Chapter 5
First Steps Toward Defining the Wind Disturbance Regime in Central Hardwoods Forests

Chris J. Peterson, Jeffery B. Cannon, and Christopher M. Godfrey

Abstract Wind disturbance is one of the most prevalent natural disturbances in the Central Hardwoods Region (CHR). All ecoregions within the CHR are subject to a greater or lesser degree to tornado, derecho or thunderstorm wind damage, with an east-to-west increase in the importance of tornadoes and derechos. At the regional scale, hurricanes decrease in importance with distance from the Atlantic and Gulf coasts. The disturbed patch sizes created by these various storms include occasional very large (e.g., >25 ha) patches, but the great majority are a few ha or less, perhaps differing from common visual impressions. Hurricane and derecho disturbance patterns appear to be more predictable in relation to topographic features, whereas tornado damage is much more stochastic. All wind disturbance types cause greater damage to larger trees, and most studies reveal interspecific differences in levels of wind damage, although such patterns are not always consistent among studies or locations. Wind disturbance commonly advances succession in second-growth forest but may set succession back in primary forests. The greatest research needs are landscape-scale patterns of damage; relationships of damage to topography and soils; clarifying the tree characteristics (e.g., architecture, wood strength, rooting depth) that underlie interspecific differences in vulnerability; and documenting ecosystem effects of wind disturbance.

Keywords Wind • Blowdown • Tornado • Hurricane • Disturbance regime

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C.H. Greenberg, B.S. Collins (eds.), *Natural Disturbances and Historic Range of Variation*, Managing Forest Ecosystems 32,
DOI 10.1007/978-3-319-21527-3_5

5.1 Introduction

Wind may be the most widespread agent of natural disturbance in the Central Hardwoods Region (CHR), as well as across temperate forests of eastern North America (White 1979; Everham and Brokaw 1996). This pervasiveness may increase or decrease over time in a nonstationary climate, though just how climate changes may alter storm size, frequency, or severity is a topic of active discussion (Trapp et al. 2007; Grinsted et al. 2013; Dale et al. Chap. 14). Nevertheless, the recent shift towards forest management modeled on natural disturbance regimes requires quantitative information on characteristics of the wind disturbance regime (e.g., Perera et al. 2004).

In this chapter, we seek to present a synthesis of wind disturbance characteristics in the CHR (Fig. 5.1; see Greenberg et al. Chap. 1, Fig. 1.1 for CHR ecoregions map), as well as the immediate impacts of these disturbances on forest structure and composition. Due to space constraints, we are not examining the longer-term patterns of regrowth and recovery following wind disturbance (e.g., Everham and Brokaw 1996; Webb 1999; Busing et al. 2009). Xi and Peet (2011) propose that the temporal scale of research be categorized as immediate (a few months to 1 year), short-term (several months to several years) and long-term (a decade to centuries); within this rubric, we will focus mostly on immediate effects, with just a few comments on longer-term effects in light of possible effects of storms on forest succession. We consider forest damage from hurricanes, tornadoes, derechos, and other types of wind event.

We should begin with a note on the organization of this chapter. The meteorology and climatology, as well as broad-scale patterns in wind event frequency and severity are distinctive for the different types of wind storms, so we organize around types of storm for these topics. In contrast, where we discuss damage patterns to forests at the stand and individual scale, we organize around forest characteristics or response variables, because at the finer scales the differences among types of storm diminish while the differences among response variables remain substantial. Further, we will attempt to highlight CHR forests to the degree possible, but will of necessity also include research from outside the CHR (Fig. 5.1). This is necessary because of the limited number of studies within the CHR, in comparison to many studies in northern hardwoods and sub-boreal forest types to the north, and coastal plain and other forests to the south. As with any active area of research, we will note areas in which research, and thus understanding, is scant.

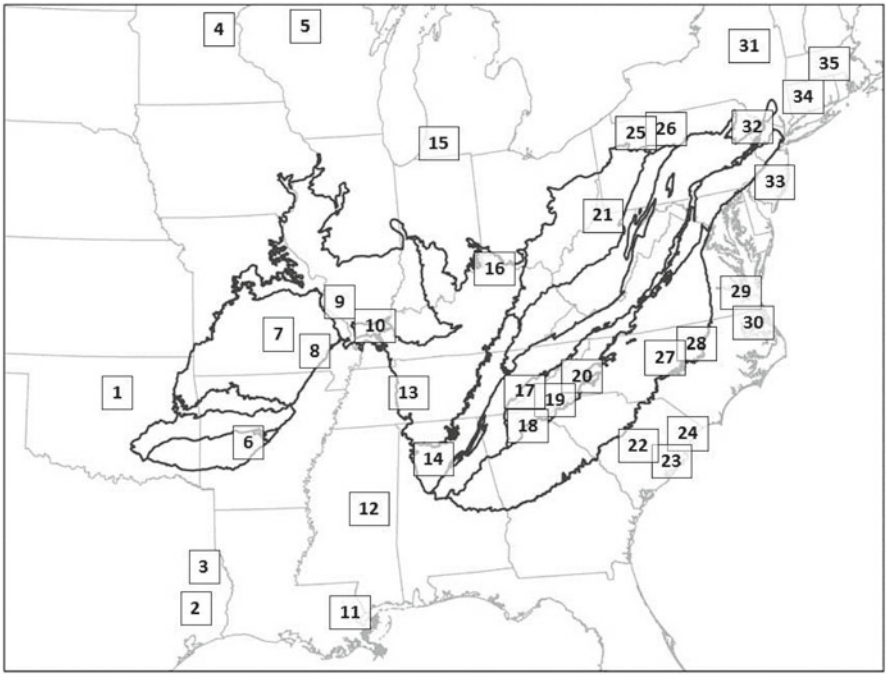

Fig. 5.1 Geographic distribution of wind disturbance studies in and near the CHR; ecoregions delineated with *dark black* lines (see Greenberg et al. Chap. 1, Fig 1.1 for ecoregion names). Numbers denote study locations, roughly from west to east, and correspond with citation number. Some citations (e.g., Peterson 2007) are listed more than once because the study reports findings from multiple locations. *1* – Myster and Malahy 2010; *2* – Glitzenstein and Harcombe 1988; *3* – Harcombe et al. 2009; *4* – Palmer et al. 2000; Arévalo et al. 2000; Allen et al. 2012; *5* – Dunn et al. 1983; Lang et al. 2009; *6* – Phillips et al. 2008; *7* – Rebertus and Meier 2001; *8* – Peterson and Rebertus 1997; *9* – Holzmueller et al. 2012; *10* – Nelson et al. 2008; *11* – Chapman et al. 2008; *12* – Kupfer et al. 2008; *13* – Peterson and Leach 2008a, b; *14* – Cowden et al. 2014; *15* – Brewer and Merritt 1978; *16* – Held and Winstead 1976; Held and Bryant 1989; Held et al. 1998; *17* – Cannon et al. unpubl; *18* – Cannon et al. unpubl; Sobhani et al. 2014; *19* – Elliott et al. 2002; *20* – Greenberg and McNab 1998; McNab et al. 2004; *21* – Rentch 2010; *22* – Putz and Sharitz 1991; Battaglia et al. 1999; *23* – Duever and McCollum 1993; *24* – Hook et al. 1991; Gresham et al. 1991; *25* – Peterson et al. 1990; Peterson and Pickett 1991; Peterson 2000; *26* – Evans et al. 2007; Peterson et al. 2013; *27* – Busing et al. 2009; *28* – Xi et al. 2008a, b; *29* – Prengaman et al. 2008; Kribel and Ware 2014; *30* – Laing et al. 2011; *31* – Robinson and Zappieri 1999; Canham et al. 2001; *32* – Peterson 2007; Sobhani et al. 2014; *33* – Matlack et al. 1993; *34* – Peterson 2007; *35* – Foster 1988; Foster and Boose 1992

5.2 Storm Characteristics and Geographic Distribution; Landscape-Scale Patterns

5.2.1 *Hurricane Disturbance*

Hurricanes are certainly the largest and probably best-studied agent of forest wind disturbance (Foster and Boose 1995; Xi and Peet 2011). The terms 'hurricane' and 'typhoon' are local names for strong tropical cyclones; they occur over all of the world's oceans, but are especially common over the tropical north Atlantic. A tropical cyclone is the generic term for a non-frontal synoptic scale low-pressure system over tropical or sub-tropical waters with organized convection (i.e., thunderstorm activity) and definite cyclonic surface wind circulation. Tropical cyclones with maximum sustained surface winds of less than 63 km per hour are usually called 'tropical depressions.' Once the tropical cyclone reaches winds of at least 63 km per hour they are typically called a 'tropical storm' and are assigned a name. If winds reach 119 km per hour, then they are called (in North America) a 'hurricane' (Landsea 2014). In the USA, hurricanes are ranked according to the Saffir-Simpson intensity scale, based on maximum wind speeds: Category 1 has winds from 119 km per hour – 153 km per hour; Category 2 has winds from 154 km per hour – 177 km per hour; Category 3 has winds from 179 km per hour – 208 km per hour; Category 4 has winds from 209 km per hour – 156 km per hour; and Category 5 has winds in excess of 253 km per hour.

The physical structure of a hurricane consists of a central circular 'eye' typically several tens of km in diameter with relatively calm winds, clear skies and low pressure, immediately surrounded by the eyewall, which is the location of intense precipitation and the highest wind speeds. Further out, multiple arms of the vortex carry rain bands that can deposit months-worth of rain within a few hours. Although some hurricanes can be compact with heavy damage restricted to areas within 30–50 km of the path of the eye, some are much larger, with damage extending out to 300 km or more from the eye (Rauber et al. 2002). Due to their extensive size, damage from hurricanes can spread over an exceptionally large area: Hurricane Katrina (2005) damaged roughly 2 million ha of timberland (Stanturf et al. 2007). Earlier, Hurricane Hugo (1989) caused damage to 1,821,000 ha in South Carolina and 1,092,600 ha in North Carolina (Xi and Peet 2011).

