Forest Ecology and Management 302 (2013) 273–279

Contents lists available at SciVerse ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Disturbance size and severity covary in small and mid-size wind disturbances in Pennsylvania northern hardwoods forests

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ARTICLE INFO

Article history:
Received 17 October 2012
Received in revised form 22 March 2013
Accepted 24 March 2013
Available online 27 April 2013

Keywords:
Disturbance
Windthrow
Gaps
Northern hardwoods
Light
Size

ABSTRACT

Do large disturbances differ from small ones in characteristics other than size? The importance of disturbances in forest dynamics is unquestioned, and the size of the disturbed area (size of gap) is the most common way of differentiating disturbances. But few studies have examined other disturbance characteristics to see if small and large disturbances are different. In northern hardwoods forests of northwestern Pennsylvania, a 2003 windstorm event created windthrow gaps ranging in size from 0.1 ha to >100 ha, allowing comparisons across a broad size spectrum, yet with similar species composition, soils, climate, and topography. We selected 17 gaps, ranging in size from 0.05 to 4.0 ha, to compare damage characteristics across a size spectrum. Disturbance severity (both proportion of trees fallen, and proportion of basal area fallen) increased significantly with gap size. Similarity in floristic composition between pre- and post-disturbance stands, decreased with increasing gap size. Larger gaps also caused greater reduction in mean size (diameter) of remaining trees. As expected, larger gaps resulted in greater canopy openness, but canopy openness was significantly influenced by both gap size and severity of canopy disturbance. These findings demonstrate that disturbance size and severity covary in northern hardwood windthrow gaps. Moreover, because of nonrandom impacts across species and size classes, immediate changes in size structure and composition of affected stands were greater in larger gaps. Managers seeking to implement disturbance-based management can use these findings to more closely mimic natural damage effects during harvest operations.

1. Introduction

Disturbances are one of the fundamental determinants of forest structure, composition, and dynamics (Turner, 2010), and their effects vary with size, severity, frequency, and other disturbance traits (White and Jentsch, 2001). Such complex and multidimensional variation can make it difficult to generalize how disturbance will impact forest regeneration (Webb, 1999). However, if there are predictable correlations among key disturbance attributes, then fewer disturbance characteristics will be required to understand disturbance impacts to forests. An example of a well-established correlation among disturbance characteristics is that large disturbances are less frequent than smaller ones, leading to consideration of 'large infrequent disturbances' as a class (Romme et al., 1998; Turner and Dale, 1998). Seymour et al. (2002) examined disturbance size and frequency across New England and the upper Midwest, and found that some theoretically possible combinations of size and frequency never occurred in nature. However, the relationship of other disturbance characteristics (e.g. severity) with disturbance size is less known. What remains unclear is the degree to which large disturbances differ from small ones, beyond being less frequent. Indeed as Turner et al. (1997) point out, there have been few attempts to rigorously address this question (see also Romme et al., 1998; White and Jentsch, 2001).

Franklin et al. (2000) argued that "from an ecological perspective it is severity of the disturbance that is of greatest interest", and severity lies at the heart of several recent conceptual models of forest dynamics (Frelich and Reich, 1999; Frelich, 2002; Roberts, 2004, 2007). Vegetation response is a function of disturbance severity and only one other key variable (Frelich, 2002), or a function of several components of severity (Roberts 2004, 2007). If size and severity are correlated, then predictive models could use size (usually easier to measure) as a surrogate for severity. Indeed, White and Jentsch (2001) state that researchers have almost universally used gap size as a surrogate for other disturbance charac-

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http://dx.doi.org/10.1016/j.foreco.2013.03.045

teristics, but without a strong empirical basis for such substitution. Given this importance, we evaluate the relationship between disturbance patch size and severity for a suite of windstorm gaps in northern hardwood forests of Pennsylvania. We are aware of only one explicit empirical examination of relationships between size and severity of disturbance patches. Turner et al. (1994), studying burned patches formed in the 1988 Yellowstone National Park fires, concluded that indeed, large burned areas are qualitatively different from small ones due to greater burn severity in larger patches.

How might size and severity covary? It is known that the most intense tornadoes (rated EF4 and EF5 on the Enhanced Fujita Scale) have larger damage paths than lower-intensity tornadoes (Brooks, 2004). Suspecting that a similar size–intensity relationship exists for thunderstorm winds, we might predict that larger convection cells in the broader storm system produce greater wind speeds, and therefore we hypothesize that (1) cells causing larger blowdown patches will inflict greater damage (i.e. higher severity). If this hypothesis is true, then several corollaries are suggested. It is known that wind disturbances selectively damage larger trees in a given stand, and that species with weaker wood generally show greater vulnerability to wind damage than their associates (Everham and Brokaw, 1996; Webb, 1999; Peterson, 2004, 2007). Therefore, greater severity of damage should cause greater reduction in (standing) tree size and greater shifts in species composition between the pre- and post-disturbance stand. Note that this expectation is distinct from the probable consequences of disturbances that are not size selective (trees are removed independently of their size, causing little change in size distributions), or from the consequences of disturbances (e.g. floods, surface fires) that preferentially remove smaller size classes (expected consequence is removal of the lower tail of the size distribution). Because of the greater removal of dominant trees by winds, evenness among species should be increased by wind disturbance; therefore we also hypothesized that greater severity of damage should increase diversity. In sum, we hypothesize that larger gaps would have (2) greater reduction in mean tree size; (3) greater change in species composition; and (4) increased species diversity.

