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Comparing methods that quantify forest disturbances in the United States' national forest inventory

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Abstract Forest disturbances play a critical role in ecosystem dynamics. However, the methods for quantifying these disturbances at broad scales may underestimate disturbances that affect individual trees. Utilizing individual tree variables may provide early disturbance detection that directly affects tree demographics and forest dynamics. The goals of this study were to (1) describe different methods for quantifying disturbances at individual tree and condition-level scales, (2) compare the differences between disturbance variables, and (3) provide a methodology for selecting an appropriate disturbance variable from national forest inventories for diverse applications depending on user needs. To achieve these goals, we used all the remeasurements available from the USDA Forest Inventory and Analysis (FIA) database since the start of the annual inventory for the lower 48 US states. Variables used included disturbance code, treatment code, agent of mortality, and damage code. Chi-square tests of independence were used to verify how the choice of the variable that represents disturbance affects its magnitude. Disturbed plots, as classified by each disturbance variable, were mapped to observe their spatial distribution. We found that the Chi-square tests were significant when using all the states and comparing each state individually, indicating that different results exist depending on which variable is used to represent disturbance. Our results will be a useful tool to help researchers measure the magnitude and scale of disturbance since the manner in which disturbances are categorized will impact forest management plans, national and international reports of forest carbon stocks, and sequestration potential under future global change scenarios.

Keywords Forest health · Disturbance regime · Landscape ecology · Ecosystem dynamics · Chi-square test

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Introduction

Forests, in addition to being the largest terrestrial sink of carbon (Pan et al., 2011; Sleeter et al., 2018; Woodall et al., 2015), also provide other important cultural benefits and ecosystem services including clean water, temperature regulation, and wildlife habitat (Balloffet et al., 2012; Jenkins & Schaap, 2018). However, globally the increasing frequency and severity of forest disturbance in recent years threaten habitat conditions and their ability to sustain these benefits (Franklin et al., 2007; Seidl et al., 2017a, 2017b; Xu et al., 2021). Forest disturbances are defined as discrete events that disrupt the integrity and functionality of ecosystems by modifying their physical environment (Nyland et al., 2016; Vanderwel et al., 2013) and reducing forest productivity (Reyer et al., 2017a, 2017b). These events can produce selective mortality or be stand replacing (Coulston et al., 2020). Disturbances can affect the ecosystem's biodiversity, resistance, and resilience after biotic and abiotic stressors (Nyland et al., 2016; Oliver & Larson, 1996) and create forest health concerns. Biotic stressors include insect feeding, diseases, animal activity, and allelopathy, while abiotic stressors include fire, flooding, snow, wind damage, and chemical pollutants (Nyland et al., 2016).

Disturbances are key processes in forest ecosystem dynamics (Oliver & Larson, 1996) and play a critical role in the spatial heterogeneity and legacies that alter the ecosystem structure and function for decades to centuries (Johnstone et al., 2016; Seidl et al., 2017a, 2017b; Turner, 2010). Often, even severe disturbances do not create a homogeneous landscape (Turner, 2010). By creating a heterogeneous landscape, disturbances can foster diversity and restart stand dynamics (Oliver & Larson, 1996; Seidl et al., 2017a, 2017b). Two types of legacies (information and material) contribute to the ecosystem's ecological memory to respond to disturbances: While information legacies include species life-history traits, material legacies include biotic and abiotic structures (e.g., nutrients) produced by single disturbance events (Johnstone et al., 2016). Both legacies enhance ecological resilience but can be lost or faded with changing disturbance regimes (i.e., severity, frequency, and timing) and environmental conditions (Johnstone et al., 2016; Turner, 2010).

Due to the climate forcing nature of some disturbances, their regimes might be altered by global climate change (Seidl et al., 2011; Seidl et al., 2017a, 2017b; Turner, 2010; Zhu et al., 2020). Historically, novel disturbance events and interactions are being observed (Johnstone et al., 2016; Turner, 2010) and their rate of change is accelerating (Turner, 2010). The change of disturbance regimes induced by climate might produce critical changes in forests and ecosystem services over the short (years to decades) and long terms (centuries) (Reyer et al., 2017a, 2017b; Seidl et al., 2011; Turner, 2010), especially in boreal and temperate forests (Brice et al., 2020; Seidl et al., 2017a, 2017b). A warmer and drier climate could facilitate fire, drought, and insects, while a warmer and wetter climate could enhance impact from wind and disease with intensified interactions between disturbances in both scenarios (Seidl et al., 2017a, 2017b). In addition, regenerating forests after disturbances are sensitive to variation in temperature (Zhu et al., 2020). However, the specific trends in disturbance size, frequency, and severity are hard to predict since our understanding is limited; disturbances are not measured in a homogeneous way and may be abrupt (e.g., wildfire), chronic (e.g., drought), or some combination (i.e., compound; Kleinman et al., 2019); and their regimes vary among regions (Cohen et al., 2016; Seidl et al., 2017a, 2017b).