Hurricane intensity may be evaluated on the basis of either low atmospheric pressure (measured in millibars), or maximum wind speeds. The most intense Atlantic basin hurricanes to strike the mainland USA have been Wilma (2005, 882 millibars), and Hurricanes Camille (1969) and Allen (1980), both of which produced wind gusts to 306 km per hour (Landsea 2014). There is apparently little or no correlation between hurricane size and intensity (Landsea 2014).

5.2.1.1 Formation and Movement

A hurricane is a vast rotating vortex that is powered by warm ocean surface waters; thus hurricanes rapidly lose intensity once they move over large land masses, a process that is further enhanced by friction with the rougher surface of land masses. The result is that such storms typically decrease to tropical storm and then to tropical depression intensity as they move further inland (Foster and Boose 1995).

Formation of a tropical cyclone requires several conditions: (a) warm ocean surface waters (at least 26.7 °C); (b) an atmosphere which cools fast enough with height such that it is potentially unstable to moist convection; (c) relatively moist layers near the mid-troposphere; and (d) low values (less than about 37 km per hour) of vertical wind shear. All this must take place at least 300 km from the equator in order for the Coriolis effect to influence the force balance of the wind. For Atlantic basin hurricanes, these conditions are usually met in one of three ways. Some tropical cyclones develop from convection within the Intertropical Convergence Zone (ITCZ), a region of persistent thunderstorm activity near the equator that corresponds with the convergence of the equatorward surface branch of the Hadley circulation in both the northern and southern hemispheres. Tropical cyclones may also form from stalled cold fronts that provide a lifting mechanism for convection in the oceans. By far the most common formation mechanism involves tropical easterly waves. These troughs of low pressure and associated regions of surface convergence result from previous convection over Africa and move westward along the easterly trade winds. Once convection initiates through any of these formation mechanisms, latent heat release from water vapor condensation in the atmosphere induces a low pressure center at the surface, which increases the surface convergence, enhancing lift, producing more thunderstorms, and so on in a positive feedback cycle. If a collection of thunderstorms does in fact organize into a tropical cyclone in this area, the system may last for several days or even 2–3 weeks as it moves westward and subsequently often northward.

Hurricanes that form over the subtropical north Atlantic ocean are initially pushed westward by the easterly trade winds, but as they near the Caribbean and/or North American continent, they eventually get pushed towards the northeast, causing many to have a parabolic overall track (Rauber et al. 2002). A weak northerly push occurs if the Bermuda high is strong and directs hurricanes into the Gulf of Mexico; a stronger push occurs if the Bermuda high is weak, and directs storms back into the central Atlantic. If the Bermuda high is intermediate in strength, the moderate push steers storms along the eastern seaboard of North America.

5.2.1.2 Climatology

Atlantic hurricanes form predominantly from July through October. The average number of hurricanes that make landfall on the USA coast follow a monthly pattern: June – 0.12; July – 0.15; August – 0.48; September – 0.67; October – 0.33; November – 0.03 (average number of hurricanes per year for the month). Their long-term trends in frequency, size and intensity have been the subject of much scrutiny, particularly because of interest in how these storm characteristics may change in the future. It is clear that hurricane occurrence fluctuates on decadal and perhaps centennial time scales (Zeng et al. 2009), with the period 1870–1900 being a time of somewhat greater hurricane activity along the eastern USA coast than most of the twentieth century.

On average, 6.2 systems per year reach hurricane force in the Atlantic basin, with a record high of 15 (2005) and low of 2 (2013). Not all of these storms make landfall, and some of those that do strike islands of the Caribbean or along the Central American coast. On average, 1.7 landfalling hurricanes strike the continental USA each year, with a high of seven in 1886 and lows of zero in numerous years (Landsea 2014). For the entire USA East and Gulf coasts, a total of 209 hurricanes have made landfall between 1901 and 2012; of these, 79 were Category 1, 49 were Category 2, 62 were Category 3, 16 were Category 4, and 3 were Category 5 (NOAA/NCDC undated a).

Different portions of the USA Atlantic and Gulf coasts have quite different risk of being hit by hurricanes. Along the southern Atlantic coast, risk is greatest along the coast of North Carolina (every 5–7 years), least on the Georgia and northern Florida coasts (every 10–13 years), and much higher again along the south (east) Florida coast (Fig. 5.2). In the Gulf, risk is greatest for sections of coastal Louisiana along the Mississippi River delta (once every 7–8 years, on average), but quickly decreases a short distance away. Coastal areas of Georgia, northern Florida and southern South Carolina have a comparatively lower frequency of hurricanes; this area comprises the South Atlantic Bight, which due to its concave shape and broad

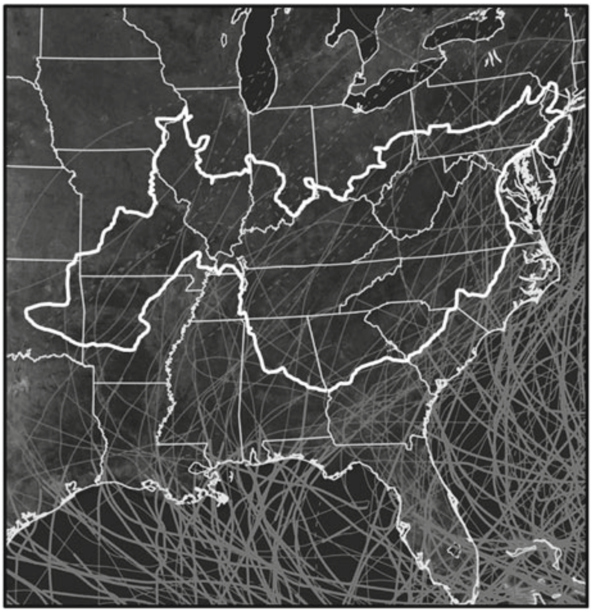

Fig. 5.2 All North Atlantic major Hurricanes (At least category 3 on the Saffir-Simpson hurricane scale), 1851–2013. Figure from NOAA Coastal Services Center 'Historical Hurricane Tracks' online tool. Heavy *white* line delineates boundary of CHR

sloping continental shelf, experiences far fewer landfalling hurricanes than areas just to the north or south.

The loss of storm intensity as a system moves over land has important implications for the geographic distribution of hurricane damage to forests (Xi et al. 2008a, b; Xi and Peet 2011), most notably that CHR forests will rarely experience a hurricane in its initial full intensity (see Fig. 5.2; dotted lines indicate storm tracks after intensity has dropped to tropical storm intensity). Maritime and lower Coastal Plain areas of the southeastern USA bear the full or substantial brunt of hurricanes, but by the time they reach the southern Appalachians, hurricane-force winds have usually diminished to tropical depression levels. In the study by Zeng et al. (2009) all areas with an expected hurricane return interval (hurricane-force winds) of <10 years were within 20 km of the coast, and all areas with an expected return interval of <100 years were within 50 km of the coast. Table 5.1 presents hurricane frequencies for several ecoregions within the CHR, broken down by storm intensity category. Several trends are immediately apparent. First, none of the CHR ecoregions experience Category 4 or Category 5 hurricane impacts, and the only ecoregion to experience Category 3 impacts (very rarely) is the Piedmont. However, even the Piedmont is seldom hit by Category 2 or Category 3 hurricanes (4 and 2 times, respectively, over the 172 years of the data archives). Moreover, Category 1 hurricanes have never been recorded in 8 of the 13 CHR ecoregions. Conversely, all ecoregions within the CHR do experience tropical storms to a greater or lesser degree; these are more often extreme precipitation than extreme wind events. Tropical storm frequencies are highest in the Blue Ridge Mountains, Northern Piedmont, and Boston

Table 5.1 Hurricane frequencies among ecoregions of the CHR, by intensity category. Frequencies are based on number of hurricane (eye) tracks that passed through or within 50 km of each ecoregion during the period 1842–2013

	Hurricane intensity category			
Ecoregion (area in km^2)	Trop. storm	Cat. 1	Cat. 2	Cat. 3
Ouachita Mountains (26,896)	1.96 (9)	0	0	0
Arkansas Valley (28,421)	1.85 (9)	0	0	0
Boston Mountains (14,178)	2.48 (6)	0	0	0
Ozark Highlands (106,391)	0.38 (7)	0	0	0
Piedmont (166,117)	1.68 (48)	0.35 (10)	0.14 (4)	0.07 (2)
Northern Piedmont (30,459)	2.50 (13)	0.57 (3)	0.19 (1)	0
Blue Ridge Mountains (46,595)	2.01 (16)	0.50 (4)	0.12 (1)	0
Ridge and Valley (115,483)	1.57 (31)	0.25 (5)	0	0
Southwestern Appalachians (37,994)	1.54 (10)	0.15 (1)	0	0
Central Appalachians (62,050)	0.47 (5)	0	0	0
Western Allegheny Plateau (81,440)	0.29 (4)	0	0	0
Interior Plateau (123,523)	0.52 (11)	0	0	0
Interior River Valleys (120,405)	0.15 (3)	0	0	0

Values are frequency per century per 10,000 km^2. Values in parentheses are raw (not adjusted for ecoregion area or unit time) number of hurricanes during the 172 years per ecoregion and category

Mountains ecoregions (Table 5.1), although the latter is probably an anomaly due to the very small area of the Boston Mountains ecoregion, compared to most others within the CHR.

5.2.1.3 Landscape-Scale Patterns

The landscape-scale distribution of hurricane damage to forests is best understood based on storm size coupled with the counter-clockwise rotating vortex storm structure. From these factors, several expectations can be derived, which have mostly been confirmed in empirical studies. First, because of the combination of both rotational and translational (forward movement) winds, storm intensity is greatest on the right side of a forward-moving hurricane; on the left side, the realized wind velocities are the difference between rotational and translational speed. Therefore, damage is usually substantially greater to the right of the path of the eye (Foster and Boose 1995; Dahal et al. 2014).

