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Annual estimates of wind disturbance in relation to time of observation in a panelized national forest inventory

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ABSTRACT

We used national forest inventory data from Michigan, Minnesota, and Wisconsin, U.S.A. to produce estimates of the annual areal extent of wind disturbance for 2005–2018. Our results indicate that at least for wind in the region, including the panel of plots assigned to the inventory year coincident with the disturbance year produces estimates that are lower than estimates computed with that specific inventory year excluded. We attributed this result to partial observation of disturbance for that year, a situation that arises from the operational necessity of a year or more being required to measure all the plots in a panel. There was modest evidence to suggest that in a five-panel inventory, including the inventory year measured furthest in time from the disturbance year being estimated can result in estimates lower than estimates computed with that specific inventory year excluded. This could occur, for example, if the signs of wind damage substantially dissipate several years after the disturbance year. For estimation of annual wind disturbance in the region, data users may consider which panels are included, with particular attention to the inventory year coincident with the disturbance year being estimated and, in the case of combinations of five panels measured consecutively, the inventory year measured furthest in time from the disturbance year.

1. Introduction

Wind is a natural factor in forests that has both positive and negative impacts for trees (Jacobs, 1936). Wind can cause tree damage and mortality, which is a negative impact when those outcomes are contrary to planned management objectives. Uprooting, breakage, bending, and leaning are some of the ways wind can damage trees. The severity of damage is influenced by a variety of biotic and abiotic factors. Notable biotic factors include tree size, species, stand conditions, and pathogens. Abiotic factors include wind intensity, soil characteristics, topographic position, and past disturbance history (Everham and Brokaw.,1996). Mortality resulting from wind typically occurs immediately, but instances of delayed mortality do occur (Harmon and Pabst, 2019).

Wind is an impactful source of tree damage and mortality in forests of the Great Lakes region of the United States (Rich et al., 2007). In the states of Michigan, Minnesota, and Wisconsin, forests cover 22.1 million hectares, which is 43 % of the total area (USDA Forest Service, Forest Inventory and Analysis Program, 2025a). Private and public ownerships account for 59 % and 41 %, respectively, of the total forest area. More public forestland is in State ownership (3.8 million ha) than Federal (3.1 million ha) or County and Municipal (2.2 million ha). The most abundant forest types by area are aspen-birch (*Populus-Betula*; 22 %), maple-beech-birch (*Acer-Fagus-Betula*; 20 %), oak-hickory (*Quercus-Carya*; 18 %), spruce-fir (*Picea-Abies*; 15 %), elm-ash-cottonwood (*Ulmus-Fraxinus-Populus*; 10 %), and white-red-jack pine (*Pinus strobus-Pinus resinosa-Pinus banksiana*; 9 %). Substantial economic activity is derived from the region's forests. In 2018, 947 million cubic feet of timber product was provided to 792 primary wood processing mills (USDA Forest Service, 2021a, 2021b, 2021c). In 2017, the forest products industry in the region provided direct employment of more than 142,000 people and direct output of more than $48 billion (Leefers et al., 2020).

Across the region, damaging winds can accompany severe thunderstorms, hailstorms, rainstorms, windstorms, tornadoes, snowstorms, and ice storms (Changnon and Kunkel, 2006). In mid-latitudes of the Northern Hemisphere, much of the high-impact weather is caused by extra-tropical cyclones (Chang et al., 2016). Extra-tropical cyclones are low pressure systems that originate outside tropical areas. Two major cyclone tracks transit the Great Lakes region. Cyclones originating in the northern Great Plains or central provinces of Canada and cyclones

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originating in the southern Great Plains are colloquially known as Alberta Lows and Colorado Lows (Hutson et al., 2024, Letson et al., 2021). Strong winds are associated with the centers of cold season cyclones in the mid-latitudes. Over the last 30 years, tracks of cold season cyclones have trended northward concentrating in areas north of 44° latitude (Hutson et al., 2024). The vast majority (85 %) of the forests in Michigan, Minnesota, and Wisconsin lie above 44° latitude (USDA Forest Service, Forest Inventory and Analysis Program, 2025a).

A primary source of forest condition and disturbance information in the region is the United States (US) Nationwide Forest Inventory (NFI) (USDA Forest Service, Forest Inventory and Analysis Program, 2025b; Bechtold and Patterson, 2005; Westfall et al., 2022). NFI is a national forest inventory conducted by the US Forest Service Forest Inventory and Analysis (FIA) program. Every time an NFI plot is measured in the field, significant disturbances that occurred on the plot since the previous measurement are noted. The type of disturbance (e.g., wind) and the year of disturbance (e.g., 2019) for up to three disturbances are recorded (Burrill et al., 2024). The record of a plot measured in 2022, assuming it was previously measured in 2017, gives an indication of presence or absence of significant wind disturbance in 2018, 2019, 2020, 2021, and 2022. This plot, depending on what other plots from the inventory are included with it, could be part of a sample that at least conceptually is suitable for estimation of the annual extent of wind disturbance in 2018, 2019, 2020, 2021, or 2022. Strictly speaking, when forming the sample to produce estimates it is panels that are included or excluded (Patterson and Reams, 2005). The example plot measured in 2022 is part of a panel of plots that together provide spatially balanced coverage of the population and that are measured around the same time period. The year prior, 2021, a different panel of plots was measured, and assuming they were previously measured in 2016, this panel could be included, depending on what other panels are included, in a sample to produce an estimate of the annual extent of wind disturbance in 2017, 2018, 2019, 2020, or 2021.

The primary objective of this study was to assess the suitability of different panels of plots when estimating the annual extent of wind disturbance in forests of the northwestern Great Lakes region (Michigan, Minnesota, and Wisconsin). Our focus was on the combination of five panels of plots measured in consecutive years and assessing whether the first (earliest measured panel relative to the disturbance year) panel and last (latest measured) panel in the sequence significantly influences annual estimates of disturbance. Our interest in the first panel stems from the potential for measurement of some plots in that panel to precede that year's wind event giving rise to significant tree damage and mortality. Comparing estimates computed with the first panel to estimates computed without it can provide an indication of the significance of this issue and whether adjustment in estimation may be needed. Our interest in the last panel stems from recognition that the indicators of disturbance will dissipate with time. Comparing estimates computed with the last panel to estimates computed without it could provide insight into whether there is a potential issue with indicators of wind damage dissipating within the time frame of the retrospective disturbance observation. Testing the suitability of different panels in disturbance estimation can inform best practices that lead to the most accurate estimates of the annual extent of wind disturbance in the region.

