

# Downed woody fuel loading dynamics of a large-scale blowdown in northern Minnesota, U.S.A.

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## Abstract

On July 4, 1999, a large-scale blowdown occurred in the Boundary Waters Canoe Area Wilderness (BWCAW) of northern Minnesota affecting up to 150,000 ha of forest. To further understand the relationship between downed woody fuel loading, stand processes, and disturbance effects, this study compares fuel loadings defined by three strata: (1) blowdown areas of the BWCAW ( $n = 34$ ), (2) non-blowdown areas of the BWCAW ( $n = 55$ ), and (3) the greater forest ecosystem in which the BWCAW lies ( $n = 228$ ). Further, relationships between downed woody fuel estimates and standing tree attributes (stand basal area and trees per hectare) were compared among study strata. Results indicate that mean 100 and >1000 h timelag fuel loadings in blowdown areas of the BWCAW (13.0 and 22.9 tonnes/ha, respectively) were substantially higher than those in both the non-blowdown areas of the BWCAW (5.8 and 16.3 tonnes/ha, respectively) and the greater forest ecosystem (6.5 and 11.3 tonnes/ha, respectively). There was no relationship between fuel loadings and trees per hectare or stand basal area. However, there did appear to be defined limits to maximum observed fuel loadings in relation to stand density attributes. This study suggests that relationships between a forest ecosystem's standing live and downed dead tree attributes are obscured by two contrasting events: widespread mortality from large-scale disturbances and the limited mortality from gradual stand development/small-scale disturbances.

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## 1. Introduction

Wind disturbs forests at scales from the individual tree (e.g., individual tree and stand-level windthrow) (Canham et al., 2001) to entire regions (e.g., hurricanes) (Foster and Boose, 1992; Boose et al., 2001). The scale and intensity of wind disturbance events have been suggested to be among the major determinants of successional trends and stand dynamics in forests (Canham and Loucks, 1984; Turner et al., 1998; Romme et al., 1998; Frelich and Reich, 1999; Peterson, 2000; Seymour et al., 2002). In particular, infrequent large-scale wind disturbance such as hurricanes or blowdowns can affect the structure, species composition, and downed woody material attributes of entire forest ecosystems in a relatively short time (Turner et al., 1998). Few researchers have studied the effect of infrequent large-scale wind disturbances on forest ecosystem

dynamics (Canham and Loucks, 1984; Peterson, 2000; Mattson and Shriner, 2001; Schulte et al., 2005). Given that large-scale wind disturbances substantially affect fuel loadings, information on the effects of large-scale blowdowns may refine our understanding of how fuel loadings vary in accordance with stand attributes such as stand structure and density. Such information would fill knowledge gaps in national efforts to mitigate forest fuel dangers across large scales (e.g., Healthy Forests Restoration Act of 2003, U.S. Public Law 108-148). Additionally, the frequency of damaging large-scale wind events may increase with any climatic changes (Peterson, 2000; Dale et al., 2001). Wind disturbance research is limited by the low frequency of large-scale wind events and lack of appropriate study sites to conduct fuel/stand dynamics research (Peterson, 2000; Canham and Loucks, 1984).

A unique research opportunity to examine severe windstorm consequences and fuel/stand attributes at various spatial scales occurred on July 4, 1999, in northern Minnesota (Mattson and Shriner, 2001). On that day, an unprecedented wind storm affected approximately 150,000 ha of the Boundary Waters

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Canoe Area Wilderness (BWCAW) within the Superior National Forest of northern Minnesota with winds greater than 140 km/h (USDA Forest Service, 2001). The resulting blowdown substantially increased the amount of fuel in the BWCAW, thus increasing the probability of wildfire escaping the wilderness (Leuschen et al., 2000). Based on remotely sensed and modeled fuel assessments, the upper range in total woody fuel loadings was estimated to have increased to 148 tonnes/ha (Leuschen et al., 2000). In contrast, the mean fuel loading in a typical BWCAW stand prior to blowdown had been estimated at 22 tonnes/ha (Leuschen et al., 2000). Given the lack of a fuel inventory (Leuschen et al., 2000) and the need for the Superior National Forest to monitor blowdown effects and mitigate fuel hazards (USDA Forest Service, 2001), the goal of this study was to use inventory data from the USDA Forest Service, Forest Inventory and Analysis Program, to assess the downed woody fuel loadings and fuel/stand relationships following a large-scale wind disturbance in the BWCAW. Specific objectives were:

- (1) to estimate and compare the fuel loadings (1, 10, 100, >1000 h timelags) (Deeming et al., 1977) and large downed woody attributes (decay and size classes of 1000 h fuels) among the three study site strata: (i) blowdown areas of the BWCAW, (ii) non-blowdown areas of the BWCAW, and (iii) forest areas of Bailey (1995) Ecological Province 212 outside the BWCAW,
- (2) to refine understanding of standing and down dead tree biomass relationships following a wind event by comparing the fuel loadings and number of standing live trees/basal area per ha for the three study strata, and

- (3) to describe the accumulation of downed woody fuels in Laurentian mixed forest ecosystems (212 ecosystem, Bailey, 1995) of the northern Great Lakes in the context of forest stand dynamics.

## 2. Study sites

### 2.1. The Laurentian mixed forests of the northern Great Lakes

Bailey (1995) delineates the 212 forest ecosystem occupying the lake-swamp-morainic plains and lowlands of the Great Lakes and New England regions as the Laurentian mixed forest ecosystem. In the Great Lakes area, the 212 ecosystem stretches from the Canadian border in northwestern Minnesota across the northern areas of Wisconsin and Michigan (Fig. 1). The 212 ecosystem has a mostly low relief with rolling hills with numerous lakes and poorly drained depressions resulting from glaciations during parts of the Pleistocene. Winters are moderately long and somewhat severe with short growing seasons and 60–114 cm of precipitation a year. The soils of the 212 ecosystem vary greatly and include large amounts of organic material (e.g., peat and muck), clay, silt, sand, gravel, and boulders. The 212 ecosystem lies between the boreal forest and broadleaf deciduous zones and is transitional in nature. The species composition is diverse, with mixtures of conifers (e.g., *Pinus resinosa* Ait., *Abies balsamea* (L.) P. Mill, *Picea abies* (L.) Karst, *Pinus strobus* (L.) Small, and *Pinus banksiana* Lamb.) and hardwoods (e.g., *Betula alleghaniensis* Britt., *Acer saccharum* Marsh., *Betula papyrifera* Marsh., *Alnus rubra* Nutt., and *Populus tremuloides* Michx.).

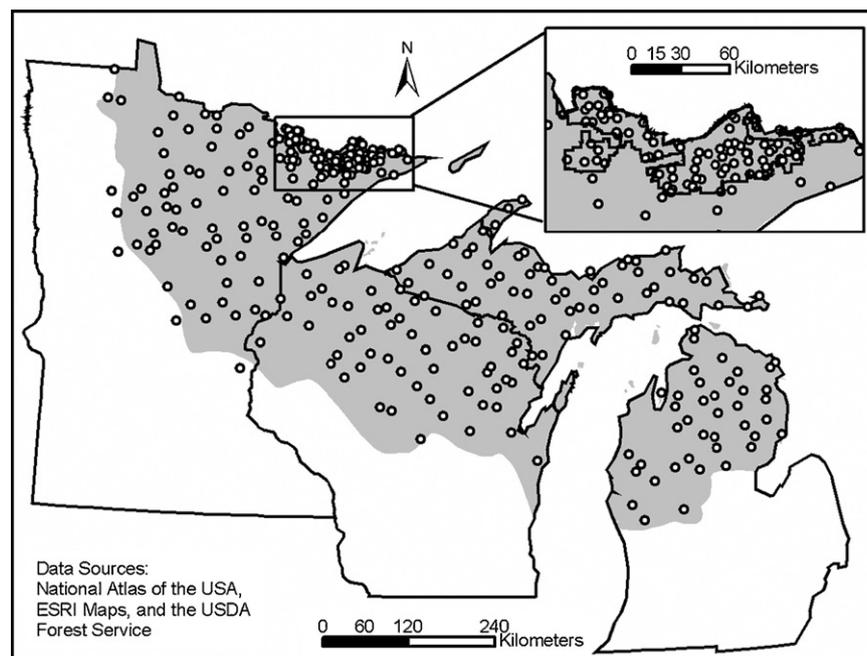


Fig. 1. Approximate plot locations (perturbed due to privacy laws) for study plots in the 212 ecosystem (grey area) and Boundary Waters Canoe Area Wilderness (boundary within inset map).