Second, damage severity is usually distributed in a 'nested' pattern, with most severe forest damage in the vicinity of the eyewall track, and lesser severities at increasing distances from the track (Stanturf et al. 2007; Xi et al. 2008b). This is driven by decreasing wind speeds at greater distances from the hurricane's eye. In their study of landscape- and regional-scale influences on forest damage from Hurricanes Hugo and Fran in North and South Carolina, Xi et al. (2008b) documented a significant decrease in damage with increasing distance from the eye.

Third, perhaps most prominent is that windward and leeward topographic positions are easily recognized given the size and location of a hurricane; forest damage is often greater on the windward positions than the leeward positions (Boose et al. 1994; Negron-Juarez et al. 2014). McNab et al. (2004) found that the remnants of Hurricane Opal created intermediate-sized gaps most frequently on southeasterly aspects at the Bent Creek Experimental Forest (BCEF) watershed in the southern Appalachians near Asheville, North Carolina. Xi et al. (2008b) also found that damage from Hurricane Fran at Duke Forest increased with exposure and slope, although the influence of aspect was not significant in that study, perhaps because the more modest terrain in the Piedmont diminished the dramatic differences in aspect that occur in the mountains. A corollary of this is that flat or gently rolling landscapes may have few sheltered, leeward positions, and consequently, forest damage may be much more widespread than in landscapes with mountains or other rugged topography that might provide some sheltered locations (Boose et al. 1994).

There are also elevational effects on forest damage in hurricanes, but they are complex. For example, Xi et al. (2008b) reported greatest damage from Hurricane Fran on ridgetops, but also found that valley bottoms sometimes were severely disturbed. McNab et al. (2004) found that localized gaps created by Hurricane Opal at the BCEF in western North Carolina were much more likely at lower elevations, with few damaged patches on ridges.

Disturbed patch size after hurricanes can be quite large in areas closer to the coast, but small blowdown patches are much more frequent. At Duke Forest

(36.017° N, 78.997° W) after Hurricane Fran, Carpino (1998) found that most patches of severe damage were ~0.2 ha in size, and the largest gaps reported by Xi et al. (2008a) were only 0.8 ha. McNab et al. (2004) documented gaps created by the remnants of Hurricane Opal with a mean size of 0.7 ha, ranging from 0.1 to 3.9 ha, at the BCEF in western North Carolina. At the small end of the size scale, scattered treefalls created by hurricanes are very similar to small gaps created by other processes (Hart Chap. 2). Nevertheless, even further inland the occasional large gap can be formed from hurricane remnants; Elliott et al. (2002) studied regeneration in a 10 ha hurricane-created gap at the Coweeta Hydrologic Laboratory in western North Carolina, 400 km from the coast.

More than a few km from the Atlantic or Gulf shoreline, most of the forest damage caused by hurricanes is directly caused by winds, although the sometimes extreme quantities of precipitation can saturate soils and cause trees to lose stability, thereby increasing the amount of damage caused by a given wind velocity. Whereas this seemingly straightforward pattern is often seen, it is not universal. Some hurricanes add relatively little precipitation prior to the impacts of the highest winds, leaving the soil less saturated and tree stability uncompromised (e.g., Hurricane Hugo 1989, in Xi et al. 2008a). In other cases, bottomland and swamp tree species (e.g., Putz and Sharitz 1991; Oswalt and Oswalt 2008; Harcombe et al. 2009) that under normal conditions grow in wet or saturated soils, may not be greatly weakened by the large amounts of precipitation in a hurricane, and therefore experience less damage.

5.2.2 Tornado Disturbance

Tornadoes are mesoscale convective phenomena that harbor the strongest known winds of all types of storms. Very powerful tornadoes have winds in excess of 375 km per hour, and individual suction vortices within a large tornado may exceed even these velocities. Countering these extreme wind velocities, individual tornadoes are far smaller than other types of wind event, with damage swaths ranging from 50 m to 4 km wide, and a few to several dozen km long; in rare cases, though, exceptionally long-lived tornadoes may have damage tracks that exceed 200 km in length (Rauber et al. 2002). Tornadoes occur on all continents, although North America is home to far greater frequencies than anywhere else on earth; the average annual number of tornadoes in the continental USA is 1,253 (NOAA/NCDC undated b), with most of those located in the eastern USA (Fig. 5.3). Tornadoes may occur singly, in small clusters, or in very large outbreaks; the infamous April 26–29, 2011 outbreak in the southeastern USA produced > 300 tornadoes, and claimed 322 lives.

In the USA, tornado intensity was classified from the 1970s through 2007 according to the Fujita scale (or F-scale). In this system, levels of damage to a variety of structures or objects were used to assign an F-scale value of 0 through 5 to any tornado, with 0 indicating the least damage and weakest tornadoes, and 5 indicating the most extreme damage and strongest tornadoes (Fujita 1971). In 2007, an

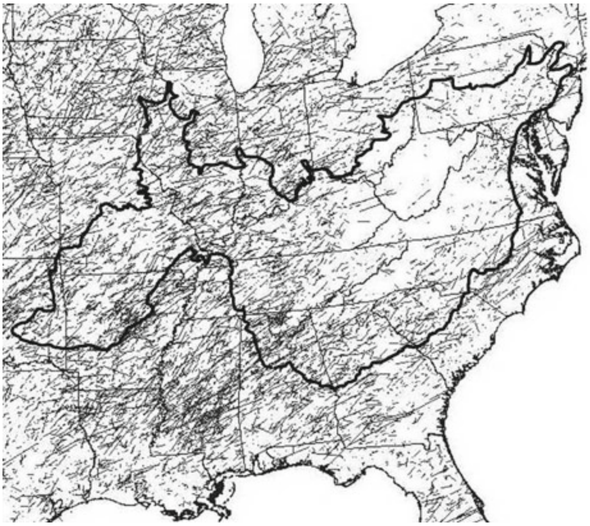

Fig. 5.3 All known tornado tracks in the eastern USA (1950–2013) with the CHR delineated in *dark* outline (Map from NOAA Storm Prediction Center's SVRGIS)

improved damage rating scale, the Enhanced Fujita scale or EF-scale, was put into practice across the United States (WSEC 2006). The EF-scale modified the wind speed estimates used in the original F-scale, and included a broader range of damage indicators (the structures or objects whose damage is used to derive the EF-scale classification). Notably, the EF-scale includes two damage indicators (DI 27 and DI 28) based on trees, but very recently, several publications have begun to point out the limitations of the tree-related DIs (Frelich and Ostuno 2012; Edwards et al. 2013). For purposes of this review, it is important to note that an entire tornado track is given a single EF-scale rating based on the most severe damage recorded in that damage track (the maximum damage); thus, a single EF-scale rating does not necessarily characterize damage along the entire track.

5.2.2.1 Formation and Movement

Tornadoes can form in a variety of circumstances, but most – especially strong tornadoes – are associated with supercell thunderstorms. Supercell thunderstorms are thunderstorms with a rotating updraft and one or more downdrafts. These storms generally require an environment with strong vertical wind shear, plus the ingredients for general thunderstorm formation, which include sufficient low-level moisture, a conditionally unstable atmosphere, and an initial lifting mechanism. Individual tornadoes may descend from a small fraction of well-developed supercell storms. The mechanisms for tornadogenesis are varied and remain a subject of ongoing research. Davies-Jones et al. (2001) review a number of these formation mechanisms in detail.

Typically, vortex rotation in tornadoes is counter-clockwise, although up to 10 % rotate clockwise. The flow field will usually contain both a tangential and a radial component. In many cases, the inward-directed radial component contributes significantly to the overall wind speed within the tornadic vortex in order to balance the rapidly rising air near the core of the tornado (Wurman et al. 2013). Indeed, studies have hinted that in some tornadic systems, a substantial fraction of the forest damage is caused by this inflow rather than by the spinning vortex (e.g., Karstens et al. 2013). The rotational velocity waxes and wanes in stochastic fashion during the brief life of a tornado. Indeed, the short periods in which vortex rotation is slow and/or very compact may produce undamaged areas in many tornado paths, giving the appearance that the vortex has lifted off the ground. However, current thinking among tornado researchers is that such 'skipping' does not actually occur, and that many historical long-track tornadoes that appeared to have gaps were either several serial vortices, or a single one that was occasionally too small or weak to leave a damage signature.

Translational movement can proceed in any direction. However, because tornadoes follow the motion of parent thunderstorms, which typically follow the general west to east motion of the mid-latitude westerlies in North America, most (roughly 70 %) tornado track movement is typically toward the east, northeast, or east-northeast. Forward speed can range from stationary to 100 km per hour (Suckling and Ashley 2006).

The small size of tornado vortices at ground level, combined with their incredible wind velocities, often results in very steep spatial gradients in wind speed. This is frequently seen in post-storm damage surveys, either of forests or of built-up areas, where very heavy damage and very light or no damage may be separated by only 10 or 20 m (Foster et al. 1998). Indeed, aerial damage surveys of residential neighborhoods sometimes reveal large single-family homes that are devastated on one side but entirely intact on the other side (Peterson and Godfrey 2014).

Somewhat distinct from other types of tornadoes are those that form within the spiral rainbands of landfalling hurricanes and are often called 'hurricane-induced tornadoes' (Agee and Hendricks 2011). These phenomena are concentrated within 400–500 km of the Atlantic or Gulf coasts. Hurricane-induced tornadoes are usually small and weak, having path lengths and widths that are substantially less than lengths and widths for supercell tornadoes (Moore and Dixon 2011). Slightly more than 80 % of landfalling Gulf coast hurricanes produce hurricane-tornadoes, with a mean of 12.2 ± 18.8 (SD) per hurricane. Moore and Dixon (2011) reported 734 tornadoes produced by 50 hurricanes during the 55-year period from 1950–2005. Of these, 42 % were F0, 36 % were F1, 17 % were F2, 4 % were F3, and 0.4 % were F4 tornadoes.

5.2.2.2 Climatology

Systematic recording of standardized data on tornadoes by the National Weather Service (NWS) began in the 1950s, although anecdotal records of course go much further back. Even in the 75 years of systematic record-keeping changes in reporting, detection, classification, and prediction mean that use of the long-term records requires caveats. Nevertheless, the NWS tornado database does contain information on >40,000 tornadoes across the entire USA since 1950, and will therefore be our primary information source on climatology and geographic distribution.