2. Methods

NFI data for this study came from the United States Department of Agriculture, Forest Service, Forest Inventory and Analysis (FIA) Program. The sample design and estimation procedures FIA uses in the NFI are documented in several publications, most notably Bechtold and Patterson (2005) and Westfall et al. (2022). Data for the three-state area of Michigan, Minnesota, and Wisconsin (Fig. 1) were downloaded from the FIA DataMart (USDA Forest Service, Forest Inventory and Analysis Program, 2025c). All data were imported into R (R Core Team, 2024) where estimates were computed and analyses performed.

The NFI employs a panelized design where a portion of the plots are sampled every year. When a plot is measured, crews check for disturbances that occurred since the last measurement or, if the plot is new, disturbances that occurred in the preceding five years (Burrill et al., 2024). The panelized design and retrospective nature of the disturbance observation in the inventory is illustrated for a five-panel example in Table 1. In most instances when an estimate is produced, all the panels in a population are pooled (Moisen et al., 2022). An example of the pooling of five panels with the specific disturbance years where disturbance presence/absence is noted is illustrated in Table 1. The term inventory year is used to denote a panel of plots and the year the plots in the panel are intended to be measured. When inventory years 2018–2022 are pooled, the single disturbance year in common is 2018. Coulston et al. (2020) demonstrated via a simulation study that the single disturbance

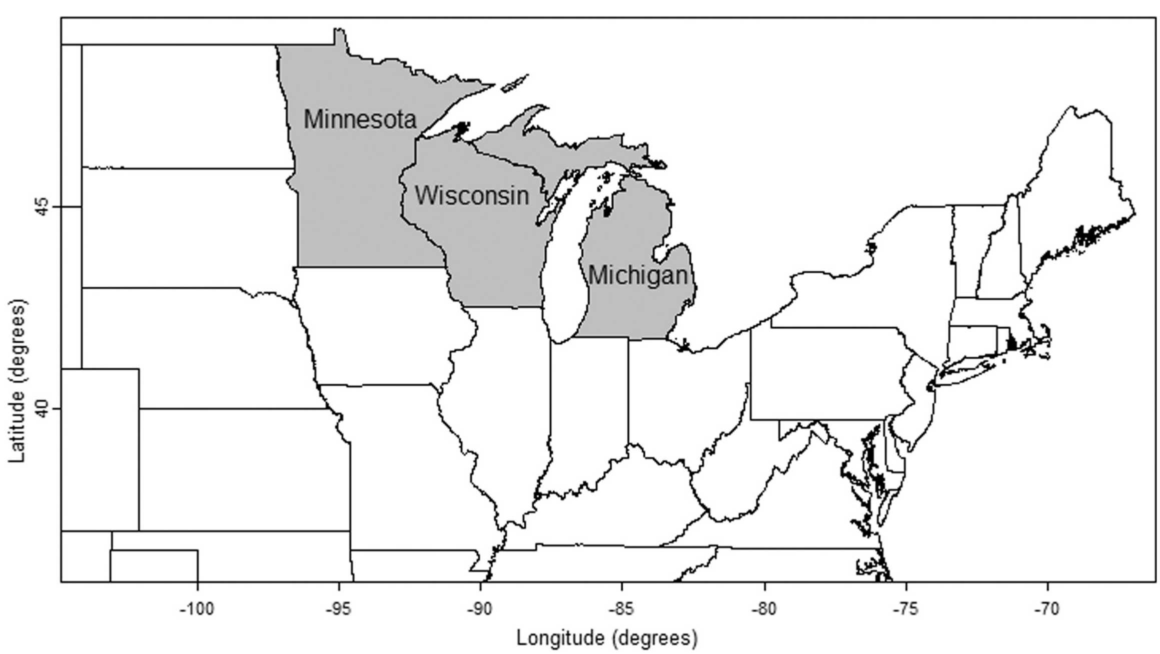

Fig. 1. States of Michigan, Minnesota, and Wisconsin in the Great Lakes region of the northern United States.

Table 1
Conceptual observation of disturbance by year in a five-panel inventory example. An X denotes that disturbance presence/absence is noted. The year 2018 is the single year in the example where disturbance presence/absence is noted for every inventory year.

	Years where a disturbance presence/absence is noted								
Inventory year	2014	2015	2016	2017	2018	2019	2020	2021	2022
2018	X	X	X	X	X				
2019		X	X	X	X	X			
2020			X	X	X	X	X		
2021				X	X	X	X	X	
2022					X	X	X	X	X

year in common among the five consecutive inventory years pooled was the only year among the disturbance years observed where standard estimation methods (i.e., post-stratified estimation) produced an estimate that had satisfactory agreement with the true population value.

Each panel provides approximately uniform spatial coverage of the population (Reams et al., 2005; Patterson and Reams, 2005). Combining all the panels when producing an estimate is a common practice in general estimation settings as lower standard errors are associated with larger sample sizes. There are situations, however, where post-stratified estimation using less than the full set of panels has produced important insights of forest condition when disturbance is present (Edgar et al., 2019). We leverage this feature of the design to produce annual estimates of wind disturbance with a set of panels and then recompute the estimate with a single panel removed. We then compute the difference between the two estimates and an estimate of the standard error of the difference estimate. A single instance of a difference could be the result of variability introduced by sampling. Where multiple instances of differences are consistently of one direction (positive or negative) and statistically significant, then other factors besides sampling variability become a possibility, such as when significant mortality is delayed or damage is ephemeral.

The term evaluation refers to a selection of panels of plots and an accompanying stratification (Burrill et al., 2024). Post-stratified estimation methods are applied to the evaluation resulting in an estimate of a population parameter and accompanying statement of uncertainty in the form of the standard error of the estimate. We started by assembling evaluations of five consecutive inventory years beginning with inventory years 2005–2009 and ending with inventory years 2018–2022 (Table 2) for each state. This process required examining the existing evaluations in the FIA database (FIADB). Minnesota has maintained a five-panel inventory since the annual inventory was initiated and thus the evaluations in FIADB already consist of five consecutive inventory years. Examination of Michigan and Wisconsin showed evaluations of five, six, and seven inventory years, an outcome of a transition from a five-panel inventory to a seven-panel inventory that started in 2014. Evaluations in FIADB ending with inventory years up to and including 2013 were constructed using five inventory years. Evaluations ending with inventory years 2014–2016 consisted of six inventory years. Evaluations ending with inventory year 2017 and later consisted of seven inventory years. We modified the FIADB evaluations for Michigan and Wisconsin after the transition to include just the five latest inventory years of the six or seven inventory years included in the FIADB evaluation. In total, 42 five-inventory year (or five-panel) evaluations (3 states x 14 years) were assembled (Table 2).