## 2.2. Boundary Waters Canoe Area Wilderness

The BWCAW, established as a wilderness area in 1978, contains 438,679 ha (Heinselman, 1996) (Fig. 1). Nearly 18% of the BWCAW is water with over 1000 portage-linked lakes and streams drawing over 200,000 visitors a year (Heinselman, 1996; USDA Forest Service, 2001). The forests of the BWCAW, an intermix of northern hardwoods and boreal forests, contain some of the largest tracts of virgin forest in the eastern U.S. (Heinselman, 1996; USDA Forest Service, 2001). Eighty-one percent of BWCAW forests are occupied by upland species of *P. abies*, *P. strobus*, *P. banksiana*, *P. resinosa*, *Acer* spp., *P. tremuloides*, and *B. papyrifera* (Heinselman, 1996). *Alnus rugosa* (Du Roi) Clausen and *Justicia americana* (L.) Vahl. wetlands make up the remaining forested areas (19%) (Heinselman, 1996). Although mostly formed from the parent material of glacial till, soils in the BWCAW range from moderately acidic granitic soils to slightly alkaline calcareous clay deposits (Heinselman, 1996). Historically, the forests of the BWCAW were fire-dominated ecosystems with nearly all stands initiated by catastrophic wildfires (Heinselman, 1973; Carlson, 2001). The dominant fire regime consisted of large-scale running crown fires or high intensity surface fires with a fire rotation length ranging from 50 to 350 years depending on forest type (Heinselman, 1973, 1996). However, since European settlement over a century ago, fire suppression activities have increased the fire rotation to approximately 1000 years (Heinselman, 1996). It has been suggested that management-induced reductions in the fire rotation would be necessary to prevent further deviation from historic, presettlement conditions in the BWCAW (Scheller et al., 2005).

## 3. Data

Standing tree and downed woody fuel data were acquired from the Forest Inventory and Analysis program (FIA) of the USDA Forest Service. The FIA program is responsible for inventorying the forests of the U.S., including both standing trees and downed woody materials on permanent sample plots established across the study area (Bechtold and Patterson, 2005). Between 2001 and 2003, FIA sampled 317 plots in forests of the upper Great Lakes by FIA with 89 plots in the BWCAW (34 in blowdown and 55 in non-blowdown areas) and 228 plots in the 212 ecosystem outside the BWCAW (Fig. 1). For details on the establishment and sampling of standing trees by the FIA program, see Bechtold and Patterson (2005). Sample plots are established at an intensity of approximately 1 plot per 2400 ha. If the plot lies in a forested area, field crews visit the site and measure tree and site variables ranging from tree sizes to forest types. FIA standing tree inventory plots consist of four 7.32 m fixed radius subplots for a total plot area of approximately 0.07 ha. All standing trees greater than 12.25 cm diameter at breast height (dbh) are inventoried on the plot, while trees less than 12.25 cm dbh are measured on a 2.07 m fixed radius microplot on each subplot.

Downed woody material sampling methods on FIA plots are detailed by USDA (2003) and Woodall and Williams (2005). The

largest fuels (>1000 h fuels), with a transect diameter greater than 7.60 cm, are sampled on each of the three 7.32 m horizontal distance transects radiating from each FIA subplot center at 30, 150, and 270°. Data collected for every >1000 h piece include transect diameter, length, small-end diameter, large-end diameter, decay class, and species. Fine woody debris (FWD) (1, 10, and 100 h fuels) is sampled on the 150° transect on each subplot. Fine woody debris with transect diameters less than 0.61 and 0.62–2.54 cm (1 and 10 h, respectively) was tallied separately on a 1.83 m slope distance transect (4.27–6.09 m on the 150° transect). Fine woody debris with transect diameters of 2.55–7.59 cm (100 h) was tallied on a 3.05 m slope–distance transect (4.27–7.32 m on the 150° transect) (for more information on fuel class definitions, see Deeming et al., 1977).

