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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.