From each of the 42 five-inventory year evaluations assembled from FIADB, we created 8 evaluations resulting in a total of 336 new evaluations for computing estimates of annual disturbance. The first evaluations constructed were of inventory years 1, 2, 3, 4, 5 and inventory years 2, 3, 4, 5. Using this notation, the common year of disturbance observation is year 1. The former evaluation includes inventory year 1 and the latter evaluation excludes it, but otherwise the two evaluations are the same. Applying this notation to the example of estimation of disturbance in 2018, the former evaluation consists of inventory years 2018, 2019, 2020, 2021, 2022 and the latter of inventory years 2019, 2020, 2021, 2022. At this point the post-stratification in the evaluation is that provided in the source FIADB evaluation. All strata in this analysis were constructed from canopy cover classes. For example, canopy cover classes 0–5, 6–50, 51–65, 66–80, and 81–100 were commonly used to define the strata. National Land Cover Database (NLCD) provides wall-to-wall classification of tree cover from which stratum weights and plot assignment to strata are based. Since inventory years are being removed, the potential exists for stratum sample sizes to drop below a specified minimum. A minimum stratum sample size of 10 plots was observed in the FIADB evaluations used in this analysis. We applied a minimum stratum sample size of 4 plots in this analysis, which is consistent with the minimum observed among all the evaluations of

Table 2
Organization of inventory years and disturbance years observations (X) utilized in this analysis.

Inventory year	Disturbance year																	
	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
2005	X																	
2006	X	X																
2007	X	X	X															
2008	X	X	X	X														
2009	X	X	X	X	X													
2010		X	X	X	X	X												
2011			X	X	X	X	X											
2012				X	X	X	X	X										
2013					X	X	X	X	X									
2014						X	X	X	X	X								
2015							X	X	X	X	X							
2016								X	X	X	X	X						
2017									X	X	X	X	X					
2018										X	X	X	X	X				
2019											X	X	X	X	X			
2020												X	X	X	X	X		
2021													X	X	X	X	X	
2022														X	X	X	X	X

annual inventory data observed in the FIADB for the three states. The minimum stratum sample size observed in the evaluation of inventory years 2, 3, 4, 5 with the FIADB evaluation stratification was four and thus no modifications to the stratification were required. We denote the post-stratification used for computing estimates with and without inventory year 1 as stratification A.

The next evaluations constructed were those aimed at assessing the inventory years furthest in time from the disturbance year. To compare estimates with and without inventory year 5, we constructed evaluations of inventory years 2, 3, 4, 5 and 2, 3, 4. For the example of disturbance in 2018, the former evaluation consists of inventory years 2019, 2020, 2021, 2022 and the latter of inventory years 2019, 2020, 2021. When the source FIADB evaluation post-stratification was applied to the evaluation of inventory years 2, 3, 4, there were 14 strata out of 2353 total strata with sample size below 4 (Table 3). A stratum with too few plots was combined with an adjacent stratum of the same estimation unit. The stratum with too few plots was usually combined with the adjacent stratum having lower canopy cover (e.g., if stratum 66–80 canopy cover had too few plots, it was combined with stratum 51–65 canopy cover). The modified post-stratification applied to estimates computed with and without inventory year 5 is referred to as stratification B (Table 3). In a similar manner, evaluations to compare estimates with and without inventory year 4 and evaluations to compare estimates with and without inventory year 3 were constructed. With progressively fewer inventory years in the evaluation, higher numbers of source FIADB evaluation post-stratifications having sample sizes below 4 were observed. Stratification D for comparing estimates with and without inventory year 3, required combining 11 estimation units in addition to many strata (Table 3). Estimation units are subpopulations of the state formed from administrative boundaries consisting of a major ownership category in a group of counties. An estimation unit lacking sufficient plot numbers was combined with a similar estimation unit nearby. For example, estimation unit Inland Census Water Unit 1, which occurs in eastern upper peninsula of Michigan, was combined with Inland Census Water Unit 2, which occurs in the western upper peninsula of Michigan.

Estimation in this analysis followed the standard post-stratified estimation methods used by the FIA program (Scott et al., 2005). For area estimates, the plot observation is the proportion of the plot in the domain of interest, computed with the following formula:

$$P_{hid} = \frac{\sum_{j}^{4}\sum_{k}^{K_{hij}} a_{mhijk}\delta_{hijkd}}{a_m\overline{p}_{mh}} \tag{1}$$

where,

P_{hid} = proportion of plot i in the domain of interest d, for plots assigned to stratum h, adjusted for stratum h plots that are partially nonsampled

a_{mhijk} = mapped area (hectares) of subplot j covering condition k on plot i assigned to stratum h

δ_{hijkd} = zero-one domain indicator function, which is 1 if condition k on subplot j of plot i assigned to stratum h belongs to the domain of interest d

K_{hij} = the number of conditions that exist on subplot j of plot i assigned to stratum h

a_m = total area (hectares) of the four subplots

$\overline{p}_{mh}$ = mean proportion of stratum h plot areas that were accessible (excluding fully nonsampled plots)

We used two domain indicators, one for annual estimates of wind disturbance and another for annual estimates of weather disturbance. A disturbance must be considered significant to be recorded. The general threshold of significance is mortality or damage to 25 percent or more of trees and affecting an area of at least 0.4 ha. When disturbance is present, information on kind and year are collected. Up to three different disturbances can be recorded (Burrill et al., 2024). Domain specification of annual wind disturbance included conditions with disturbance code 52 (Wind) in any of the three disturbances and accompanying disturbance year matching the year being estimated. For example, an annual estimate of wind disturbance in 2018 required at least one of the possible three disturbance observations to have disturbance code 52 and disturbance year 2018. Wind is one type among a group of weather-related disturbance types that are often grouped together to produce weather disturbance estimates. Domain specification for weather disturbance included conditions with disturbance codes of 50 (Weather), 51 (Ice), 52 (Wind), 53 (Flooding), or 54 (Drought) in any of the three disturbance fields and accompanying disturbance year matching the year being estimated. Wind or weather disturbances recorded as occurring continuously (i.e., disturbance year code of 9999) did not meet domain criteria.