Tornado climatology is well-established. Although tornadoes can and do occur in any month of the year in the southeastern USA, the peak period is April through July. However, the period of peak tornado activity varies geographically. Peak activity is earliest in the southeastern and southern plains states, and activity is progressively later further north. Thus the Gulf states have their most frequent tornadoes in March and April, whereas tornadoes in Minnesota and the Dakotas are most frequent in July. There is a secondary peak in the Gulf coast states in late fall. Diurnal distribution of tornadoes shows that they are concentrated in the late afternoon and early evening (Rauber et al. 2002).

Nationally, the majority of tornadoes are 'weak' (EF0 and EF1), a modest fraction are 'strong' (EF2 and EF3), and only a few are 'devastating' (EF4 and EF5). Within the CHR 4,358 tornadoes were recorded during 1993–2012 (Fig. 5.4), and were distributed among intensity classes as: EF0 – 42.1 %; EF1 – 38.2 %; EF2 – 14.4 %; EF3 – 4.4 %; EF4 – 0.8 %; and EF5 – 0.01 %. Thus for the CHR as a whole, an average of 218 tornadoes touch down annually.

Tornadoes have been documented in all states of the USA, but they are by far more common east of the Rocky Mountains (Fig. 5.3). Tornado occurrence is also markedly lower in the Appalachian sections of West Virginia and Virginia, the upper peninsula of Michigan, and northern New England. The greatest concentrations of tornadoes in historical times has been in two areas: the widely-known 'tornado alley' running from Oklahoma, through Kansas, Nebraska and Iowa, and

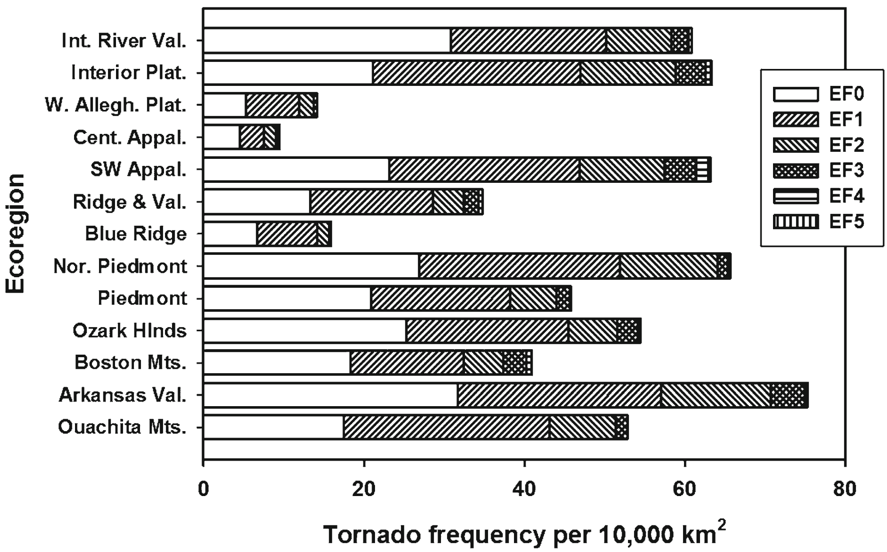

Fig. 5.4 Frequency of tornado touchdowns in CHR ecoregions by EF-scale rating (F-scale prior to 2007) (1993–2012)

the less-well-known 'Dixie alley,' consisting of Arkansas, northern Louisiana, Mississippi and Alabama.

The average numbers of tornadoes for the CHR as a whole is useful to compare to other forest types, but such numbers belie substantial variation among ecoregions within the CHR (Fig. 5.4). During the 20-year period of 1993–2012 (more accurate than the entire historical tornado record, because weather radars came into widespread use in the early 1990s and therefore probably revealed tornadoes that would have previously gone undetected or unreported) the highest tornado density was in the Arkansas Valley (75.3 per 10,000 km^2) and Northern Piedmont (65.7 per 10,000 km^2), and the lowest density was in the Central Appalachians (9.5 per 10,000 km^2) and Western Allegheny Plateau (14.1 per 10,000 km^2). Thus, different ecoregions within central hardwood forests experience approximately an 8-fold difference in frequency of tornado touchdown. Even these numbers do not fully convey risk of severe disturbance, which of course has the greatest ecological effects. Considering only strong and devastating tornadoes (EF2 and greater) for the 20 years of 1993–2012, the highest frequency is found in Arkansas Valley (18.29 per 10,000 km^2), the Interior Plateau (16.35 per 10,000 km^2), and Southwestern Appalachians (16.32 per 10,000 km^2). These three ecoregions are also those with the highest proportion of all tornadoes in the EF2 or greater category.

Distributions of tornado path lengths and widths were recently synthesized by Brooks (2004) for the period 1950–2001, and by Malamud and Turcotte (2012, length only) for the period 1982–2011, who found that both path length and path width increase substantially with tornado intensity, albeit with substantial variation in the relationship. Mean path length in Malamud and Turcotte's study increased from F0 to F5 tornadoes, respectively, as follows: 1.5, 5.4, 12.1, 25.3, 44.3, and 64.4 km. Brooks (2004) also showed that path width values increased from a mean of 28 m for F0 tornadoes, to 555 m for F5 tornadoes. Note that these and most other published analyses of tornado path length and width are based on the lengths and widths reported by the NWS storm damage survey teams. Beginning in 1994, widths were reported as the maximum width, whereas prior to 1994, the mean width was recorded. Moreover, it has become clear to the first author that the storm damage survey teams may consider the tornado beginning and ending points to be the very first or last tree or structure that exhibits any damage, even if the more representative levels of tornado damage are hundreds of m away. This likely leads to a substantial overestimation of path lengths for our purposes here (namely to develop some idea of the area of forest damaged, how serious the damage is, and when and where it happens). The upshot is that for forestry or ecology purposes, calculations of the area affected would likely be severely overestimated if based on the length and (maximum) width values drawn from the NWS tornado database.

As a preliminary step toward remedying the data limitations just described, we have begun to quantify tornado damage path widths by directly measuring the width of the damage at regular intervals (currently either every 200 m or every 500 m) along the entirety of a tornado path. We have results from 21 tornadoes to date. In each case, we measured damage width perpendicular to the overall trajectory of the tornado. Of necessity, we considered 'visually substantial' canopy damage, which

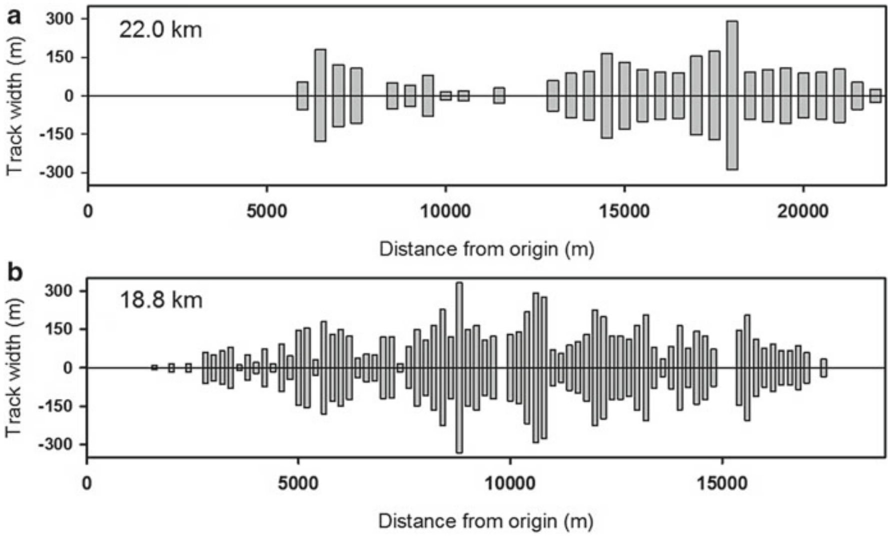

Fig. 5.5 Variation in damage track width in two 2012 tornadoes that passed predominantly through forested landscapes. Width measurements taken every 200 m (**b**), or every 500 m (**a**). Absence of a *vertical* bar at a given distance from origin indicates zero damage width at that point

roughly translates to >25 % of canopy removal by the tornado. Nonforested segments of the tornado path were excluded. Locations where there was no visible damage were recorded as zero width. Figure 5.5 shows two representative tornado tracks with reported track lengths of 22.0 and 18.8 km, respectively; note that width varies greatly along the damage path, with several episodes of widening and narrowing. Note also that at several of our width-sampling points, there was no discernable path, leading us to record a width of zero. Figure 5.6 then presents a summary of our width measurements on 21 tornado tracks, in comparison to the reported path width from the NWS storm damage surveys. Clearly the reported width greatly exceeded the measured width in all cases, sometimes being two – threefold greater than the mean of our width measurements. Mean measured damage path width varied from roughly 100 m to roughly 500 m in our sample.