For wind disturbances in particular, we know of no published studies that compare characteristics of windthrow gaps across a large range of gap sizes, though numerous studies have examined the 'small' ($\ll$0.5 ha) end of the gap size spectrum (e.g. Runkle, 1981, 1982, 1985; Canham, 1988; Poulson and Platt, 1989; Lertzman, 1992; Royo et al., 2010). In this study, we exploit the existence of numerous recently-created windthrow gaps that span the small-to-medium size range (0.05–4 ha; Evans et al., 2007). Using gaps created at the same time and in the same general area reduced variation in canopy composition, elevation, soil type, and time since disturbance, among other factors, thereby allowing us to hone in on the relationship between gap size, severity, and immediate change in forest vegetation.

In applied contexts, the rise of disturbance-based management (Attiwill, 1994; Perera et al., 2004; Drever et al., 2006) has managers seeking quantitative ranges for natural disturbance characteristics; these natural ranges can provide boundaries for size, severity, shape, etc., of disturbances resulting from human forest interventions. The rationale is that forest species are likely to be adapted to natural disturbance characteristics, and therefore forest plant communities are unlikely to experience severe detrimental impact from the natural events that are typical in a region. Consequently, management actions that fall within the range of natural variability in size, severity, frequency, and other characteristics, should have minimal negative impact on community and ecosystem structure and function, and therefore be more sustainable. While a great deal of research has documented size and frequency of disturbance regimes in temperate forests (Runkle, 1985; Everham and Brokaw, 1996; Webb, 1999), little attention has been directed towards severity. Those studies that employ historical reconstructions (e.g. Lorimer, 1977; Canham and Loucks, 1984; Foster, 1988a), can provide great temporal depth and sometimes extensive spatial coverage, but they seldom evaluate severity.

2. Materials and methods

2.1. Study sites

Previous studies have documented the patterns of damage to northern hardwood forests of Allegheny National Forest in western Pennsylvania, following tornadoes in 1985 (Peterson and Pickett, 1991) and 1994 (Peterson 2000, 2007). In this study, we focus on the 'small' to 'medium' part of the size continuum, by examining 17 canopy gaps created by a severe windstorm that struck northwestern Pennsylvania in July 2003. The storm created >200 gaps within Allegheny National Forest (ANF), ranging in size from 0.1 ha to >40 ha.

The ANF is characterized as having a continental climate, with warm summers and long, cold winters, with an average July temperature of 18.9 °C and an average annual temperature of 7.8 °C. Precipitation averages 1067 mm per year, with 38% falling between June and October (Bjorkbom and Larson, 1977). The majority of ANF, and all of our study sites, are located on the Allegheny Plateau, a rugged highland characterized by broad level plateaus dissected by steep river valleys; elevations range from 305 to 732 m. Soils are mostly sandstones and siltstones, and are rocky and acidic (Table 1). According to soil surveys, all of the sites were considered to have only 'slight' risk of treefall, on the basis of soil characteristics; while fragipans are often present, rooting depth is almost always >50 cm, implying that variation in severity of damage is not likely due to soil differences (Table 1).

The vegetation of the gaps we studied is classified as the Allegheny hardwoods variant of the broader northern hardwoods type. Major dominant tree species are *Acer rubrum*, *Acer saccharum*, *Prunus serotina*, and *Fagus grandifolia*, with somewhat lesser abundances of *Tsuga canadensis*, *Betula alleghaniensis*, *Betula lenta*, and *Fraxinus americana*. Understory vegetation is dominated by *Acer pensylvanicum* and *F. grandifolia* (mostly root sprouts) in the shrub layer, and a variety of mesic forest ferns (e.g. *Dennstaedtia punctilobula* and *Thelypteris noveboracensis*) and forbs (e.g. *Oxalis acetosella*) in the field layer (Royo et al., 2010). Large gaps often have extensive carpets of *Rubus allegheniensis* (Peterson and Pickett, 1995; Peterson and Carson, 1996).

2.2. Field methods

Aerial reconnaissance of the ANF shortly after the July 2003 storm showed >200 gaps, which were manually drawn onto a map (Evans et al., 2007). We randomly selected gaps within several size categories to choose our 17 study sites. Gaps were sampled during July and August 2004. To characterize gap size, we measured two perpendicular axes, and used these to define the length of dimensions for the appropriate geometric shape (oval, circle, half-circle) for calculating area (in m^2) of the gap (Table 1).

Within each disturbed area, we established several parallel transects across the gap, on which damage survey points were distributed in a stratified random manner. For the 13 larger gaps, we sampled 16 damage survey points whereas the four smallest gaps had 7–13 survey points, because of space limitations. The damage survey points nearest the disturbed area edge were a minimum of 7.5 m from the intact forest; all others were further into the disturbed area. All trees (>10 cm dbh) within 7.5 m of a damage survey point were tallied for species, size (diameter at 1.4 m, or