The stratum mean estimator is:

$$\overline{P_{hd}} = \frac{\sum_{i}^{n_h} P_{hid}}{n_h} \tag{2}$$

where,

n_h = number of plots in stratum h

The variance estimator is:

$$v(\overline{P_{hd}}) = \frac{\sum_{i}^{n_h} P_{hid}^2 - n_h\overline{P_{hd}}^2}{n_h(n_h-1)} \tag{3}$$

The estimate of total area in the domain of interest for the estimation unit is:

$$\widehat{A}_d = A_T\sum_{h}^{H} W_h\overline{P_{hd}} \tag{4}$$

where,

A_T = total area (hectares) in the estimation unit

W_h = weight for stratum h

The variance estimator is:

$$v(\widehat{A}_d) = \frac{A_T^2}{n}\left[\sum_{h}^{H} W_h n_h v(\overline{P_{hd}}) + \sum_{h}^{H}(1-W_h)\frac{n_h}{n}v(\overline{P_{hd}})\right] \tag{5}$$

where,

n = number of plots in the estimation unit

Estimates and variances for estimation units were summed to derive the estimate and variance for the study area. Two estimates were compared by computing differences and standard errors of differences. The difference was computed as the estimate computed without the specified inventory year minus the estimate computed with the inventory year included. The variance of the difference was computed as the variance of the estimate without the inventory year plus the variance of the estimate with the inventory year minus two times the covariance. A covariance was computed using equations 4.18 and 4.19 from Scott et al. (2005). Using the method described by Zheng (2004), factors were

Table 3
Number of estimation units and strata for the post-stratifications used in the analysis.

Stratification	Comparison of estimates computed using inventory years			Number of estimation units	Number of strata
A	1, 2, 3, 4, 5	and	2, 3, 4, 5	672	2353
B	2, 3, 4, 5	and	2, 3, 4	672	2339
C	2, 3, 4	and	2, 3	672	2290
D	2, 3	and	2	661	2079

applied to the covariance to account for the fact that the two evaluations were neither completely independent nor completely dependent. An approximate 95 % confidence interval was computed as:

$$\text{estimate of the difference} \pm 1.96 \times \text{standard error of the difference} \quad (6)$$

and an interval that did not include 0 was taken as evidence of a statistically significant difference.

3. Results

Annual estimates of wind disturbance computed without the inventory year coincident with the disturbance year were higher in all 14 years compared (Table 4 and Fig. 2). The largest observed difference was 14,537 ha, which occurred in 2016. An estimate of 109,423 ha was computed from inventory years 1, 2, 3, 4, 5, which for 2016 was inventory years 2016, 2017, 2018, 2019, 2020. An estimate of 123,961 ha was computed from inventory years 2, 3, 4, 5, which in this case was inventory years 2017, 2018, 2019, 2020. Differences in wind estimates were statistically significant in 8 of the 14 years.

In 13 of the 14 years compared, estimates of weather disturbance were higher when the inventory year coincident with the disturbance year was excluded (Table 4 and Fig. 2). The single exception to this pattern of higher estimates was 2013, where the estimate without inventory year 2013 (i.e., inventory years 2014, 2015, 2016, 2017) was 6320 ha lower than the estimate with inventory year 2013 included (i.e., inventory years 2013, 2014, 2015, 2016, 2017). Of the 14 years of weather estimates compared, 9 of the annual differences were statistically significant.

Examination of plot measurement dates suggested the observation of disturbance may not be complete in the inventory year coincident with the disturbance year. In inventory year 2017, 26.8 % and 73.2 % of plots with at least one forestland condition had measurement years of 2016 and 2017, respectively (Fig. 3). Plots measured in 2016 would have no record of a disturbance in 2017. The record for plots measured in 2017 would depend on the timing of the disturbance relative to the measurement date. For inventory year 2017, the first quarter of 2017 was the quarter with the highest number of plots measured, and any disturbance occurring after, which encompasses three-quarters of the year, would not be recorded on plots measured in the first quarter. An early start (i.e., year prior) to measurement of an inventory year and measurement throughout the inventory year was observed for other inventory years (Fig. 3).

The next comparison was of estimates computed with and without inventory year 5, the inventory year measured furthest in time from the disturbance year (Table 5 and Fig. 4). For wind, the largest difference observed was 15,379 acres in 2011. An estimate of 73,398 ha was computed from inventory years 2, 3, 4, 5, which for 2011 included inventory years 2012, 2013, 2014, 2015. An estimate of 88,777 ha was computed from inventory years 2, 3, 4, which in this case was inventory years 2012, 2013, 2014. Of the 14 years compared, differences were positive for 10 years and negative for 4 years. There were 6 years that had a significant difference and in each case the difference was positive (i.e., estimate without inventory year 5 was higher). Weather estimates also included positive (11 years) and negative (3 years) differences. Like wind, the largest observed difference was in 2011. Of the 14 years of differences, 4 were significant.

The largest difference (absolute value) in estimates with and without inventory year 4 was observed in 2015 for both wind and weather (Table 6 and Fig. 5). In the case of wind, an estimate of 53,943 ha was computed with inventory years 2, 3, 4, which for 2015 was inventory years 2016, 2017, 2018. An estimate of 14,405 was computed with inventory years 2, 3, which for 2015 includes inventory years 2016, 2017. The estimate was 39,538 ha lower when inventory year 4 (i.e., 2018) was removed. For both wind and weather, a mix of positive (8 years) and

Table 4
Estimates with and without inventory year 1, the inventory year coincident with the disturbance year. Difference estimates in bold indicate significantly different from 0.

	Inventory years 1, 2, 3, 4, 5			Inventory years 2, 3, 4, 5			Difference	
Disturbance year	Plots (number)	Estimate (ha)	Standard error (ha)	Plots (number)	Estimate (ha)	Standard error (ha)	Estimate (ha)	Standard error (ha)
Wind (52 Wind)								
2005	42,518	19,184	4968	32,909	25,065	6622	**5881**	1772
2006	40,208	18,004	4664	30,858	21,881	5995	3877	2199
2007	37,995	9214	3197	28,563	10,164	3726	950	1490
2008	35,780	14,323	4126	28,806	18,021	5170	**3698**	1062
2009	35,945	17,853	4374	28,793	20,691	5189	2838	1699
2010	35,005	23,568	5752	27,706	26,080	6983	2512	2544
2011	33,917	62,726	8679	26,779	73,398	10,512	**10,672**	3067
2012	32,912	65,152	9454	25,694	69,309	10,516	4157	5347
2013	31,803	31,685	8162	24,665	35,604	9414	3918	4513
2014	30,862	36,945	8456	24,650	45,716	10,543	**8772**	1922
2015	30,759	34,648	8279	24,548	42,774	10,479	**8126**	2556
2016	30,580	109,423	12,281	24,447	123,961	13,913	**14,537**	5693
2017	30,480	37,088	7045	24,371	44,204	8565	**7116**	2069
2018	30,458	36,806	8622	24,261	46,941	11,100	**10,135**	2637
Weather (50 Weather, 51 Ice, 52 Wind, 53 Flooding, 54 Drought)								
2005	42,518	32,833	6346	32,909	41,874	8351	**9041**	2250
2006	40,208	36,220	6586	30,858	45,892	8616	**9672**	2787
2007	37,995	20,928	5092	28,563	22,852	5970	1923	3089
2008	35,780	29,914	6158	28,806	33,609	7310	3695	2438
2009	35,945	53,681	7827	28,793	60,026	9195	**6344**	3149
2010	35,005	46,665	7545	27,706	49,645	8888	2800	3491
2011	33,917	92,962	10,472	26,779	104,841	12,214	**11,879**	4546
2012	32,912	97,182	12,175	25,694	98,559	12,865	1377	7449
2013	31,803	50,977	10,395	24,665	44,657	10,081	−6320	7373
2014	30,862	52,500	10,022	24,650	60,622	12,227	**8112**	3021
2015	30,759	43,009	9099	24,548	53,916	11,608	**10,907**	3162
2016	30,580	142,147	13,703	24,447	163,399	15,777	**21,252**	6055
2017	30,480	64,396	10,334	24,371	76,096	12,705	**11,701**	3391
2018	30,458	45,229	9307	24,261	57,059	11,896	**11,830**	2617