## 4. Analysis

Per unit area estimates (tonnes/ha) for the fuel hour classes followed Brown's (1974) estimation procedures. Logs per hectare estimates were determined using DeVries' (1986) estimation procedures (Woodall and Williams, 2005). All study plots were classified as inside or outside BWCAW blowdown areas by overlaying plot locations on blowdown area sketch maps provided by the Minnesota Department of Natural Resources (MNDNR) (Befort, 2005). The coarse-scale MNDNR blowdown mapping allowed development of blowdown and non-blowdown study strata. Means and associated standard errors were determined among the three study strata for total fuels, individual fuel classes (1, 10, 100, and >1000 h), and >1000 h size/decay classes. Means and associated standard errors for total fuels (by fuel hour class) were determined by trees per hectare class. The significance of differences in means among study strata for fuel classes, >1000 h size/decay classes, and stand density was tested using an analysis of variance (ANOVA). Differences in means among study strata were deemed significant at the 0.05 level. Finally, the outer-limit of the relationship between a study plot's total fuels and total standing live tree basal area (model: total fuels = standing live basal area) was assessed using quantile regression (94th percentile regression) (SAS quantreg procedure, for example see Zhang et al., 2005).

## 5. Results

The mean total fuel loadings (all fuel hour classes) in BWCAW blowdown areas (39.54 tonnes/ha) was nearly double the fuel loadings in the 212 ecosystem (20.60 tonnes/ha) and non-blowdown BWCAW strata (24.34 tonnes/ha) ( $p$ -value < 0.0001). In particular, BWCAW blowdown areas have nearly twice the 100 and >1000 h fuels as the 212 ecosystem and BWCAW non-blowdown areas ( $p$ -value = 0.0003, Fig. 2). The mean fuel loading of 100 h fuels in the BWCAW blowdown areas was 12.98 tonnes/ha compared to 5.7 tonnes/ha in non-blowdown areas. There were less obvious differences among the study strata for smaller-sized fuels with the little substantial difference in the absolute values of 1 and 10 h fuel loading means (Fig. 2). However, differences in 1 h means

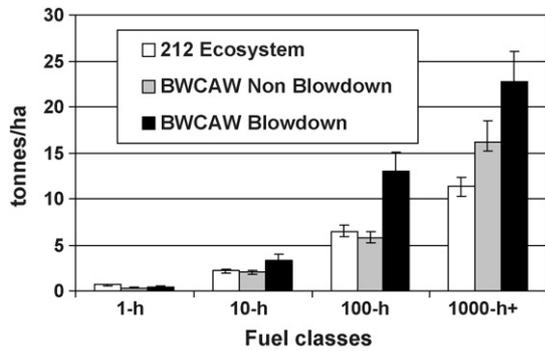


Fig. 2. Means and standard errors of fuel class estimates for forested FIA plots.

among study strata were significant ( $p$ -value = 0.0235) while 10 h means were not significantly different ( $p$ -value = 0.0642).

The mean number of >1000 h fuel pieces by size and decay classes did not differ among the three study strata (Tables 1 and 2,  $p$ -values > 0.3). The smallest size class (7.60–20.20 cm) constituted 83% of mean per hectare >1000 h pieces in BWCAW blowdown areas (Table 1). Similarly, the 212 ecosystem and non-blowdown areas of the BWCAW had proportions of 84 and 86%, respectively. For all study strata, over 50% of the number of >1000 h fuels were in decay classes 2 and 3 (Table 2).

Trees per hectare and tonnes of downed woody fuels were not strongly related among the three study strata (Fig. 3). However, BWCAW blowdown locations had higher mean fuel loadings ( $p$ -value < 0.0001) when trees per hectare were low (<750 tph) as compared to non-blowdown areas and the 212 ecosystem. When the number of standing trees per hectare was high, all three strata exhibited nearly the same mean total fuel loading.