Our current understanding about forest disturbances comes from dissimilar monitoring efforts, producing challenges when comparing and synthesizing estimates across different disturbance agents, regions, and time periods (Cohen et al., 2016). The three most common approaches to quantify disturbances and their impacts are as follows: remote sensing, forest inventories, and simulation models. Remote sensing methods with coarse resolution are useful at a regional scale but have trouble capturing small-scale disturbances (high omission error) (Cohen et al., 2016; Zhu et al., 2012). On the other hand, inventory-based estimates in the USA have been collected in a consistent and detailed manner for the past two decades through the Forest Inventory and Analysis (FIA) program (Burrill et al., 2018). However, this inventory has long remeasurement periods (i.e., 5–10 years), with insufficient detail on temporal record length as well as on the timing of the disturbance (since it is collected retrospectively from the previous visit) (Cohen et al., 2016; Coulston et al., 2020; Randolph et al., 2021; Wilson et al., 2019). Simulation models use forest inventory data to predict broader effects of disturbances at regional scales, as well as for carbon dynamics or changes in mortality regimes (Coulston et al., 2020; Vanderwel et al., 2013; Zhu et al., 2012).

When considering forest inventory variables, the scale at which disturbances are monitored is critical for choosing which disturbance variables to use. If a tree-level study is intended, a dissociation exists between condition-level (a mapped domain on a forested plot) disturbance variables (as measured by the US forest inventory) and tree-level growth, which could affect growth predictions (Glasby et al., 2019). In addition, small gaps produced by disturbances are not captured at a broad scale (Glasby et al., 2019; Wilson et al., 2019). Other methods to evaluate individual trees suggested the use of specific tree-level variables from FIA such as using damage agent codes (Fei et al., 2019; Randolph et al., 2021) and the agent of mortality but the latter does not capture affected but live trees (Glasby et al., 2019; Ward et al., 2021).

Therefore, quantifying forest disturbances at aggregated scales (i.e., condition-level) generally underestimates the disturbances that affect individual trees and subsequently affects the magnitude and scale of forest health problems. This is a problem especially when creating reports that inform carbon accounting and management efforts. Some examples include overestimating the forest productivity or carbon sequestration potential (Fei et al., 2019) due to a lack of detail in capturing disturbances. To help address this problem, we set up a study that looks at the ability of different disturbance variables from the US' national forest inventory to capture what is happening at different scales: individual tree and condition. Specific research objectives of this study were to (1) describe different methods for quantifying disturbances at different scales using the Forest Inventory and Analysis (FIA) data, (2) compare the differences in presence of disturbance using different forest inventory variables, and (3) provide a methodology for selecting an appropriate disturbance variable for use in national forest inventories. We hypothesize that the more detailed the disturbance variable, the more comprehensive a disturbance analysis will be and the more affected plots we will capture. This research will allow us to better understand the impacts of the choice of disturbance variable on research reports and provide the tools and approaches that managers need for enhancing forest health, productivity, and carbon sequestration. Understanding the spatial extent and timing of disturbance events and their impacts is crucial for effective management and policies (Coulston et al., 2020).

Methods

Data collection

The study area corresponds to the 48 conterminous US states, which together represent diverse forest types, disturbance histories, and population dynamics. We used ground data collected by the USDA Forest Inventory and Analysis (FIA) program from the start of its annual inventory (varies by state, but approximately in 2000) until 2020 (Burrill et al., 2018). This program monitors forestland conditions under different ownerships in the USA. The FIA data is organized as a relational database and grouped into different phases and tables according to the scale and level of detail of the data. The ground-sampled FIA plots that we used for this study were remeasured approximately every 5 years for eastern states and every 10 years for western states. The sample area that each plot covers is 0.4 hectares which were divided into four fixed-radius (7.32 m) permanent sample subplots. These subplots are organized in a cluster, with subplot 1 being at the center and subplots 2 through 4 located 36.6m away at azimuths of 120°, 240°, and 360°. In each subplot, trees with a diameter at breast height (dbh) greater than 12.7 cm are measured on the entire subplot. We used the rFIA package (Stanke et al., 2020) to download the FIA data for the 48 lower states.

We used the four FIA variables that record forest disturbances plus a newly created variable from the FIA data: **(1)** Disturbance code [DSTRBCD1, 2, and 3]; **(2)** Cause of death (agent) code [AGENTCD], from here on "agent of mortality"; **(3)** Damage agent code [DAMAGE_AGENT_CD1, 2, and 3] + agent of mortality; **(4)** Disturbance code + treatment code [TRTCD1, 2 and 3] (Burrill et al., 2018); and **(5)** agent of mortality 25% or higher. These variables measure disturbance in a different scale, magnitude, and level of detail and allow us to study disturbances that align with different research interests. Our goal was to use different variables and combinations of them that were available from the FIA database to demonstrate the different outcomes when using each variable.