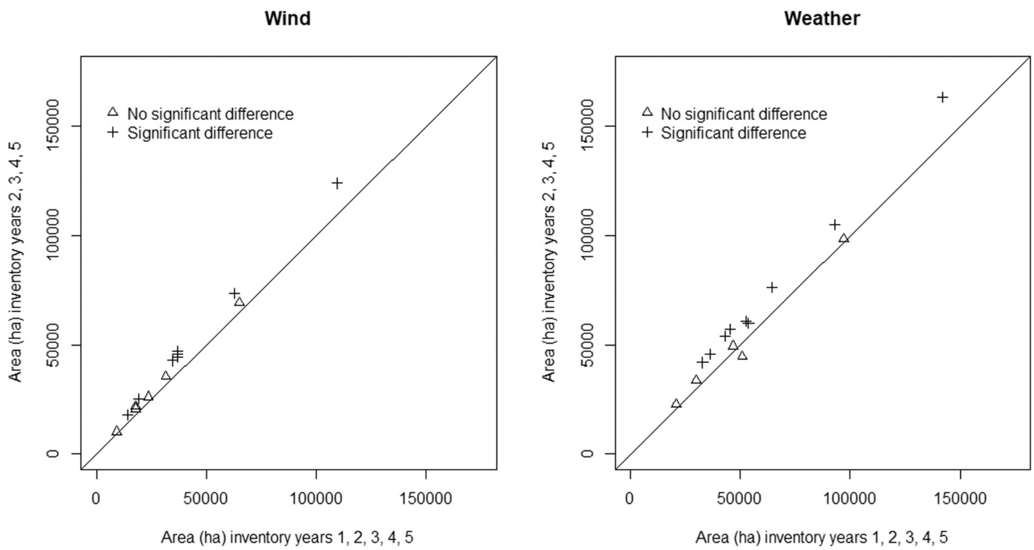

Fig. 2. Estimates with and without inventory year 1, the inventory year coincident with the disturbance year.

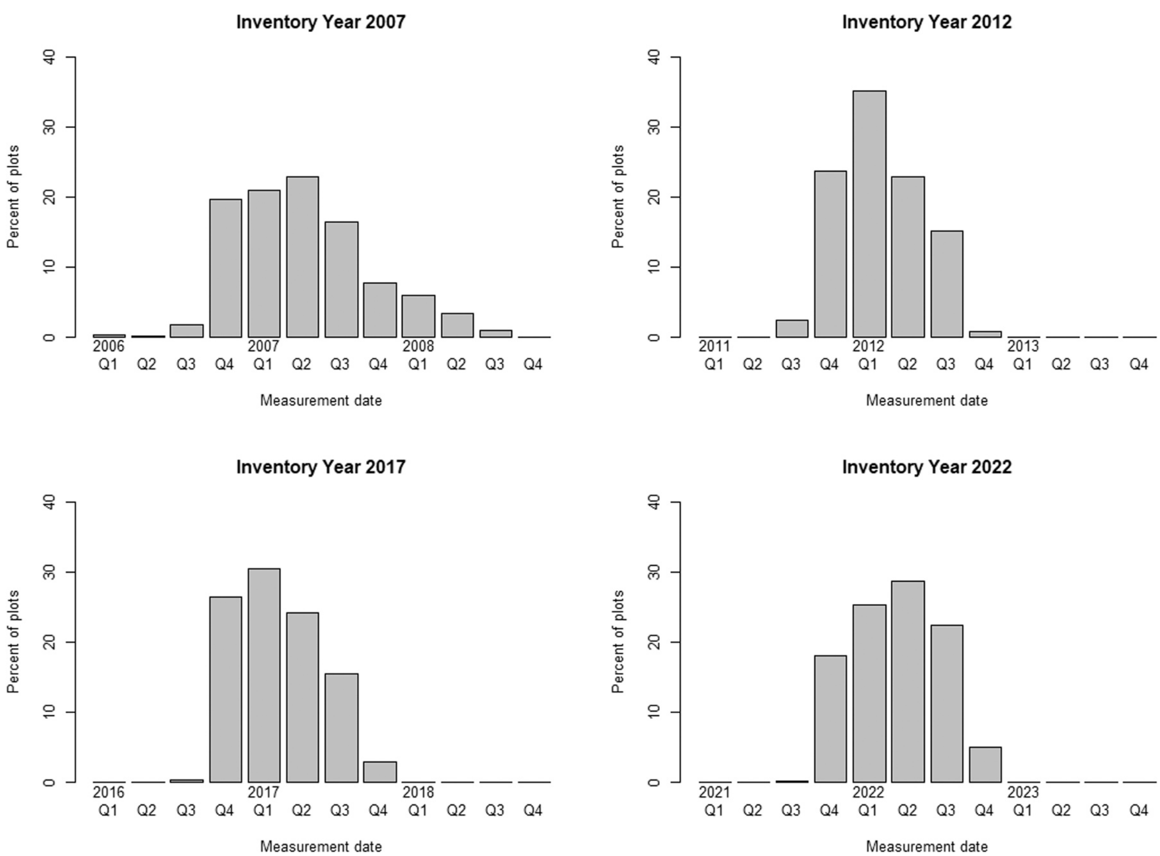

Fig. 3. Measurement date of plots with at least one forestland condition, inventory years 2007, 2012, 2017, and 2022.

negative (6 years) differences were observed. Differences were significant in 3 of the 14 years for both wind and weather.

The final comparison was of estimates computed with and without inventory year 3 (Table 7 and Fig. 6). The largest difference between estimates with and without inventory year 3 was 61,381 ha observed for weather in 2016. An estimate of 202,214 ha was computed with inventory years 2, 3, which for annual disturbance in 2016 included inventory years 2017, 2018. An estimate of 263,595 ha was computed with inventory year 2, which was inventory year 2017. More negative differences were observed than positive differences. None of the 14 years of differences were significant for wind. Two of the 14 years of differences, both of which were positive, were significant for weather.