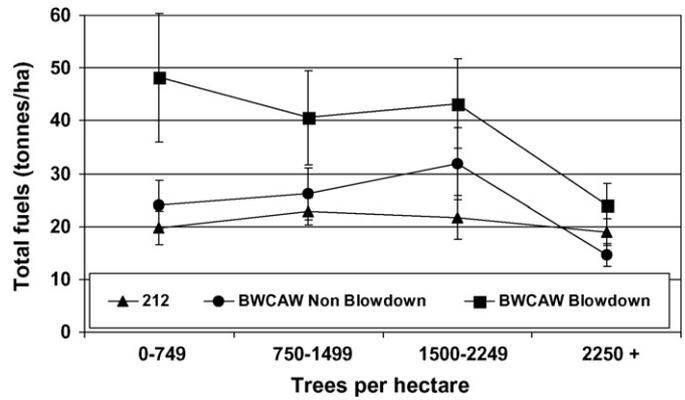


Fig. 3. Means and standard errors of total fuel estimates (tonnes per hectare) by classes of trees for three study strata (212 ecosystem, BWCAW no damage, and BWCAW damage).

No relationship was evident between total basal area and total fuel loadings for any of the three study strata (Fig. 4). However, there appeared to be a maximum observed limit to the amount of downed woody fuels in relation to stand density. Quantile regression results of this outer-limit relationship (total fuel = standing live basal area) indicated a negative slope at the 94th percentile (Fig. 4, dotted line) (slope = -0.3310,  $p$ -value = 0.0892) ... as stand density increases, maximum downed woody fuels decreases.

6. Discussion

Our study found only slight differences in the loadings of the smallest-sized fuels (1 h) between blowdown and non-blowdown areas of the BWCAW, but found significant and substantial differences in the mean estimates for the larger

Table 1 Mean 1000 h pieces per hectare by diameter class and study stratum (blowdown and non-blowdown areas of BWCAW and 212 ecosystem)

Piece diameter (cm)	Pieces per hectare								
	Laurentian (212 ecosystem)			BWCAW no damage			BWCAW damage		
	Mean	Standard error	% of Total	Mean	Standard error	% of Total	Mean	Standard error	% of Total
7.6–20.2	383	24	84	394	50	86	413	53	83
20.3–33.0	64	6	14	62	9	14	78	11	16
33.1–45.7	6	1	1	2	1	0	6	2	1
>45.8	2	1	0	0	0	0	2	1	0

Table 2 Mean 1000 h pieces per hectare by decay class and study stratum (blowdown and non-blowdown areas of BWCAW and 212 ecosystem)

Decay class	Pieces per hectare								
	Laurentian (212 ecosystem)			BWCAW no damage			BWCAW damage		
	Mean	Standard error	% of Total	Mean	Standard error	% of Total	Mean	Standard error	% of Total
1	43	7	9	23	14	5	55	24	11
2	108	12	24	94	24	20	119	24	24
3	147	12	32	116	17	25	153	25	31
4	104	9	23	100	14	22	86	14	17
5	53	8	12	126	26	27	84	21	17

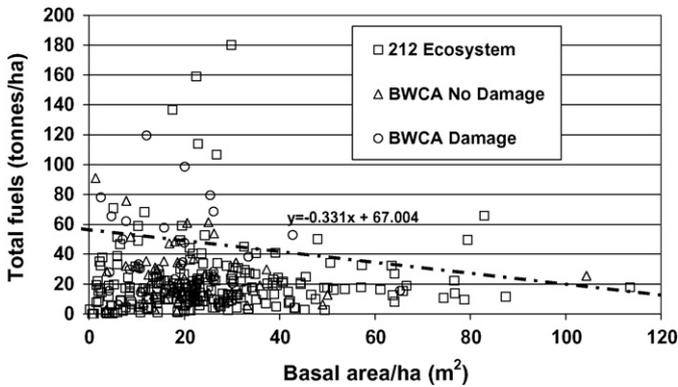


Fig. 4. Relationship between total fuel loadings and stand basal area for three study strata (212 ecosystem, BWCAW non-blowdown, and BWCAW blowdown) with defined outer-limit of points.