5.2.2.3 Landscape-Scale Patterns

In contrast to hurricanes, there has been very little research to date on landscape-scale pattern of tornado disturbances in the CHR, or any other regions, in fact. As with several other topics in this chapter, we draw as necessary from studies outside the CHR when patterns and trends are likely to be similar. Foster et al. (1998) pointed out that in general, tornado disturbances are much more linear than other types of large infrequent disturbance, and cover much smaller areas per event than hurricanes or volcanic eruptions. They further noted that although tornadoes are

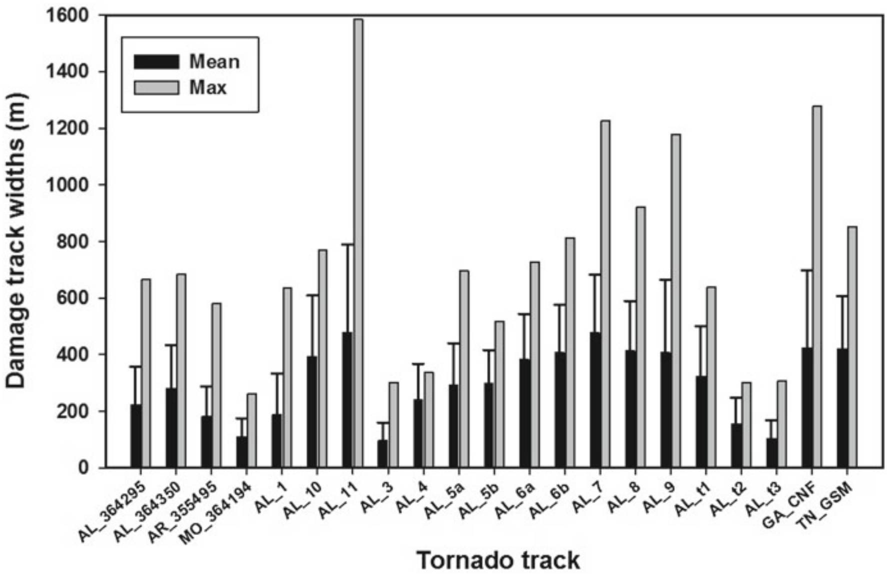

Fig. 5.6 Mean (+SD) (Measured from post-tornado inspection of Google Earth imagery, or our own GIS analyses of aerial photos) and maximum (reported in National Weather Service storm surveys) tornado track widths, for 21 tornado tracks in Georgia, Alabama and Tennessee, formed on 27 April, 2011. X-axis labels are simply tornado track names and have no other significance. Track widths measured from Google Earth or aerial photos consider 'visibly substantial' damage but do not include scattered individual treefalls as part of the damage track

known to leave undamaged segments along the path, this phenomenon does not seem to have a consistent relationship with landforms or topography.

The most detailed work to date has taken place in our lab, led by the second author (Cannon et al. unpubl. data). Two long-track tornadoes that occurred within the late April 2011 outbreak were studied using aerial photos and remote sensing analyses: one in Chattahoochee National Forest (CNF) in northern Georgia, and one in the far western end of Great Smoky Mountains National Park (GSMNP) in Tennessee. These two storms were rated EF3 and EF4 by the NWS. Because the EF-scale is based mainly on damage to man-made structures rather than vegetation, these ratings need to be interpreted cautiously; for example the GSMNP tornado earned its rating on the basis of severe damage to a single metal-truss utility tower (i.e., one point; Godfrey and Peterson 2014). The CNF tornado had a total track length of 65.9 km, but the damage path accounted for roughly 89 % (58.8 km) of that length; a total of 4,493 ha were damaged by this tornado. The GSMNP tornado had a total track length of 31.7 km, but a damage path that was 85 % (26.9 km) of that length.

To quantify the extent, severity, and pattern of tornado damage in these two damage tracks, we used a supervised classification within ArcGIS, based on 20-cm resolution aerial photos (visible spectrum) taken within 2 months of the tornadoes (Cannon et al. unpubl. data). The output of this analysis consisted of all 4-m pixels

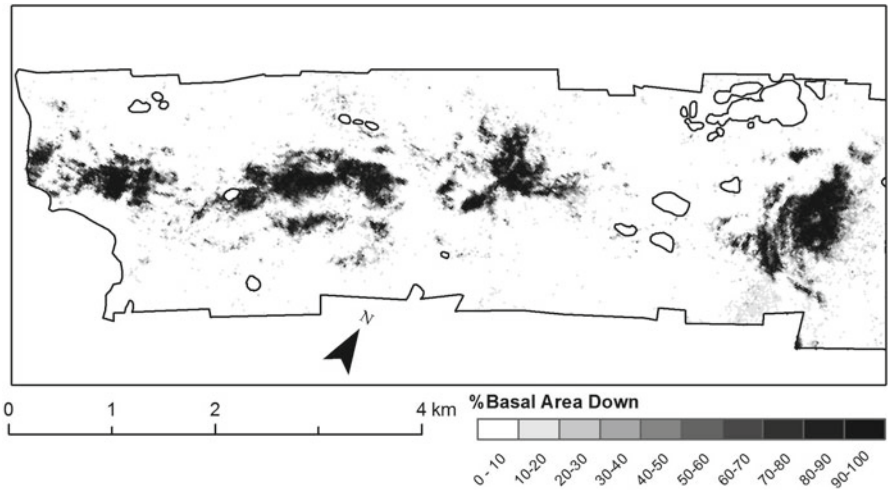

Fig. 5.7 Output of a supervised classification of aerial photos of the 27 April 2011 tornado at Chattahoochee National Forest in northern Georgia showing the westernmost 8 km of the damage track. *White* indicates intact or very slightly damaged forest; *darker shading* indicates more severe damage

classified into one of five levels of disturbance severity; severity was defined as amount of canopy disruption, and therefore included both uprooted and trunk broken trees (Fig. 5.7). Note that in Fig. 5.7, 'basal area down' refers to total basal area (BA) of trees that were either uprooted or trunk broken, which are the two primary mechanisms by which trees are removed from the canopy. After the classification pixels were aggregated and averaged in 20 m × 20 m grid cells to derive the final severity maps. Several important qualitative features of the damage severity maps should be mentioned prior to examining the quantitative details. First, these damage tracks, and many (most?) other tornado tracks do not simply create a binary 'damaged vs. undamaged' swath as might a lawnmower through grass. The tornado vortex commonly changes in size and rotational velocity, leaving areas with light or no damage that might incorrectly imply that the vortex has lifted off the ground, and has complex interactions with topography. Second, despite visual impressions, we reinforce earlier researcher's cautionary notes (Foster et al. 1997; Cooper-Ellis et al. 1999) that the most severe damage is typically a rather small fraction of total affected area. Third, following findings by Turner et al. (1994) after the 1988 Yellowstone fires, the great majority of the disturbed landscape has abundant biological legacies (cf. Franklin et al. 2000) and is seldom far from remnants of intact or lightly damaged forest, thus providing access for propagules and mobile organisms.

As with many other types of disturbance, the largest fraction of affected area in both tornadoes experienced low severity of disturbance (compare to Table 5.1 for hurricanes). For example, 83.9 % of the CNF tornado track lost <20 % of BA, whereas only 3.5 % experienced >80 % BA loss. Trends were similar in the GSMNP track: 70 % of area had <20 % BA loss, whereas 5 % had >80 % BA loss. Another pattern consistent among both tornado tracks was that the total area damaged was surprisingly evenly distributed among damage severity classes, partly due to the patch characteristics described below.

In both tornadoes, complex damage patterns resulted from interactions between tornado tracks and topography, defying some of the expected generalizations. Middle elevations and south- or southeast-facing slopes suffered the greatest damage levels, probably because they bore the brunt of direct tornado impact. In contrast to the easily identified ‘sheltered vs exposed’ dichotomy for landscapes subject to hurricanes, it is impossible to predict any location as ‘sheltered’ from a tornado, even if its path were known prior to the event. This is because although it is common for tornadoes to leave steep valley bottoms undamaged, particularly if the path is perpendicular to the long axis of the valley, there are also many cases of tornadoes tracking up and down valley slopes to cause damage along the bottoms as well as adjacent ridges. In addition, the paths of tornadoes can be quite erratic, with many known cases of the damage path apparently getting ‘entrained’ and tracking lengthwise up valleys. Thus the small size and erratic behavior of tornadoes precludes identifying sheltered and exposed locations that can be identified with some confidence in the context of hurricane (or derecho; see below) damage.

Both of the 2011 tornado tracks we studied created patches of widely varying size, shape and severity (Figs. 5.7 and 5.8; Table 5.2). In this context, we define severity as proportion of pre-disturbance BA that was downed (uprooted or trunk broken), while recognizing that alternative definitions are also possible. For example, in the CNF tornado track analysis, a total of 4,866 disturbed patches (having

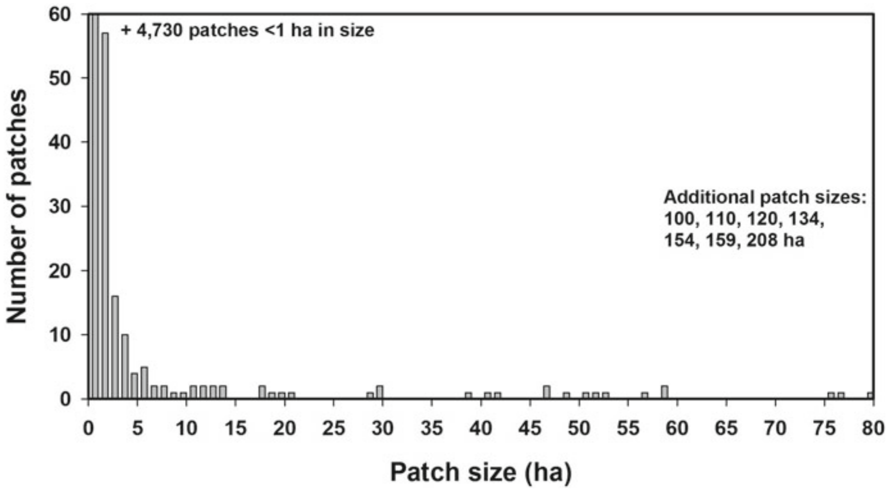

Fig. 5.8 Damaged patch size-frequency histogram for tornado damage swath in Chattahoochee National Forest, northern Georgia. The ‘4,730’ in the *upper left* indicates frequency of patches <1.0 ha in size. The seven largest patch sizes are reported in the note at *upper right* in order to avoid extending the x-axis excessively. See text for details

Table 5.2 Disturbed patch characteristics in five wind-damaged sites in CHR forests

Study	Number of patches	Mean patch size (ha)	Minimum patch size detected or reported (ha)	Maximum patch size (ha)	Predominant aspect
Rebertus and Meier (2001)	38	0.79	0.05	20.1	North, East
McNab et al. (2004)	30	0.69	0.10	3.9	Southeast
Xi et al. (2008a)	109	0.12	0.006	0.80	–
Cannon et al. unpubl. – CNF	4,866	0.57	0.04	207.4	–
Cannon et al. unpubl. – GSMNP	2,487	1.01	0.04	497.8	–

CNF Chattahoochee National Forest, Georgia, *GSMNP* Great Smoky Mountains National Park, Tennessee

>10 % B.A. loss) were identified, with ~97 % of those being <1 ha (Fig. 5.8); an additional 1.8 % were 1–5 ha, and the largest single patch was 207.4 ha (Table 5.2, Cannon et al. unpubl. data). We analyzed patch characteristics with the Fragstats software, and found that patch size increased but patch number decreased with damage severity (i.e., with increasing severity patches were larger but fewer). In this analysis, plots with 0–20 % of B.A. downed (as inferred from the air photos) were considered 'low severity'; those with 21–40 % B.A. downed were considered 'intermediate,' and those with >40 % BA downed were considered 'high severity.' Damaged patches had the most complex shapes at intermediate severity levels, and became slightly simpler in shape at the high and low end of the severity spectrum. Finally, the distance between similar patches was greatest for high severity patches and least for low severity patches (Fig. 5.7). We propose the term 'dissolved bull's-eye' to describe the typical patch damage pattern where damage is most severe near the center, and becomes less severe and more dissected near the periphery of the patch.