A common scale of analysis for disturbance studies is at the condition level (DSTRBCD). The FIA plot design delineates a condition boundary if there are observable changes in land use, vegetation, reserved status, forest types, ownership, or stand density, among others that occur within the plot (Burrill et al., 2018). Conditions are categorized as disturbed since the last inventory (disturbance code variable) if this disturbance has an extension greater or equal to 0.4 ha (one acre) and has affected (mortality or damage) at least 25% of the trees within that condition (Burrill et al., 2018). Up to three disturbance codes are recorded per condition for this variable out of the 31 possible codes.

The agent of mortality (AGENTCD) is a tree-level variable that records the cause of the death of a tree which was alive at the previous measurement and is now dead or removed (Burrill et al., 2018). There are nine possible codes in the FIA database for this variable. We created the variable "agent of mortality >25%" to be equivalent to the disturbance condition variable but recorded at a tree level. This variable was created by calculating the proportion of trees disturbed within each plot and the plots with less than 25% disturbed trees were labeled as *not disturbed* for a specific agent. Similar to the agent of morality variable, we kept up to three disturbance agents per plot. The damage agent code (DAMAGE_AGENT_CD) is also a tree-level variable that records up to three damage agents (recorded in order of importance) found in the tree while it is inspected from bottom to top, including roots, bole, branches, and foliage (Burrill et al., 2018). The FIA database contains 31 generic codes for this variable with more than 100 subcodes that correspond to more detailed agent species (See Appendix J from Burrill et al., 2018). For our analysis, we combined the damage agent code variable with the agent of mortality to give a more complete representation of disturbances rather than only the damaged trees. These two variables are recorded at a tree level, so to combine them, we homogenized the categories recorded by each variable. Since the damage agent code has 31 generic codes, as described above, we recategorized them to match the nine codes of the agent of mortality. Once homogenized, we scaled up to a plot level to prevent duplication and removed those duplicate records on the same plot for a specific agent and time period.

Finally, the treatment code (TRTCD) is a condition-level variable that describes silvicultural treatments that occurred on the stand. Conditions are assigned a treatment code if there have been any silvicultural intervention since the last inventory that affected at least 0.4 ha (one acre) in size (Burrill et al., 2018). Up to three treatment codes are recorded per condition for this variable out of the five possible codes. Despite silvicultural treatments being intended as a way to benefit remaining trees in the stand, since broader implications of our study include looking at stand growth and carbon sequestration potential when disturbances happen in the stand, we considered silviculture as a disturbance source. However, only *cutting*, *site preparation*, and the *other silvicultural treatment* categories were considered as disturbance variables for this study. For a full list of treatment code variables available in the FIA, see Burrill et al. (2018). For our analysis, we combined treatment code with the disturbance code variable since treatment code by itself would only give us information on silviculture disturbance, which is not included in the disturbance codes. This combination of variables gave us a more complete representation of disturbances occurring at a condition level. To combine these variables, we recategorized all the treatment code variables to "silviculture" and added those as an extra category to the disturbance code variable.

Data analysis

The data were organized for the different time periods available (initial time t_i and final time t_f) and scaled up for each plot so that disturbances that happened in the same plot but in different conditions were not repeated. Disturbances were regrouped and homogenized into nine categories: insect, disease, fire, animal, weather, vegetation, silviculture, not disturbed, and other.

Chi square tests

The comparison between variables was conducted with Chi-square tests of independence using the *chisq.test()* function in R (R Core Team, 2020). The Chi-square test tells us if there are nonrandom associations between the variables (independence) (Hess & Hess, 2017; Lancaster & Seneta, 2005).

For the chi-square tests, we built contingency tables for each of our six groups of disturbance variables: disturbance code, agent of mortality, agent of mortality 25%, damage agent code, damage agent code + agent of mortality, and disturbance code + treatment code. These represent the different combinations of variables for forest disturbances. Within each table, the plots were categorized into not disturbed (ND), disturbed by one agent (simple disturbance—SD), and disturbed by more than one agent causing a multiplicative effect (compound disturbance—CD, Sturtevant & Fortin, 2021). The definition of disturbance explained above was prevalent in our decision to consider a plot disturbed or not (See 3 section).

We conducted five tests with an alpha of 0.05: (A) Disturbance code vs agent of mortality, (B) Disturbance code vs agent of mortality >25%, (C) Disturbance code vs agent of mortality + damage code, (D) Disturbance code + treatment code vs agent of mortality + damage code, and (E) Disturbance code vs agent of mortality vs agent of mortality at 25% threshold vs agent of mortality + damage code vs Disturbance code + treatment code. The chi-square tests were done for individual states (See Supplementary material 2) and for all states combined (Table 3). Our null hypothesis was that there is no association between variables (they are independent); in other words, the way we build the disturbance variable is independent from the result. Consequently, our alternative hypothesis was that there is an association between variables.

Mapping disturbances

We used the approximate plot locations provided by FIA to represent the disturbances at a national-level scale. We used the *tidyverse* (Wickham et al., 2019) and *ggspatial* (Dunnington, 2021) R packages to produce maps of the different disturbance variables observed throughout the study period. In addition, to focus on specific disturbances, we selected certain states which are known to be affected by those disturbances and compared the disturbance patterns and frequency according to the FIA variables used. The case studies that we selected were (1) fire in California, Oregon, and Washington; (2) insects in Maine, New Hampshire, Vermont, Massachusetts, Rhode Island, Connecticut, New York, Pennsylvania, and New Jersey; (3) weather in Minnesota, Wisconsin, and Michigan; and (4) disease in Minnesota, Wisconsin, Iowa, Illinois, and Missouri.