fuels (100 and >1000 h). The smallest fuel pieces may decay quickly and disappear from wind-disturbed ecosystems while the larger fuels take longer to decay and thus are resident in the ecosystem for longer periods. The greatest differences in fuel loadings among study strata were for 100 h fuels. Although there were expectations that BWCAW blowdown fuel loadings might exceed 100 tonnes/ha based on fuel models (Leuschen et al., 2000), this study found a mean total fuel loading of only 40 tonnes/ha. Despite only a doubling of fuel loadings in blowdown areas, the fire danger implications of the 100 h fuels (i.e., tree branches, small boles, and fallen crowns) in BWCAW blowdown areas may outweigh the lack of substantial fuel loading increases in other fuel classes. Because 100 h fuels release a substantial amount of energy during forest fires, more extreme fire behavior and intensity should be expected in blowdown areas. Although there were significantly more >1000 h fuels in BWCAW blowdown areas than in the other two study strata, the distribution of decay and size classes indicates that the accumulation of fuels from fallen trees is the same whether tree mortality was primarily the result of normal stand development, such as suppression mortality in the 212 ecosystem, or large-scale wind disturbances such as in the BWCAW blowdown. However, it may be postulated that this study's rather broad >1000 h decay and size classes did not precisely reflect the likely larger and more freshly fallen tree boles found in the wilderness areas since >1000 h fuel loadings were found to be higher in BWCAW areas.

This study found no discernible relationship between total downed woody fuel loadings and trees per hectare or total stand basal area. Studies in other forest ecosystems (McMinn and Hardt, 1993; Norden et al., 2004) have found similar results . . . a lack of strong correlation between standing tree and downed and dead tree attributes. Whereas stand-level characteristics (e.g., standing live tree basal area) and topography may serve as important predictors of post-disturbance damage in many forest ecosystems (Veblen et al., 2001), they may not elucidate forest disturbance processes in the rather topographically homogenous regions of the upper Great Lakes (Schulte et al., 2005). Predicting fuel loadings based on stand density measures may not be possible in a post-disturbance situation. However, stand density may define a maximum limit for fuel loadings. In this

study, the maximum amount of downed woody fuel was negatively related to standing tree density. The left side of this relationship may be influenced by stands that recently had a major disturbance resulting in heavy fuel loadings and low standing tree density. In contrast, the right side of this relationship may be influenced by heavily stocked stands that have not yet had pervasive density-induced mortality. The amount of downed woody fuel in upper Great Lakes forests may be more dependent on the successional trends and disturbance history (both natural and anthropogenic) than standing live tree density measures.

Building upon these results, we propose there are two stand development processes at work that confound correlations between fuel loadings and standing tree attributes. First, some stands progress through stages of stand development with only density-induced mortality and occasional individual tree blowdowns (Canham and Loucks, 1984; Frelich and Graumlich, 1994). For these stands, a relatively constant amount of downed woody materials may persist through stand development—a zero sum balance between mortality and the decay of older woody materials. Second, some stands experience sudden stand-level disturbances such as those observed in the blowdown areas of the BWCAW (for examples, see Canham and Loucks, 1984; Frelich and Graumlich, 1994; Peterson, 2000; Woods, 2004). For these stands, there are sudden reductions in stand density and simultaneous increases in fuel loadings. These two stand development/disturbance processes of frequent, small-scale wind disturbances and infrequent, large-scale wind catastrophes in upper Great Lakes forests were documented by previous research (Canham and Loucks, 1984; Frelich and Graumlich, 1994; Schulte et al., 2005); however, no suggestion was made with regards to prediction of fuel loadings. Canham and Loucks (1984) suggested these two disturbance processes are ecologically and climatologically distinct. While the characteristics of small-scale blowdowns are highly dependent on individual tree and site attributes such as tree size, canopy structure, and prevailing winds (Canham and Loucks, 1984; Canham et al., 2001), the forest characteristics of large-scale catastrophic blowdowns appear more dependent on aspects of the unique/severe storm system and topography (Canham and Loucks, 1984). If both processes are occurring over a region, they confound attempts to predict downed woody fuel loadings for individual stands based on standing tree attributes, a result found in this study.