5.2.3 Derecho Disturbance

Derechos are widespread, straight-line windstorms associated with thunderstorm convection (in contrast to the rotational winds in tornadoes and hurricanes). The meteorological and climatological study of these phenomena is still young (15–18 years) (Ashley and Mote 2005). On the other hand, several ecological studies of forest damage and recovery from derechos have been completed. These provide a solid evidential foundation for generalizations about the impact of derechos, with the qualifier that much of the damage and recovery work has taken place outside of the strict definition of CHR forest types.

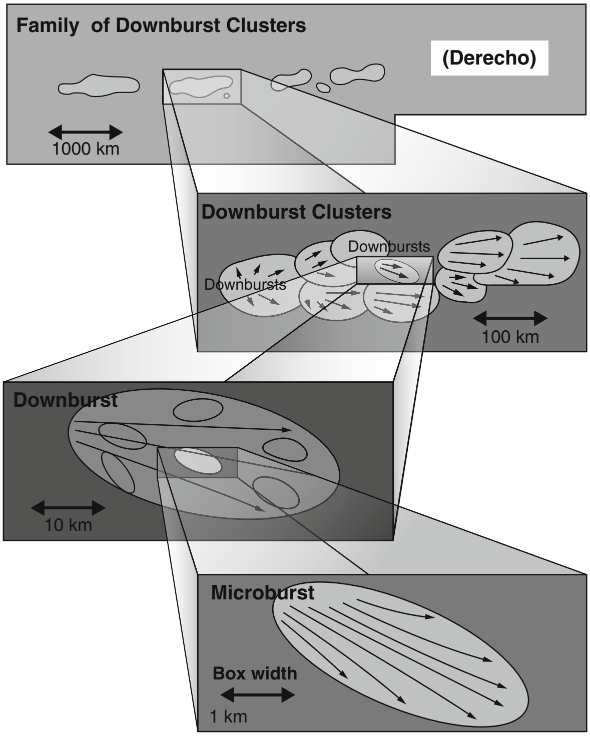

Fig. 5.9 Schematic diagram illustrating hierarchical nature of derecho systems (From Corfidi et al. undated)

Derechos are best understood as a hierarchical phenomenon (Fig. 5.9) in which the entire derecho is composed of several downburst clusters, which in turn are composed of multiple downbursts. The downbursts themselves have dimensions of about 8–10 km and may last for several minutes; these may in turn be further decomposed into individual microbursts. Technically, a derecho is defined as "a concentrated area of convectively induced wind gusts greater than 26 m per second that has a major axis length of 400 km or more" (Ashley and Mote 2005). Note in particular the criterion of a minimum damage swath length of 400 km; as such, derechos are arbitrarily distinguished from somewhat smaller (i.e., 40–400 km length) downburst clusters that are functionally similar. Obviously these storms occur over a large spatial scale; the recent July 2012 derecho over the central eastern USA encompassed much of the Ohio Valley.

5.2.3.1 Formation and Movement

Derechos often form in association with mesoscale features called quasi-linear convective systems, which are essentially long, continuous lines of strong thunderstorms. Evaporative cooling within downdrafts develops a strong cold pool at the surface, which propagates outward from the initial convection, lifting warm and moist air along the resulting gust front and producing more convection. The cycle repeats itself serially as the system moves forward. Thus, a derecho can be considered to be a series of discrete, downwind-developing individual thunderstorm cells (Corfidi et al. undated). The strengthening cold pool induces strong inflow of air from aloft (the rear inflow jet), which carries higher momentum air downward toward the surface. This propagating cold pool can push outward, resulting in a bowed representation (i.e., a 'bow echo') in a radar display (Corfidi et al. undated). Derechos typically propagate at 80 km per hour or greater (perhaps over 110 km per hour), but the unidirectional surface winds can reach well over 160 km per hour.

5.2.3.2 Climatology

Although derechos can and do occur in any month, researchers recognize a primary and secondary seasonal peak in derecho frequency. The primary peak, called warm-season derechos, is from May through August (69 % of events), and the smaller secondary peak, called cool-season derechos, is in October-December (Corfidi et al. undated). In their review, Ashley and Mote (2005) identified 377 derechos in the 18-year period from 1986–2003, for an annual average of nearly 21 over the continental USA. As with all severe weather phenomena, there is substantial year-to-year variation, with their 18-year climatology documenting a maximum of 42 events (1998) and a minimum of 2 events (1988).

Most derecho events produce surface winds that are less than catastrophic, but the more powerful storms can have winds equivalent to a category 4 hurricane. For example, the 16 July 1980 derecho event over Illinois and Michigan had 243 km per hour winds (Ashley and Mote 2005).

The geographical distribution of derechos is broadly similar to that of tornadoes (Fig. 5.10). Research has identified two primary 'corridors' of derecho frequency, each associated with a different season. Warm-season events tend to be concentrated over central Oklahoma, Arkansas and Missouri, with a lobe of the high-frequency isopleth extending to the states surrounding southern Lake Michigan (southern Wisconsin, northern Illinois, and northern Indiana). Cool-season events are concentrated in the lower Mississippi Valley, and northeastward in the vicinity of the Ohio River. Despite these concentrations over the south-central USA, many of the ecological studies have been associated with derechos in Wisconsin (e.g., Dunn et al. 1983; Canham and Loucks 1984), Minnesota (Peterson 2004; Rich et al. 2007; Moser and Nelson 2009), Pennsylvania (Evans et al. 2007; Peterson et al. 2013), and New York (Jenkins 1995; Robinson and Zappieri 1999; Canham et al. 2001). Post-derecho studies within the CHR include Leach (2003), Peterson and Leach (2008a, b), and Holzmueller et al. (2012).

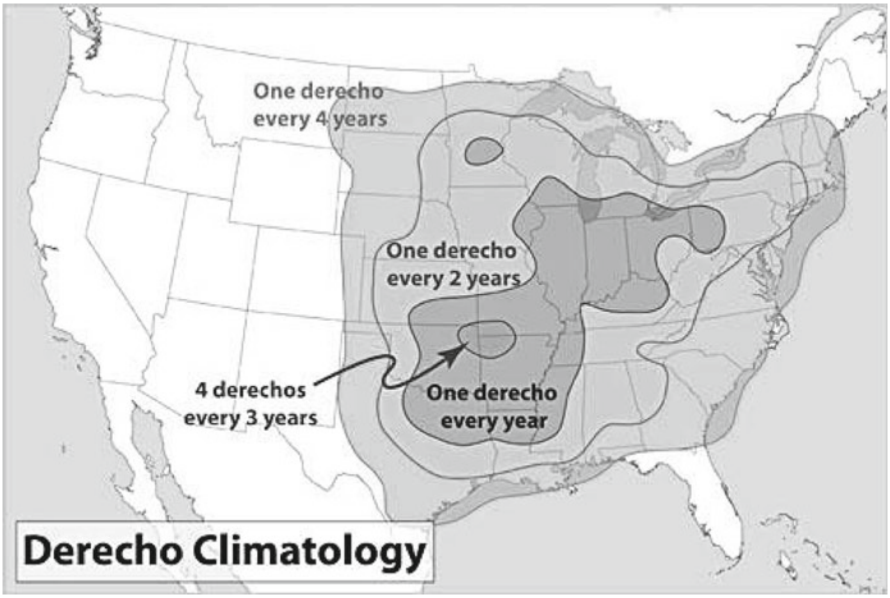

Fig. 5.10 Geographic distribution of frequency of derechos in the eastern USA (From NOAA Storm Prediction Center, 'About Derechos' FAQ website, accessed 10 December, 2014)

5.2.3.3 Landscape-Scale Patterns

Derecho damage can approach small hurricanes in spatial scale. A derecho in 1977 over Minnesota and northern Wisconsin had a path 266 km long and 27 km wide, virtually leveling 240,000 ha of forest (Canham and Loucks 1984). Just beyond the northern limit of CHR, a derecho over western Pennsylvania in July of 2003 damaged 5,000 ha of the 258,000 ha examined by Evans et al. (2007). At a more modest scale, a 5 May 1999 derecho in west-central Tennessee damaged ~3,000 ha within Natchez Trace State Forest alone (Peterson and Leach 2008a).

The size and distribution of damage patches that result from derechos has been examined in several cases, although none within the CHR. Canham and Loucks (1984) used historical reconstruction based on land survey records for northern Wisconsin to estimate that the highest-frequency size class of disturbance patches was <6 ha. In the July 2003 Pennsylvania event, damaged patches ranged from single treefall gaps to 114 ha, although mean and median patch sizes were 4.78 and 2.18 ha, respectively (Evans et al. 2007).