Results

The initial exploration of the FIA data for different disturbance variables for the lower 48 US states revealed some important foundational knowledge. Each variable is recorded at a different scale (aggregated to a condition or tree level) and is able to represent a different level of detail on the disturbance agent (Table 1). The variable chosen to evaluate disturbance effects also shows distinct disturbance patterns and frequency.

Visualization

The number of plots that are considered disturbed when using different variables and the ability of each variable to discriminate between a simple or compound disturbance present in a plot are represented in Fig. 1 and Table 2. The disturbance code variable and the agent of mortality >25% show similar patterns of disturbance. However, with the agent of mortality and damage agent codes variables, the number of disturbed plots increases as disturbances that affect a small amount of trees will now show and make the whole plot be considered as disturbed. The damage agent code variable has a more detailed description of the agent and therefore it is possible to better distinguish between simple and compound disturbances. In addition, the disturbance code + treatment code variable only shows a slight increase in disturbances at the condition level, but still less than the tree-level variable of agent of mortality + damage agent code.

Figure 2 represents the agent of mortality variable for the eight homogenized disturbance categories for all states together (See Supplementary material 1 for similar graphs by region). The red horizontal line represents the 25% threshold that resembles the way the disturbance code variable records disturbances. The top panel shows a box plot which helps observe summary statistics (median and interquartile ranges), while the lower panel represents a violin plot where the shape of the distribution can be observed. We note in this figure that most disturbance types would not be represented if we only considered a condition-level variable with a 25% threshold. Mainly the disturbances that tend to affect stands at larger extents such as fire and silviculture would be predominant.

Table 1 Number and percent of Forest Inventory and Analysis plots by disturbance type in the 48 US states since the start of their annual inventory year until 2020. We included all available FIA remeasurements, which for some states they represent up to four remeasurements. The number of plots for the disturbance code variable indicates the number of plots that had a disturbance at least 1 acre in size that affected 25% of the trees or more. For the agent of mortality and damage code variables, the number of disturbed plots indicates the number of plots where at least one tree was disturbed by a specific agent. Disturbance subcategories were obtained from Burrill et al. (2018)

Variable	Variable's level of detail and scale	Disturbance type	Disturbance subcategory	Number of plots	Percent (%)
Disturbance code (DSTRBCD)	Somewhat detailed (Condition-level variable)	Animal	Beaver, porcupine, deer/ungulate, bear, rabbit, domestic animals/livestock	13,708	1
		Disease	Disease damage to understory vegetation and trees (including seedlings and saplings)	12,344	0.9
		Fire	Ground or crown fire damage	13,540	0.99
		Insect	Insect damage to understory vegetation and trees (including seedlings and saplings)	12,723	0.93
		Vegetation	Suppression, competition, vines	2774	0.2
		Weather	Ice, wind, flooding, drought	12,485	0.91
		Other	Unknown, unsure, other, human (not silviculture), geologic	4906	0.36
		Not disturbed	No visible disturbance	1,300,356	94.72
		Total		1,372,836	100
Treatment code (TRTCD)	Somewhat detailed (Condition-level variable)	Silvicultural treatment	Cutting, site preparation (i.e., slash burning, chopping, clearing), other (i.e., pruning, girdling, and chaining)	83,271	100
Agent of mortality (AGENTCD)	Not very detailed (Tree-level variable)	Animal	Animal	1941	0.28
		Disease	Disease	44,109	6.44
		Fire	Fire	5641	0.82
		Insect	Insect	23,610	3.45
		Silviculture	Silvicultural or land clearing activity (death caused by harvesting or other silvicultural activity including girdling and chaining)	32,735	4.78
		Vegetation	Suppression, competition, vines/kudzu	32,684	4.77
		Weather	Weather	28,042	4.09
		Other	Unknown, not sure, other, death from human activity not related to silvicultural or land clearing activity	66,364	9.69
		Not disturbed	No agent recorded	449,665	65.66
		Total		684,791	100

Table 1 (continued)

Variable	Variable's level of detail and scale	Disturbance type	Disturbance subcategory	Number of plots	Percent (%)
Damage code + agent of mortality (DAMAGE_AGENT_CD + AGENTCD)	Damage agent: very detailed. Agent of mortality: not very detailed. When homogenizing these two variables we lose detail. (Tree-level variables)	Animal	Wild animals (i.e., birds, deer, bear, porcupine, beaver), domestic animals (i.e., cattle, horses)	22,690	2.47
		Disease	General diseases, root/butt diseases, cankers, stem decays, parasitic/epiphytic plants, Decline Complexes/Dieback/Wilts, foliage diseases, stem rusts, broom rusts	135,025	14.69
		Fire	Damage >20% of bole circumference, stems, and crown	9095	0.99
		Insect	General insects, bark beetles, defoliators, chewing insects, sucking insects, boring insects	45,069	4.9
		Silviculture	Harvest	33,896	3.69
		Vegetation	Competition, overtopped shade intolerant trees	36,076	3.92
		Weather	Abiotic damages such as wind, snow, ice	40,261	4.38
		Other	Other damage, unknown damage, multiple disturbances, invasive plants, human	139,427	15.17
		Not disturbed	No recorded disturbance	457,612	49.79
		Total		919,151	100