For Great Lakes State forest managers, the probability of any given forest having high fuel loadings as the result of a major blowdown event is low. In contrast, there is a higher likelihood that fuel loadings are the result of gradual stand development processes such as individual tree mortality and self-shading. Therefore, foresters wishing to limit downed woody fuel loadings should focus on reducing tree mortality and favoring species mixtures/densities that avoid self-shading that produces high amounts of branch shedding. The occurrence of widespread blowdown events in Great Lakes forests suggests that even the best attempts to maintain a forest with low fuel loadings may be confounded by sudden disturbance events that can more than double fuel loadings.

## 7. Conclusions

In the BWCAW blowdown, fuel loadings were only substantially different for larger-sized fuels when compared to neighboring, non-blowdown forests. Given the possibility of future blowdown events (e.g., hurricanes) across forests of the United States, it should be acknowledged that the fire danger from smaller-sized fuels may be ephemeral, while dangers from larger-sized fuels may linger for years. However, in the upper Great Lakes forests the combination of frequent individual tree mortality events (e.g., suppression) with infrequent catastrophic disturbances (e.g., blowdowns) complicates efforts to both predict and manage fuel loadings. This study suggests an upper limit to maximum fuel loadings based on standing tree density; however, the range of possible fuel loadings is still considerable. Efforts to estimate and manage fuel loadings across large scales may be aided by a better understanding of forest ecosystem processes that involve disturbances like individual tree mortality and catastrophic windthrow.