In several respects, the interaction of derecho winds with local topography parallels that of hurricane winds, with damage concentrated on exposed locations facing the direction of origin of the winds. Similar to what might be expected after a hurricane, Jenkins (1995) studied impacts of a 1995 derecho even in the Adirondack

Mountains of New York, noting that nearly all of the larger disturbed patches "are on the tops, west, or northwest slopes of hills or ridges. The air photos and satellite images look like someone spray-painted the ridge tops, pointing the can east-southeast and tipping it down at about a forty-five degree angle." Evans et al. (2007) found that the 2003 Pennsylvania derecho caused greater damage with increases in elevation, and with increases in topographic position relative to surroundings, and that damage decreased with greater elevational variability (rougher topography).

5.2.4 Other Types of Wind Disturbance

A variety of storm types affect many forests across the central and eastern USA (Webb 1999). In particular, we wish to focus attention on mountain waves, a type of meteorological phenomenon that is well known in other mountainous areas (e.g., Rocky Mountains or Sierra Nevada Mountains where they are called Chinook or Santa Ana winds, respectively), but was only recently recognized (Gaffin 2009) for the southern Appalachian Mountains in the CHR. To date, forest damage caused by mountain waves has not been studied.

Mountain waves are anomalously high winds in the foothills of mountain ranges. They occur where strong winds flow nearly perpendicularly toward a mountain range with a relatively gentle windward slope and relatively steep lee slope. The incoming winds are lifted by the windward slope, and if they encounter a stable air mass over the crest of the mountains, are redirected back down the lee slope in the form of waves. Experts often call attention to the analog of a standing wave in fast-flowing rivers on the downstream side of large boulders (Kemp 2010).

In the vicinity of the southern Appalachians, the Smoky Mountains in GSMNP provide an unusually high, unbroken ridgeline that exceeds 1,500 m for more than 56 km; notably (and contrary to the generally north-south trending Appalachian range as a whole), the Smokies ridgeline is almost exactly east-west, meaning mountain waves could form on the north and western sides when there are strong southerly winds, or on the south and east sides when there are northerly winds. The very limited data available to date (e.g., Gaffin 2009; J Renfro, GSMNP, pers. comm.) suggest that in GSMNP, mountain waves are usually on the northwest side of the mountains.

In the southern Appalachians, mountain wave winds are concentrated along the foothills. Their actual size and geographic distribution are currently unknown, but they can be exceedingly intense events. Three recent events in or near the northwest part of GSMNP produced documented wind speeds of 162, 171, and 177 km per hour (Kemp 2010). Such winds are thought to produce forest damage at a scale of tens to perhaps a few 100 ha per event (J Renfro, pers. comm.), although no quantitative data on impacts to forests exists. Mountain wave frequency (not all as severe as the extreme cases just mentioned) is indicated from long-term monitoring at the Cove Mountain meteorological station within GSMNP, where 52 mountain waves were recorded between 1999 and 2007 (Gaffin 2009).

5.3 Impacts at the Stand and Tree Scale

5.3.1 Stand- and Tree-scale Patterns

At the tree- and stand-scale there are well-established trends in damage patterns that generalize across types of wind event. Perhaps most general is the increasing probability of tree damage with size, documented in most wind-damage studies within the CHR (Peterson 2007; Xi et al. 2008a), but this relationship is not universal (e.g., Chapman et al. 2008; Oswalt and Oswalt 2008; Harcombe et al. 2009). Even when not examined directly, the increasing vulnerability among larger trees is widely confirmed by most studies reporting greater BA loss compared to density loss (Greenberg and McNab 1998; Peterson and Leach 2008a; Busing et al. 2009; Holzmueller et al. 2012).

Forest type or species composition is not necessarily a consistently good predictor of damage patterns, even when species differ in their vulnerability to wind damage, suggesting that abiotic variables (either site or storm features) sometimes play more important roles in determining damage. In northwestern Pennsylvania, Evans et al. (2007) found that forest type was not generally a useful predictor of wind damage level, although red maple (*Acer rubrum*) stands on wet sites were consistently more heavily damaged than other forest types. Instead, they reported that structural features such as mean tree size or age were especially important predictors (Evans et al. 2007). Nevertheless, many studies have reported that levels of damage varied among species (e.g., Greenberg and McNab 1998; Leach 2003; Busing et al. 2009). Notably, not all of these studies separated the species effect itself from obvious interacting factors such as tree size or age, leaving open the question of how widespread the species differences really are. Peterson (2007), in a review of several studies, was able to statistically isolate species effects from size effects, showing that there were modest but consistent differences among species. For example, sugar maple (*A. saccharum*) consistently emerged as more resistant than many other species. However, other studies have shown that interspecific differences can be inconsistent among studies. Xi et al. (2008a) found that loblolly pine (*Pinus taeda*) had high risk of damage in a North Carolina tornado, but low risk relative to other species in two hurricanes (Hugo and Fran). The authors attributed these differences to stand structures causing the focal species to be either more exposed or more sheltered.

The type of tree damage from severe winds is variously categorized, but most researchers recognize an important distinction between standing undamaged trees, lightly damaged trees (defoliated, small branches broken), uprooted trees, and those with broken trunks. In particular, uprooted trees create treefall root pits and root plates (also called root balls or mounds), and these have several implications for subsequent community and ecosystem dynamics that are not induced by trees with broken trunks (Beatty 1984; Schaetzl et al. 1989). The pit/mound complex diversifies microenvironmental conditions, providing a variety of establishment microsites for seeds and thus facilitating increased diversity among tree seedlings and herb-layer species (Peterson et al. 1990; Harrington and Bluhm 2001; Collins and Battaglia 2002). These microsites also have soil respiration rates distinct from the surrounding intact soil (Millikin and Bowden 1996).

Treefall pit/mound sizes are consistently correlated with tree diameter at breast height (DBH). A synthesis of studies across 10 sites and >1,000 pit/mound complexes in six states (Sobhani et al. 2014) found that a single relationship explained roughly 54 % of the variation in size of root pits: ln pit size = −4.859 + (1.561 * ln DBH) (pit size in m^2 and DBH in cm). Similarly, a single relationship explained 56 % of variation in root mound size: ln mound size = −4.909 + (1.460 * ln DBH). Coverage by recently-formed treefall pit/mound complexes has been reported in a number of locations, and is typically less than 10 or 11 %. For example the area of recent pit/mound complexes was estimated at 5.9 % after a tornado in the Blue Ridge Mountain ecoregion of northern Georgia (Sobhani et al. 2014); 1.6–4.3 % in hurricane gaps of western North Carolina (Greenberg and McNab 1998); 2.0 % after a derecho in west-central Tennessee (Leach 2003); and 2.4–6.0 % after a tornado in Arkansas (Phillips et al. 2008). The coverage of these microsites can in some cases be directly linked to greater vulnerability of particular species. For example, Battaglia et al. (1999) found 4.9 % coverage of pit/mound complexes in a pine-bottomland hardwood stand where the dominant pines were heavily damaged, but only 1.7 % coverage in a nearby bottomland hardwood stand without canopy pines.

The type of damage to trees is widely considered to be strongly influenced by soil saturation and therefore precipitation preceding and during storm events. For example, Xi et al. (2008a) documented that a large proportion of fallen trees were uprooted at Duke Forest following Hurricane Fran, which caused >22 cm of rain in the 48 h preceding high winds. In contrast, the relatively drier Hurricane Hugo caused more trunk breakage than uprooting (see similar trends in Busing et al. 2009). They further contrasted these two hurricanes with tree damage following a 1988 tornado with little precipitation at nearby Umstead State Park, where 70 % of the fallen trees had trunk breakage (Xi et al. 2008a). Greenberg and McNab (1998) reported more than twice as much uprooting as trunk breakage after Hurricane Opal (15 cm of rain at their study site), which appears consistent with this trend (see also Rebertus and Meier 2001). Similarly, Peterson and Rebertus (1997) contrasted tree damage across swamp, bottomland, and upland sites in southeastern Missouri after a tornado, and found trunk breakage to be threefold more common overall, despite greater uprooting than trunk breakage in the swamp site (see also Cowden et al. 2014 for another example with predominantly trunk breakage). Platt et al. (2000) found that slash pine (*P. elliottii)* stands in south Florida damaged by Hurricane Andrew experienced more (often twice as much) trunk breakage than uprooting; while Andrew was quite dry for a hurricane, they attributed the tree damage pattern in part to tree roots being anchored in shallow limestone bedrock. Additionally, in four southern Appalachian (Blue Ridge Mountain ecoregion) post-tornado sites studied by Peterson and Snyder (unpubl. data), uprooting was the most prevalent form of treefall in three of the four sites.

The prevailing mode of treefall can differ substantially for the same species among sites, as well as among species within a site. For example, Greenberg and McNab (1998) note that almost all scarlet oak (*Quercus coccinea*) in their western North Carolina study uprooted, but that 90 % of the fallen scarlet oak from an eastern Kentucky site were snapped (Romme and Martin 1982). Peterson (2007), in describing patterns from central Tennessee (Interior Plateau ecoregion), found that northern red oak (*Q. rubra*) had a six-fold greater probability of uprooting than trunk breaking, compared to either chestnut oak (*Q. montana*) or white oak (*Q. alba*). Therefore we conclude precipitation and soil saturation alone cannot fully explain why trees uproot versus break; other factors such as soil depth, bedrock fracturing, presence or absence of impermeable soil layers, and tree wood properties must also be considered.

The differences in resistance or vulnerability among species are illustrated at the stand scale by the extent of change in species composition and diversity after wind disturbance. How disturbance effects are interpreted depends partly on the interval between wind disturbance and sampling; a wind disturbance that decreases or removes several dominant species from the canopy would be seen as having a negative effect on diversity if sampling was conducted soon after the disturbance. However, if advance regeneration saplings or newly established seedlings were sampled some years later, then the disturbance would be seen as resulting in increased diversity. Greenberg and McNab (1998) found quite small changes in species composition of their five gaps in western North Carolina. Xi et al. (2008a) emphasized that Hurricane Fran caused substantial structural change at Duke Forest, but little immediate compositional change.