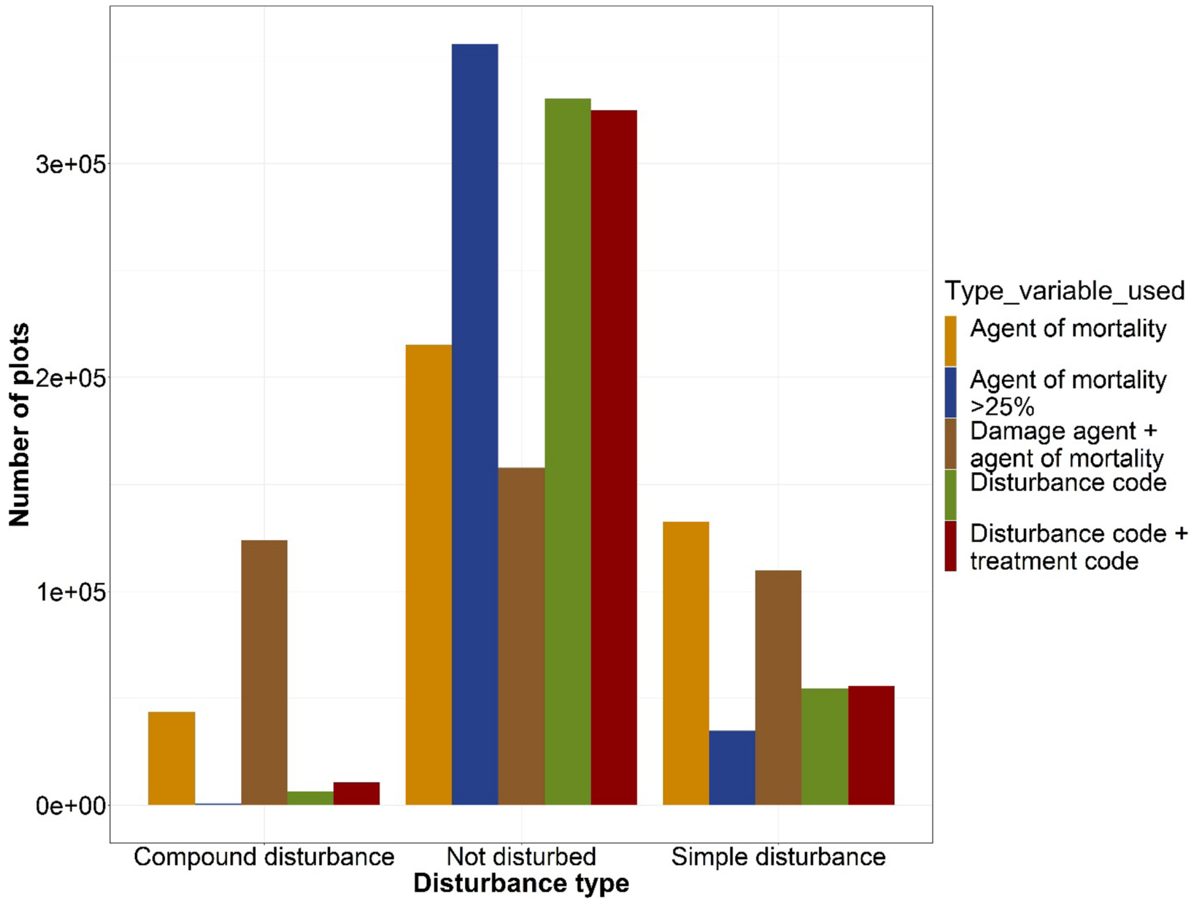

Fig. 1 Number of plots considered disturbed for the different variables used

However, disturbances that usually affect the stand at smaller scales (usually less than 25% of the trees) such as insects and disease would probably not be captured unless they were an invasive species (which have a different behavior and affect larger portions of the stand during a short time interval). From this figure, it is clear that if research interests require capturing any evidence of disturbance, a tree-level variable should be considered instead of a condition-level one.

