varied from 8% to 15% as fuel moisture content varied from 25% to 0% (i.e., radiated fraction was higher for dry fuels, Smith et al., 2013). This is a large range that would not likely be encountered either within a given wildland fire or among fires. Differences among fuel types are also expected (Smith et al., 2013). Data from spreading fires in 8×8 m plots indicated that fire radiated fraction varied by a standard deviation of 3% among plots (Kremens et al., 2012) as litter moisture in these plots varied from 8% to 14% of dry weight.

For our experiments at PNWR, we were not able to measure fuel moisture before the prescribed fire, but several lines of reasoning suggest that the moisture content of consumed fuels was similar between gaps and intact stands and, thus fire radiated fraction can be assumed to be reasonably constant among gap and non-gap areas. First, the prescribed fire was applied to all plots under consistent weather on the same day and fuel composition varied modestly. Second, data from a related study (Cannon et al., *unpublished data*) shows that the total biomass of the dominant seedlings (*P. taeda* and *Liquidambar styraciflua*) were relatively similar in gap ($23.1\ g\ m^{-2}$) and intact plots ($29.3\ g\ m^{-2}$) so differences in moisture of live fuels is not expected. Grass biomass was higher in gaps, but grasses were cured during our late dormant-season fires. Finally, intact stands had relatively low basal areas (basal area $17–27\ m^2\ ha^{-1}$; mean canopy openness in intact plots was 16.6%), reducing potential differences in fuel drying rates between gaps, where increased wind and solar radiation would be expected. As such, we expect that any effect of variation in fuel moisture and, thus, radiated fraction, between gap and intact plots would be modest. If fuels were more moist in intact plots, the differences were not enough to obscure the results that in non-crown microsites of gap plots all three descriptors of fire radiation were lower than in intact plots (Fig. 6), supporting a conclusion that fuel consumption was also lower in non-crown gap plots than in intact plots.

Although most of the energy dissipated from flame fronts is from convection (Kremens et al., 2012), convection is difficult to measure even at a single point much less over wide areas as can be done for radiation. Given that radiative fraction can be expected to fall within reasonable bounds within a given fire and given that the instruments are sensitive to radiation from even low-intensity flame fronts (Kremens et al., 2012), we believe we are justified in assuming that dual-band radiometer measurements of FRFD are proportional to combustion rates, peak FRFD is proportional to fireline intensity, and FRED is proportional to fuel consumption.

One final caveat regarding the radiometer measurements should be noted. Due to the extremely high combustion rates within downed crowns in gap plots two of the radiometer sensors in those microsites saturated at the highest flux measurement of $59.1\ MJ\ m^{-2}$. However, because fire radiative flux density is recorded at a rate of 1 Hz, and because the period of saturation was brief, less than 0.02% of the readings from each of the two radiometers were saturated. Saturation in the radiometers leads to underestimates of measured fire radiation. Because the saturated radiometers measurements were in the downed crowns, our conclusion that measured fire combustion rates and totals were highest in those sites is conservative.

4.4. Conclusions and management implications

This research further supports the concept of the "ecology of fuels" (Mitchell et al., 2009), where understanding fire effects within a system requires understanding of how fuels link fire behavior and vegetation response. Here, we demonstrate how relatively small areas of downed trees create highly heterogeneous fuels and increased fire radiation and (by inference) fire intensity and fuel consumption in localized areas. Because the intensity of fire is linked to plant mortality at both small and large spatial scales (e.g., Wiggers et al., 2013; Keeley, 2009, respectively), we expect the largest ecological effects of fire on changes in recruitment patterns to be in localized areas of overstory disturbance, where downed trees created patches of higher than average intensity and consumption. In this study, wind disturbance altered several fire radiation characteristics in localized areas. However, because litter input could be reduced following the removal of trees from the canopy, (O'Brien et al., 2008), subsequent fires in these plots are expected to be less intense due to lower fuel continuity. Thus the interaction between wind and fire depends on the both the spatial distribution, order, and the timing of disturbances.

This study sheds light on the mechanisms of interaction between two common forest disturbances—wind disturbance and prescribed fire. Like more extreme disturbances, forest gap-level wind disturbance can interact synergistically with fire to create the potential for more intense fires than possible without prior wind disturbance. The observed interaction between wind disturbance and fire is more complex than a simple addition of fuel as has been hypothesized in previous research. Rather, wind disturbance can increase fire intensity and heterogeneity through changes in fuel composition, consumption, and spatial distribution.

Several temporal and spatial aspects of the wind–fire interaction warrant further exploration. In this study, wind disturbance influenced the combustion characteristics of a prescribed fire one year after the experimental wind disturbance. However, this interaction could change if the time between disturbances increases and processes such as fuel decomposition and deposition alter fuel composition further. Moreover, because vegetation recovery can depend on the type and severity of disturbance, we expect plant communities to differ both between intact plots and gap plots, especially around areas with extreme fire behavior such as downed crowns, and are currently investigating this possibility in a parallel study. In some cases, using a prescribed fire following a wind disturbance may be an opportunity for managers to favor specialist rather than generalist plant communities after wind disturbance (Cannon and Brewer, 2013; Brewer et al., 2012). For example, Cannon and Brewer (2013) describe how utilizing prescribed fire following wind disturbance may help restore dwindling upland oak communities in Mississippi. With a better understanding of how disturbances interactively affect forest recovery, managers can make more informed decisions on how to manage wind-disturbed forests.

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Table A1
Parameters for modeling the exponential semivariograms of total fuel (Mg ha^{-1}) in SGeMS (Remy et al., 2009) within treatments including, numbers of lags, lag separation distance, lag tolerance distance, sill, and range distance. The nugget was zero for all models. There was no spatial autocorrelation found within the intact:pre-burn plots.

Treatment combination	No. of lags	Lag separation (m)	Lag tolerance (m)	Sill (Mg ha^{-1})	Range (m)
Gap:pre-burn	10	4	2	27	10
Gap:post-burn	10	2	1	7.5	8.2
Intact:pre-burn	NA	NA	NA	NA	NA
Intact:post-burn	10	5	2.2	4	11

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Appendix A

(See Table A1).

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