Species diversity appears to be either unaffected or negatively affected by wind disturbance, and we propose that the magnitude of the negative effect increases with severity of wind disturbance. In Greenberg and McNab's (1998) study, species diversity (Shannon's index) changed very slightly and inconsistently. Cowden et al. (2014) examined changes in a north-central Alabama site (Sipsey Wilderness) after an EF1 tornado, and found no significant difference in species diversity between undamaged controls and moderately-damaged plots. The study by Leach (2003) after a 1999 derecho over west-central Tennessee and by Holzmueller et al. (2012) after a derecho over southern Illinois; both showed little change in species diversity, and were both of moderate severity of damage. Peterson and Rebertus (1997) reported that of nine large plots damaged in a Missouri tornado, seven saw declines in Shannon diversity, and seven also lost at least one pre-disturbance tree species. Figure 5.11 shows the immediate change in Shannon's diversity index due entirely to removal of the fallen trees, on a plot-by-plot basis across four sites (Peterson unpubl. data). Although there is a hint that very modest wind damage severities sometimes result in slightly increased diversity (probably due to reduction of dominance by the more abundant species), diversity steadily declines as wind damage severity increases. Thus in terms of immediate changes, wind disturbance will most often decrease diversity among the canopy tree species.

Finally, also at the stand scale, wind disturbances may advance, set back, or have little effect on the successional status of the species assemblage. Given that larger

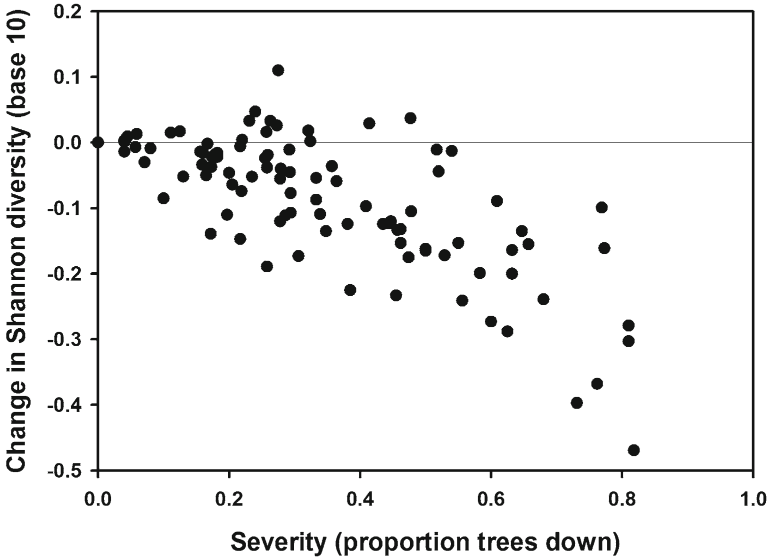

Fig. 5.11 Immediate change (pre-storm to post-storm) in canopy tree diversity from four CHR locations. Diversity calculated as Shannon's H' index, base 10, using density as the abundance measure. Post-storm calculation uses standing trees after uprooted and trunk-broken trees removed. Alternative formatting of figure with severity defined as proportion of basal area down gives very similar results. One location previously reported in Peterson and Rebertus (1997); data from remaining locations unpublished. Points are 20 × 20 m or 30 × 30 m plots

trees are generally more damaged than smaller trees, canopy dominant species tend to be differentially removed or decreased by wind disturbance. When the canopy dominants are pioneer (e.g., black locust (*Robinia pseudoacacia*) or yellow-poplar (*Liriodendron tulipifera*)) or mid-successional (e.g., most oaks and hickories (*Carya* spp.)) species, as is common in CHR secondary forests, the net result is to leave an assemblage with greater dominance by late-successional species (Nelson et al. 2008; Xi et al. 2008b; Holzmueller et al. 2012). In some cases, a pre-disturbance dominant species is effectively completely removed from the canopy and lacks regeneration, causing a more pronounced shift, as was documented in the case of loblolly pine after Hurricane Hugo by Battaglia et al. (1999). In contrast, when primary forests dominated by late-successional species are disturbed, the immediate net effect is neutral (e.g., Held et al. 1998) but succession may eventually be set to an earlier stage if a new cohort of pioneer or mid-successional seedlings becomes established (e.g., Dunn et al. 1983). Xi et al. (2008a) described a composite of the above patterns, where heavy damage to dominant pines shifted some stands to more advanced stages of succession, whereas less heavily damaged hardwood stands were set back to an earlier stage. We propose a broad conceptual model for secondary forests, in which low- to moderate-intensity wind damage advances succession by removing some of the pre-storm canopy dominants and releasing later-successional subcanopy and sapling stems, whereas high severity damage sets succession back to an earlier stage by sufficiently opening the canopy and removing subcanopy vegetation so that early-successional species can establish. The high-severity component of this model has been demonstrated in several cases (some outside of the CHR), wherein entirely new cohorts of early-successional species establish, rather than simply release of advanced regeneration or regrowth of surviving canopy individuals (Dunn et al. 1983; Peterson and Pickett 1995; Nelson et al. 2008).

5.3.2 Ecosystem Effects of Wind Disturbance: Carbon Cycling and Budgets

Compared to community ecology and forestry-related research, ecosystem-oriented research in major wind-disturbed areas has been very limited. Recent syntheses of carbon cycling effects of various types of disturbance (Amiro et al. 2010; Goetz et al. 2012; Kasischke et al. 2013) point to only a single integrated (flux tower) study after wind disturbance in temperate forests of North America (Li et al. 2007), although such work has been conducted in Europe (Thurig et al. 2005), in mangroves off the Florida keys (Barr et al. 2012), and in a few tropical sites (Vargas and Allen 2008). Indeed, among the topics considered in this chapter, the ecosystem effects of wind disturbance is least understood, yet important because regional and continental-scale trends in carbon budgets are known to be substantially influenced by major disturbance (Kurz et al. 2008). Unfortunately, space limitations constrain what can be discussed in this chapter and we therefore cannot do justice to this topic. Until a review and synthesis focused on these types of disturbances is written we direct interested readers to the existing reviews mentioned above.

5.4 Summary and Conclusions

Wind disturbance has been the subject of a great deal of research in temperate forests of eastern North America, although somewhat less within the CHR than other nearby regions. Although far from complete, the available information is sufficient to roughly define a wind disturbance regime, and thus provide benchmarks to guide management decisions. The climatology and geographic distribution of hurricanes and tornadoes is well established, with roughly inverse east-west trends (hurricanes decreasing and tornadoes increasing) across the CHR. Derechos have been studied for a much shorter period, so the climatologies and geographic patterns are perhaps a bit less firmly grounded, but the existing approximately 15–18 year time frame is sufficient to define first approximations. Mountain waves are newly-recognized phenomena that are locally important in the southern Appalachians, and their climatology remains poorly known. Combining all of the above, the Arkansas Valley, Ouachita Mountains, Interior Plateau, and Southwest Appalachians ecoregions have the greatest risk of wind damage from tornadoes and derechos, whereas weakening hurricanes are an important disturbance, especially in the Piedmont ecoregion. The Central Appalachians have probably the lowest rate of wind disturbance among the CHR ecoregions.

The distribution of patch sizes created by wind disturbances is one topic where informal visual impressions may greatly mislead the unwary. Multiple studies attest that the great majority of patches are quite small (e.g., <1–2 ha), even though a few may be much larger (to several tens of hectares); the empirical distribution of sizes is approximated by a negative exponential. This is counter to most observers' visual impressions of wind-disturbed areas (cf. Foster et al. 1997).

Severe wind events have strong interactions with topography; these are most easily predicted for hurricanes, somewhat less easily for derechos, and rather poorly for tornadoes. For the larger-scale storms (hurricanes and derechos), knowledge of the peak wind direction is sufficient to identify locations on the landscape that will be sheltered and thus experience less or no wind damage. For example, on the right (east) side of a northward-moving hurricane, winds will be predominantly from the south, causing most damage on south-facing slopes and flat areas, and leaving north-facing slopes undisturbed. Such predictions are precluded by the erratic behavior of tornadoes. Similarly, hurricanes and derechos often cause greater damage at higher elevations (but see counter-example in McNab et al. 2004), whereas tornadoes may or may not track up and down valley slopes, and sometimes even follow the long axis of valleys for several km.

At the stand and tree scale, wind damage is rather unpredictable for a particular tree or stand, but much more predictable in the aggregate (e.g., Peterson 2004). Larger trees are consistently more damaged than smaller trees, and there are often differences among species in damage at particular sites. The interspecific differences, however, appear to be contingent on absolute size, relative size, stand density, and edaphic factors, so broad trends among species are harder to identify. Despite such caveats, numerous studies identify sugar maple as consistently less damaged than surrounding trees, whereas species in the red oak group often suffer greater damage than their neighbors. In bottomland contexts, water tupelo (*Nyssa aquatica*) and bald cypress (*Taxodium distichum*) frequently suffer less damage than other species in the stand. The concentration of damage in dominant size classes means that wind disturbance will typically advance succession in secondary stands; in contrast, a severe disturbance may set back succession to an earlier stage in primary forest stands. Immediate changes in species composition are often subtle in comparison to structural change, although very severe wind events do in fact lead to major changes in species composition. Species diversity is also often changed very little, but when disturbance is sufficiently severe, diversity is most often decreased.

In sum, the trends identified above should enable forest managers to identify which forests are most likely to experience wind disturbance, and what type of storm is most likely at any particular locale. Known sizes of damaged patches, along with knowledge of size and species effects on tree vulnerability and resistance to wind, should facilitate informed decision-making that allows management actions to follow trends seen in natural disturbances.

Acknowledgements Much of our recent work was sponsored by grants AGS-1141926 and DEB-1143511 from the Physical and Dynamic Meteorology, and Population and Community Ecology programs of the National Science Foundation; earlier funding came from a cooperative agreement between University of Georgia and the USDA Forest Service, Southern Research Station. For some of this work, JBC was supported by a Climate Change Youth Initiative fellowship from the National Park Service. We thank the many field assistants over >20 years whose labor in difficult conditions provided the raw data for some of the trends reported here. Tornado track widths were laboriously measured on the aerial photos by Michael Bailey, Somer Rowe, and Tiffany Erickson.

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