Table 2 Number of plots disturbed by agent type and the corresponding percentage of the total number of plots analyzed by variable type

Number of plots	Not disturbed	Simple disturbance	Compound disturbance	Total
Agent of mortality	215176 (54.97%)	132702 (33.9%)	43584 (11.13%)	391462 (100%)
Agent of mortality >25%	355961 (90.93%)	34825 (8.90%)	676 (0.17%)	391463 (100%)
Disturbance code	330319 (84.38%)	54692 (13.97%)	6451 (1.65%)	391464 (100%)
Damage agent + agent of mortality	157862 (40.33%)	109729 (28.03%)	123871 (31.64%)	391465 (100%)
Disturbance code + treatment code	324913 (83%)	55869 (14.27%)	10680 (2.73%)	391465 (100%)

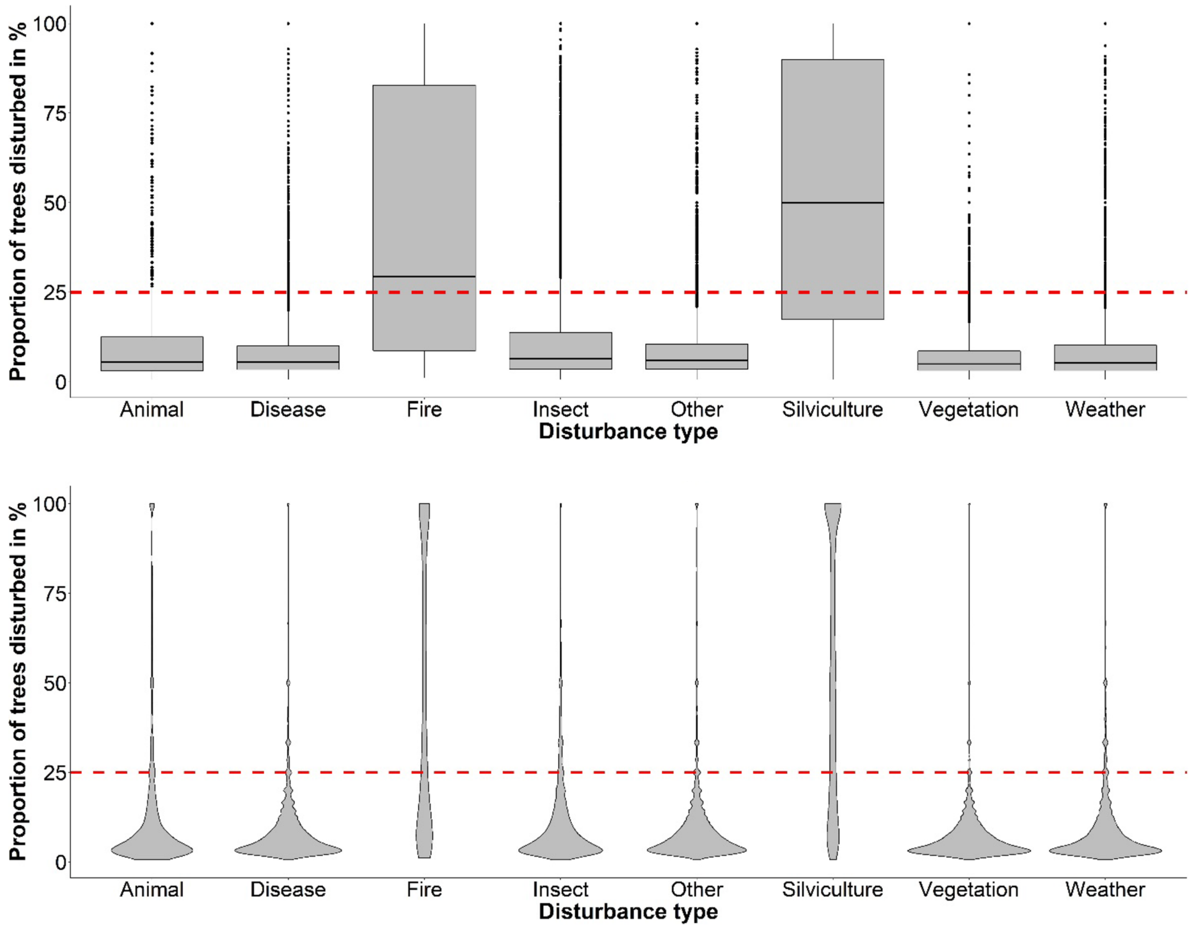

Fig. 2 Agent of mortality variable represented for all 48 US states. Cumulative data shown since the start of the annual inventory year for each state. The red dotted line represents the 25% threshold that the condition-level disturbance variables would use for including a disturbance. Top panel represents a box plot and lower panel represents a violin plot.

Chi square tests

Results from the chi-square tests for all states together were significant for our five tests with a p-value lower than 0.05 (Table 3). Therefore, we reject the null hypothesis for all and conclude that there is an association between the variables. In other words, the variable that we use for capturing disturbances makes a difference in the number of plots considered non disturbed, disturbed by one agent (simple

Table 3 Chi-square comparisons between disturbance variables at a national level

Comparison	*p* value	df	Chi-square
Disturbance code vs agent of mortality 100%	< 2.2e-16	2	84309
Disturbance code vs agent of mortality 25% threshold	< 2.2e-16	2	9550.4
Disturbance code vs agent of mortality + damage code	< 2.2e-16	2	184933
Disturbance code + treatment code vs agent of mortality + damage code	< 2.2e-16	2	170338
Disturbance code vs agent of mortality vs agent of mortality at 25% threshold vs agent of mortality + damage code vs Disturbance code + treatment code	< 2.2e-16	8	479391

disturbance), or disturbed by multiple agents (compound disturbances). This has important implications for attribution and estimating forest land area impacted by disturbance. In addition, when performing the Chi-square tests for individual states, the only non-significant test was from Delaware when comparing the disturbance code variable vs the agent of mortality >25%. All the other tests had a significant p value (See Supplementary material 2 for the complete tables).