4. Discussion

Our results present a strong case for leaving out the inventory year coincident with the disturbance year when estimating the annual extent of wind and weather disturbance in the upper Great Lakes region. This result does not point to a problem with panel inventories per se but rather reflects operational realities typical of broad-scale inventories.

Table 5
Estimates with and without inventory year 5, the inventory year furthest from the disturbance year. Difference estimates in bold indicate significantly different from 0.

	Inventory years 2, 3, 4, 5			Inventory years 2, 3, 4			Difference	
Disturbance year	Plots (number)	Estimate (ha)	Standard error (ha)	Plots (number)	Estimate (ha)	Standard error (ha)	Estimate (ha)	Standard error (ha)
Wind (52 Wind)								
2005	32,909	25,065	6622	25,757	30,458	8304	**5393**	2057
2006	30,858	21,881	5995	23,559	24,816	7350	2935	2680
2007	28,563	10,164	3726	21,425	13,407	4911	**3243**	1188
2008	28,806	18,021	5170	21,589	12,865	5083	−5156	3760
2009	28,793	20,691	5189	21,655	27,317	7002	**6625**	2082
2010	27,706	26,080	6983	21,494	29,161	7843	3081	4031
2011	26,779	73,398	10,512	20,568	88,777	13,072	**15,379**	3129
2012	25,694	69,309	10,516	19,561	65,457	11,490	−3852	6365
2013	24,665	35,604	9414	18,556	44,275	12,397	**8671**	3967
2014	24,650	45,716	10,543	18,453	51,678	13,635	5962	5035
2015	24,548	42,774	10,479	18,439	53,958	13,900	**11,184**	4075
2016	24,447	123,961	13,913	18,414	133,812	16,421	9851	7228
2017	24,371	44,108	8561	18,338	34,223	7554	−9885	6585
2018	24,261	46,941	11,100	18,173	45,413	12,927	−1528	6392
Weather (50 Weather, 51 Ice, 52 Wind, 53 Flooding, 54 Drought)								
2005	32,909	41,874	8351	25,757	47,783	10,125	5909	3213
2006	30,858	45,892	8616	23,559	51,876	10,530	5984	3780
2007	28,563	22,852	5970	21,425	29,699	7927	**6847**	2353
2008	28,806	33,609	7310	21,589	29,220	7425	−4390	5045
2009	28,793	60,026	9195	21,655	74,124	11,853	**14,098**	4551
2010	27,706	49,465	8888	21,494	58,043	10,519	8578	4454
2011	26,779	104,841	12,214	20,568	127,756	15,278	**22,914**	3890
2012	25,694	98,559	12,865	19,561	98,559	14,672	0	7122
2013	24,665	44,657	10,081	18,556	51,521	12,945	6864	4675
2014	24,650	60,622	12,227	18,453	69,129	15,766	8507	6127
2015	24,548	53,916	11,608	18,439	68,079	15,215	**14,163**	4088
2016	24,447	163,399	15,777	18,414	170,746	18,368	7346	8671
2017	24,371	76,000	12,702	18,338	69,415	13,383	−6586	8230
2018	24,261	57,059	11,896	18,173	52,246	13,574	−4813	7209

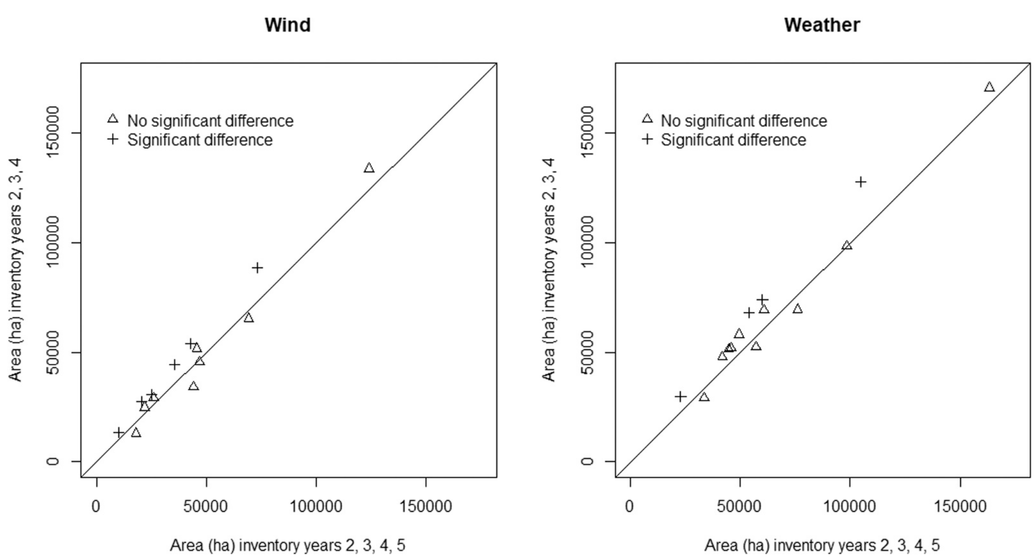

Fig. 4. Estimates with and without inventory year 5, the inventory year furthest from the disturbance year.

Under current operational procedures, measurement of the panel assigned to an inventory year begins in earnest in the fourth quarter of the year prior and continues into the calendar year equal to the inventory year. The observation of disturbance for the year equal to the inventory year is therefore not complete. This issue becomes more pronounced where wind disturbance tends to occur later in the year (e. g., fall). The sample size is reduced by approximately 20 % when four inventory years are used rather than five and sampling error percentages may therefore be expected to increase. Interestingly, we observed only a slight increase in the average sampling error percentages, from 22.8 % to 23.5 %, for annual wind estimates with and without inventory year 1, respectively. Standard errors increased an average of 21.9 %, but so did the estimates, which increased an average of 18.4 %

There was modest evidence to suggest that leaving out the inventory year furthest in time from the disturbance (i.e., inventory year 5 in our analysis) can produce larger estimates of wind and weather disturbance in the upper Great Lakes region. Our analysis cannot confirm the reason for this finding, but dissipation of the damage indicators associated with both disturbance types is one plausible explanation. There was no strong evidence to indicate withholding any of the other inventory years tested (i.e., inventory year 3 or 4) was warranted.

For annual estimates of wind and weather disturbance in the upper

Table 6
Estimates with and without inventory year 4. Difference estimates in bold indicate significantly different from 0.