## References

- Bailey, R.G., 1995. Description of the Ecoregions of the United States. USDA, Forest Service Miscellaneous Publication 1391.
- Bechtold, W.A., Patterson, P.L. (Eds.), 2005. Forest Inventory and Analysis National Sample Design and Estimation Procedures. USDA Forest Service. General Technical Report, SRS-GTR-80.
- Befort, B., 2005. Sketch Map of BWCAW Blowdown Affected Areas. Minnesota Department of Natural Resources.
- Boose, E.R., Chamberlain, K.E., Foster, D.R., 2001. Landscape and regional impacts of hurricanes in New England. *Ecol. Monogr.* 71, 27–48.
- Brown, J.K., 1974. Handbook for Inventorying Downed Woody Material. USDA Forest Service INT-GTR-16.
- Canham, C.D., Loucks, O.L., 1984. Catastrophic windthrow in the presettlement forests of Wisconsin. *Ecology* 65, 803–809.
- Canham, C.D., Papaik, M.J., Latty, E.F., 2001. Interspecific variation in susceptibility to windthrow as a function of tree size and storm severity for northern temperate tree species. *Can. J. Forest Res.* 31, 1–10.
- Carlson, D., 2001. Heterogeneity of fire severity in the Boundary Waters Canoe Area Wilderness: causes, consequences and management implications. M.S. Thesis. University of Minnesota, St. Paul.
- Dale, V.H., Joyce, L.A., McNulty, S.G., Neilson, R.P., Ayres, M.P., Flannigan, M.D., Hanson, P.J., Irland, L.C., Lugo, A.E., Peterson, C.J., Simberloff, D., Swanson, F.J., Stocks, B.J., Wotton, B.M., 2001. Climate change and forest disturbances. *Bioscience* 51, 723–734.
- Deeming, J.E., Burgan, R.E., Cohen, J.D., 1977. The National Fire-danger Rating System. USDA Forest Service Research Paper INT-RP-226.
- DeVries, P.G., 1986. Sampling Theory for Forest Inventory: A Teach-Yourself Course. Springer-Verlag, Berlin, pp. 242–279 (Chapter 13).
- Foster, D.R., Boose, E.R., 1992. Patterns of forest damage resulting from catastrophic wind in central New England, USA. *J. Ecol.* 80, 79–98.
- Freligh, L.E., Graumlich, L.J., 1994. Age-class distribution and spatial patterns in an old-growth hemlock-hardwood forest. *Can. J. Forest Res.* 24, 1939–1947.
- Freligh, L.E., Reich, P.B., 1999. Neighborhood effects, disturbance severity, and community stability in forests. *Ecosystems* 2, 151–166.
- Heinselman, M.L., 1996. The Boundary Waters Wilderness Ecosystem. University of Minnesota Press, Minneapolis.
- Heinselman, M.L., 1973. Fire in the virgin forests of the Boundary Waters Canoe Area. *Minn. Quatern. Res.* 3, 329–382.
- Leuschen, T., Wordell, T., Finney, M., Anderson, D., Aunan, T., Tine, P., 2000. Fuel Risk Assessment of the Blowdown in the Boundary Waters Canoe Area Wilderness and Adjacent Lands. USDA Forest Service, Superior National Forest, Duluth, MN.
- Mattson, W.J., Shriner, D.S. (Eds.), 2001. Northern Minnesota Independence Day Storm: A Research Needs Assessment. USDA Forest Service, North Central Research Station. General Technical Report NC-GTR-216.
- McMinn, J.W., Hardt, R.A., 1993. Accumulations of coarse woody debris in southern forests. In: McMinn, J.W., Crossley, Jr., D.A. (Eds.), *Biodiversity and Coarse Woody Debris in Southern Forests. Proceedings of the Workshop on Coarse Woody Debris in Southern Forests: Effects on Biodiversity*. Atlanta, GA, October 18–20 USDA Forest Service Gen. Tech. Rep. SE-GTR-94.
- Norden, B., Ryberg, M., Gotmark, F., Olausson, B., 2004. Relative importance of coarse and fine woody debris for the diversity of wood-inhabiting fungi in temperate broadleaf forests. *Biol. Conserv.* 117, 1–10.
- Peterson, C.J., 2000. Catastrophic wind damage to North American forests and the potential impact of climate change. *Sci. Total Environ.* 262, 287–311.
- Romme, W.H., Everham, E.H., Freligh, L.E., Sparks, R.E., 1998. Are large, infrequent disturbances qualitatively different from small, frequent disturbances? *Ecosystems* 1, 524–534.
- Scheller, R.M., Mladenoff, D.J., Crow, T.R., Sickley, T.A., 2005. Simulating the effects of fire reintroduction versus continued fire absence on forest composition and landscape structure in the Boundary Waters Canoe Area, northern Minnesota, USA. *Ecosystems* 8, 396–411.
- Schulte, L.A., Mladenoff, D.J., Burrows, S.N., Sickley, T.A., Nordheim, E.V., 2005. Spatial controls of pre-euro-American wind and fire disturbance in northern Wisconsin (USA) forest landscapes. *Ecosystems* 8, 73–94.
- Seymour, R.S., White, A.S., deMaynadier, P.G., 2002. Natural disturbance regimes in northeastern North America: evaluating silvicultural systems using natural scales and frequencies. *Forest Ecol. Manage.* 155, 357–367.
- Turner, M.G., Baker, W.L., Peterson, C.J., Peet, R.K., 1998. Factors influencing succession: lessons from large, infrequent natural disturbances. *Ecosystems* 1, 511–523.
- USDA Forest Service, 2001. Final Environmental Impact Statement for the Boundary Waters Canoe Area Wilderness Fuel Treatments, vol. 1. USDA Forest Service, Superior National Forest, Eastern Region, Milwaukee, WI.
- USDA Forest Service, 2003. Forest Inventory and Analysis National Core Field Guide. Field Data Collection Procedures for Phase 3 Plots, vol. II. USDA Forest Service, North Central Research Station, pp. 265–298 (Version 1.6, Section 14).
- Veblen, T.T., Kulakowski, D., Eisenhart, K.S., Baker, W.L., 2001. Subalpine forest damage from a severe windstorm in northern Colorado. *Can. J. Forest Res.* 31, 2089–2097.
- Woodall, C.W., Williams, M.S., 2005. Sample Protocol, Estimation Procedures, and Analytical Guidelines for the Down Woody Materials Indicator of the Fia Program. USDA Forest Service. General Technical Report GTR-NC-256.
- Woods, K.D., 2004. Intermediate disturbance in a late-successional hemlock-northern hardwood forest. *J. Ecol.* 92, 464–476.
- Zhang, L., Bi, H., Gove, J.H., Heath, L.S., 2005. A comparison of alternative methods for estimating the self-thinning boundary line. *Can. J. Forest Res.* 35, 1507–1514.