Mapping disturbances

Different disturbance agents are predominant when using each disturbance variable (Fig. 3, Table 1). Fire, insects, weather, animals, and disease are the

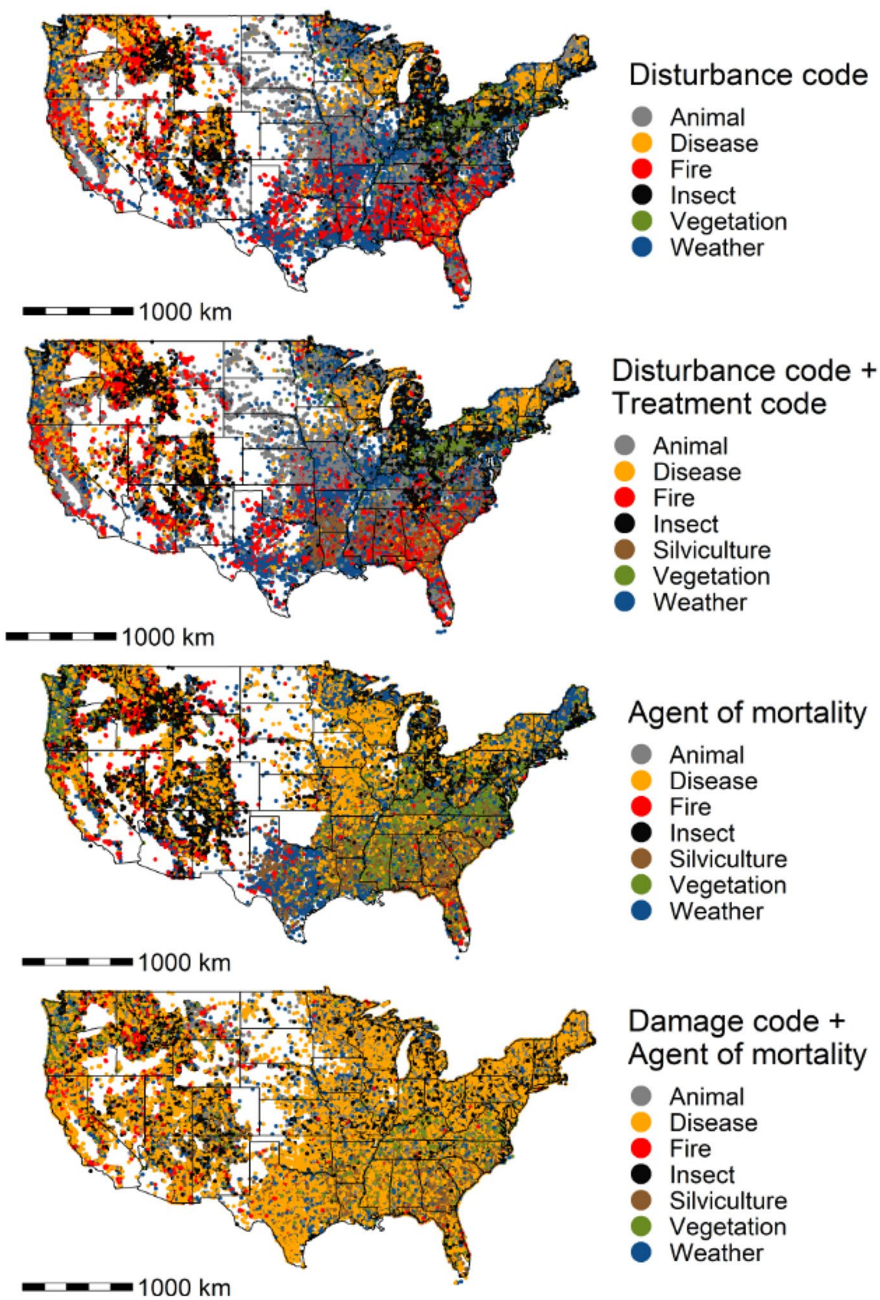

Fig. 3 Cumulative disturbances since the start of the FIA annual inventory period until 2020. The "Other" category was removed from the graph to better highlight the location of the rest of the disturbance categories

most frequent disturbances when considering the condition-level variable disturbance code and disturbance code + treatment code. However, when using tree-level variables that capture disturbances at a smaller scale, we start seeing that other disturbances that were not captured at a condition-level are now captured. This is because some disturbances like disease that tend to affect individual trees rather than affecting a whole stand (except for invasive species, which more often result in stand-replacing events) can be captured now. For example, when looking at the agent of mortality tree-level variable, diseases are a more predominant disturbance followed by weather, vegetation, and silviculture in the eastern states. We observe here that disturbances which usually affect scarce individual trees are more often captured when using tree-level variables. As we go into more detail and combine not just dead trees (with the agent of mortality) but also damaged trees, we are able to see the whole picture of the effects of disturbances. By including these two variables, we can not only capture more disturbances but also the ones affecting live but damaged trees. Using these two variables, disease is the most dominant disturbance in the map. It is important to note that all the disturbances overlap and the most frequent are the ones that are better captured in this form of visualization.