	Inventory years 2, 3, 4			Inventory years 2, 3			Difference	
Disturbance year	Plots (number)	Estimate (ha)	Standard error (ha)	Plots (number)	Estimate (ha)	Standard error (ha)	Estimate (ha)	Standard error (ha)
Wind (52 Wind)								
2005	25,757	30,458	8304	18,783	37,057	11,268	6600	4470
2006	23,559	24,816	7350	16,407	13,580	6197	−11,235	5947
2007	21,425	13,407	4911	14,126	9985	5425	−3422	3704
2008	21,589	12,865	5083	14,451	19,109	7637	**6244**	2477
2009	21,655	27,317	7002	14,437	29,395	9064	2078	4633
2010	21,494	29,161	7843	14,356	23,743	9216	−5418	5427
2011	20,568	88,777	13,072	14,356	88,823	15,549	46	8347
2012	19,561	65,457	11,490	13,350	73,423	15,111	7967	8506
2013	18,556	44,275	12,397	12,423	52,116	17,171	7841	6480
2014	18,453	51,954	13,654	12,344	32,321	10,063	−19,633	12,398
2015	18,439	53,943	13,899	12,242	14,405	5880	**−39,538**	13,442
2016	18,414	133,812	16,421	12,306	158,436	21,977	**24,624**	9491
2017	18,338	34,223	7554	12,305	26,344	8069	−7879	5727
2018	18,173	45,413	12,927	12,140	47,459	16,484	2046	1834
Weather (50 Weather, 51 Ice, 52 Wind, 53 Flooding, 54 Drought)								
2005	25,757	47,783	10,125	18,783	51,636	12,762	3853	5910
2006	23,559	51,876	10,530	16,407	37,053	10,480	−14,823	7687
2007	21,425	29,699	7927	14,126	18,132	8479	−11,567	5994
2008	21,589	29,220	7425	14,451	32,327	9571	3107	4808
2009	21,655	74,124	11,853	14,437	94,938	16,557	**20,814**	7446
2010	21,494	58,043	10,519	14,356	55,839	12,817	−2204	7334
2011	20,568	127,756	15,278	14,356	134,221	18,643	6466	9598
2012	19,561	98,559	14,672	13,350	105,687	19,185	7128	10,150
2013	18,556	51,521	12,945	12,423	60,679	17,923	9158	6805
2014	18,453	69,404	15,782	12,344	43,993	12,752	−25,411	13,812
2015	18,439	68,064	15,214	12,242	33,540	10,852	**−34,524**	14,089
2016	18,414	170,746	18,368	12,306	201,813	24,337	**31,067**	10,967
2017	18,338	69,415	13,383	12,305	63,104	14,378	−6311	10,121
2018	18,173	52,246	13,574	12,140	52,453	16,867	206	4113

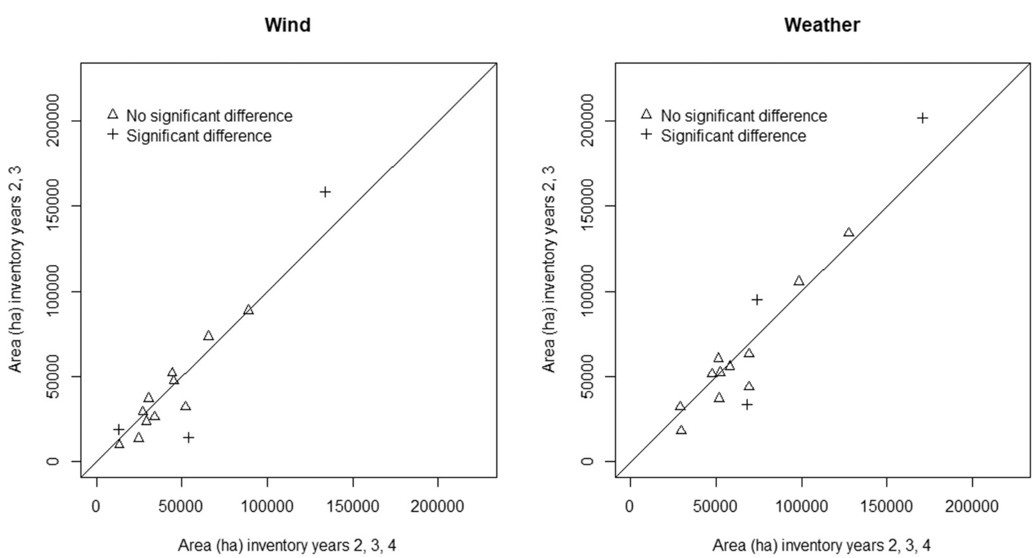

Fig. 5. Estimates with and without inventory year 4.

Great Lakes region, estimates computed from evaluations of inventory years 2, 3, 4 and inventory years 2, 3, 4, 5 can be compared. These two estimates and their differences may be evaluated in terms of what else is known about the disturbance event or events (Edgar et al., 2019). It seems reasonable to assume that the rate of dissipation of damage indicators can vary depending on characteristics of the disturbance itself such as kind and severity. For example, a rare event like a derecho causing severe and extensive damage over large areas may leave a clear imprint on affected forests (e.g., Goff et al., 2021). Characteristics of the trees and forests impacted including species composition, size distributions, stand densities, and growth rates would also seem to be factors that could influence the length of time indicators remain detectable (Everham and Brokaw.,1996). The disturbance code that was used in this analysis indicates that mortality and damage of 25 % or more was present and does not convey information to the extent to which that threshold may have been exceed. There are other data in the NFI not considered in this analysis that may be able to provide additional characterization of disturbances (Fitts et al., 2022). Also, the occurrence of other disturbances or treatments (e.g., salvage) after the wind or weather event but before plot measurement could alter the indicators of the original event.

An objective of this study was to develop an approach that could be

Table 7
Estimates with and without inventory year 3. Difference estimates in bold indicate significantly different from 0.

	Inventory years 2, 3			Inventory year 2			Difference	
Disturbance year	Plots (number)	Estimate (ha)	Standard error (ha)	Plots (number)	Estimate (ha)	Standard error (ha)	Estimate (ha)	Standard error (ha)
Wind (52 Wind)								
2005	18,783	37,057	11,268	9350	31,623	13,278	−5435	11,363
2006	16,407	13,580	6197	9433	16,093	8923	2512	4081
2007	14,126	9985	5425	6974	19,309	10,646	9324	5171
2008	14,420	19,109	7637	7141	6710	6524	−12,399	7690
2009	14,436	29,336	9045	7299	37,704	13,940	8369	9590
2010	14,356	23,743	9216	7138	17,601	13,739	−6142	9146
2011	14,356	88,823	15,549	7218	68,904	19,195	−19,919	15,147
2012	13,348	73,423	15,111	7138	57,981	17,503	−15,443	13,851
2013	12,403	52,552	17,206	6203	32,373	22,029	−20,179	13,978
2014	12,344	32,321	10,063	6211	31,933	15,870	−388	10,931
2015	12,241	14,405	5880	6133	7895	6429	−6510	4799
2016	12,304	158,837	21,974	6108	187,590	34,539	28,753	24,048
2017	12,304	26,344	8069	6196	12,535	7749	−13,809	7873
2018	12,118	47,718	16,500	6102	59,686	28,327	11,968	14,149
Weather (50 Weather, 51 Ice, 52 Wind, 53 Flooding, 54 Drought)								
2005	18,783	51,636	12,762	9350	41,888	15,158	−9748	12,877
2006	16,407	37,053	10,480	9433	33,963	13,565	−3090	8770
2007	14,126	18,132	8479	6974	33,951	16,070	**15,819**	6972
2008	14,420	32,576	9577	7141	25,580	11,650	−6996	9575
2009	14,436	94,879	16,547	7299	75,601	20,315	−19,278	16,392
2010	14,356	55,839	12,817	7138	73,062	21,911	17,223	12,815
2011	14,356	134,221	18,643	7218	133,815	26,281	−406	18,360
2012	13,348	105,687	19,185	7138	100,410	24,437	−5277	16,832
2013	12,403	61,115	17,956	6203	38,852	22,941	−22,263	15,173
2014	12,344	43,993	12,752	6211	44,619	20,793	627	13,550
2015	12,241	33,540	10,852	6133	39,365	18,845	5825	7045
2016	12,304	202,214	24,335	6108	263,595	39,578	**61,381**	26,021
2017	12,304	63,104	14,378	6196	36,662	14,534	−26,441	14,132
2018	12,118	52,711	16,882	6102	69,911	29,272	17,200	14,667

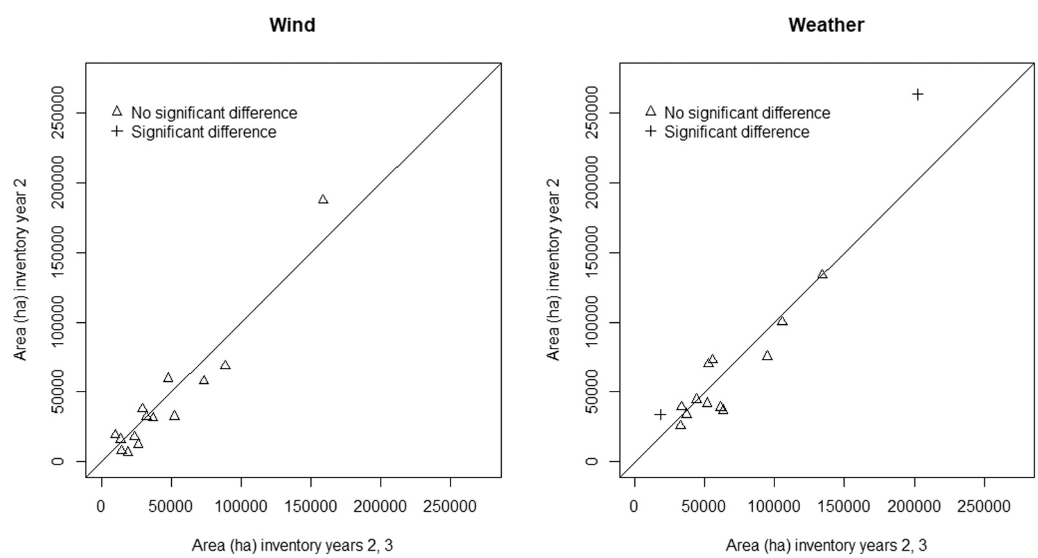

Fig. 6. Estimates with and without inventory year 3.

applied broadly to the NFI. There are currently 30 different kinds of disturbance monitored in the NFI (Burrill et al., 2024); this analysis focused on one (i.e., wind) individually and five (i.e., weather, ice, wind, flooding, and drought) collectively. The approach used in this study can be applied to the full range of disturbances (i.e., insect, disease, fire, animal, weather, vegetation, unknown, human-induced, and geologic) with the modification being in the domain specification. Furthermore, treatment information (i.e., cutting, site preparation, artificial regeneration, natural regeneration, and other silvicultural treatment) is collected in a manner like disturbance and therefore is amenable to the approach applied here.

Although we limited our analysis to evaluations consisting of five panels, the approach applied here is applicable to inventories of seven and ten panels that are used by the NFI in the eastern and western US, respectively. Measurement protocols call for assessing disturbance since last measurement, which for seven and ten panels equates to seven and ten years of retrospective observation, respectively. The increased length of retrospective observation suggests analysis of this type is more relevant and important to conduct. The more panels used in an inventory, the less impactful a decision to exclude a panel is on the overall sample size. For example, a decision to exclude the first and last inventory years in five-, seven-, and ten-panel inventories results in overall sample size reductions of approximately 40 %, 29 %, and 20 %, respectively

Our analysis focused exclusively on five panels, which is the number of panels in Minnesota and was the number of panels in Michigan and Wisconsin until inventory year 2014. Seven panels are currently in use in Michigan and Wisconsin. In this analysis, all estimates use the full network of plots in Minnesota and estimates for 2005–2009 use the full network of plots in Michigan and Wisconsin. Later estimates, those for 2010–2018, use less than the full network of plots with the amount depending on the specific year. The 2018 estimate, for example, uses approximately 5/7 of the plot network in Michigan and Wisconsin.

5. Conclusion

Wind is an important agent of change in the forests of the Great Lakes region. Accurate information on the extent of damage and mortality resulting from wind is important to forest management, planning, and policy. Annual estimates of the areal extent of wind disturbance can be produced in a rotating panel forest inventory such as that in use by the US NFI. The panel design and the retrospective nature of the disturbance observation create a unique set of plot observations relative to the year that an annual estimate of disturbance is being computed. Analysis conducted in this paper indicates the importance of careful consideration when combining panels of plots to produce an annual estimate of disturbance. While our analysis focused on annual estimates of wind disturbance in the Great Lakes, the approach developed here is broadly applicable to other regions, disturbances and treatments monitored in the NFI. Thus, analyses of the type conducted in this be paper may provide useful insights if applied to other disturbance agents in the region and other regions.

CRediT authorship contribution statement

Christopher Edgar: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **James A. Westfall:** Writing – review & editing, Methodology, Formal analysis, Conceptualization.

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Declaration of Competing Interest

I have nothing to declare.

Data Availability

Data used in this study are publicly-available at the Forest Inventory and Analysis DataMart (https://apps.fs.usda.gov/fia/datamart/datamart.html)

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