We recorded 4906 disturbances classified as "other" for the disturbance code variable and for the disturbance code + treatment code variable, 66 364 for the agent of mortality, and 139 427 for damage agent + agent of mortality.

Case studies

When using variables that capture small scale and magnitude disturbances, we are able to capture more plots (Fig. 4). However, fire and insect disturbances do not follow the expected trend of increasing the number of plots when increasing the level of detail in the variable to use. With the agent of mortality variable, we were able to capture less disturbed plots rather than with the condition-level variable of disturbance code. This might be due to the nature of the agent of

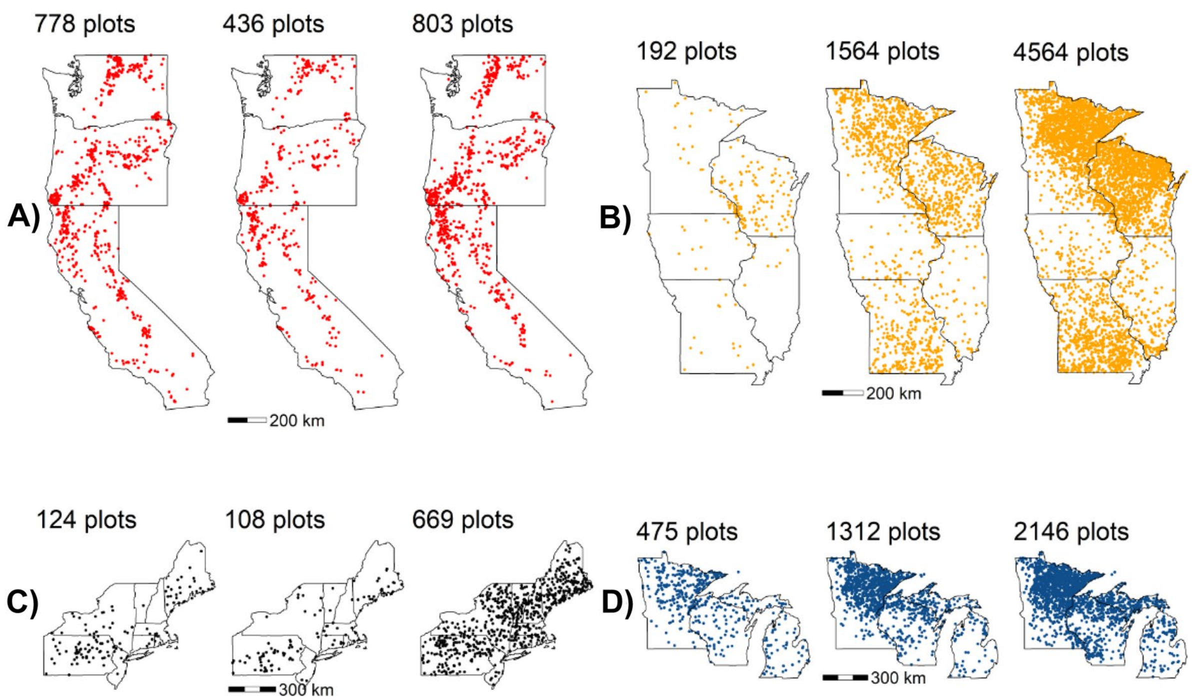

Fig. 4 Disturbance categories by regions of interest for disturbance code, agent of mortality, and agent of mortality + damage codes from left to right. (**a**) Fire in California, Oregon, and Washington; (**b**) disease in Minnesota, Wisconsin, Iowa, Illinois, and Missouri; (**c**) Insects in Maine, New Hampshire, Vermont, Massachusetts, Rhode Island, Connecticut, New York, Pennsylvania, and New Jersey; panel D) Weather in Minnesota, Wisconsin, and Michigan. Treatment codes are not included here since all are considered silviculture disturbance.

mortality variable, which captures only dead trees. For example, plots that were affected by a controlled fire that did not kill trees would not show as disturbed for the agent of mortality variable. However, when adding the damage agent, we gain that level of detail and more trees would be now included as disturbed.

Selection of disturbance variable

The selection of which disturbance variable to use can be difficult. Therefore, we built a decision tree that guides the process of selection based on different criteria (Fig. 5). Some of the criteria we propose to help variable selection are the specific research objectives of the disturbance study, the scale at which the study is being conducted (e.g., would a tree-level analysis be better or is a condition-level enough?), the magnitude of disturbance we want to capture (i.e., stand replacing disturbances or diffused disturbances), and the type of damage that we want to capture (e.g., dead trees, damaged trees, both).

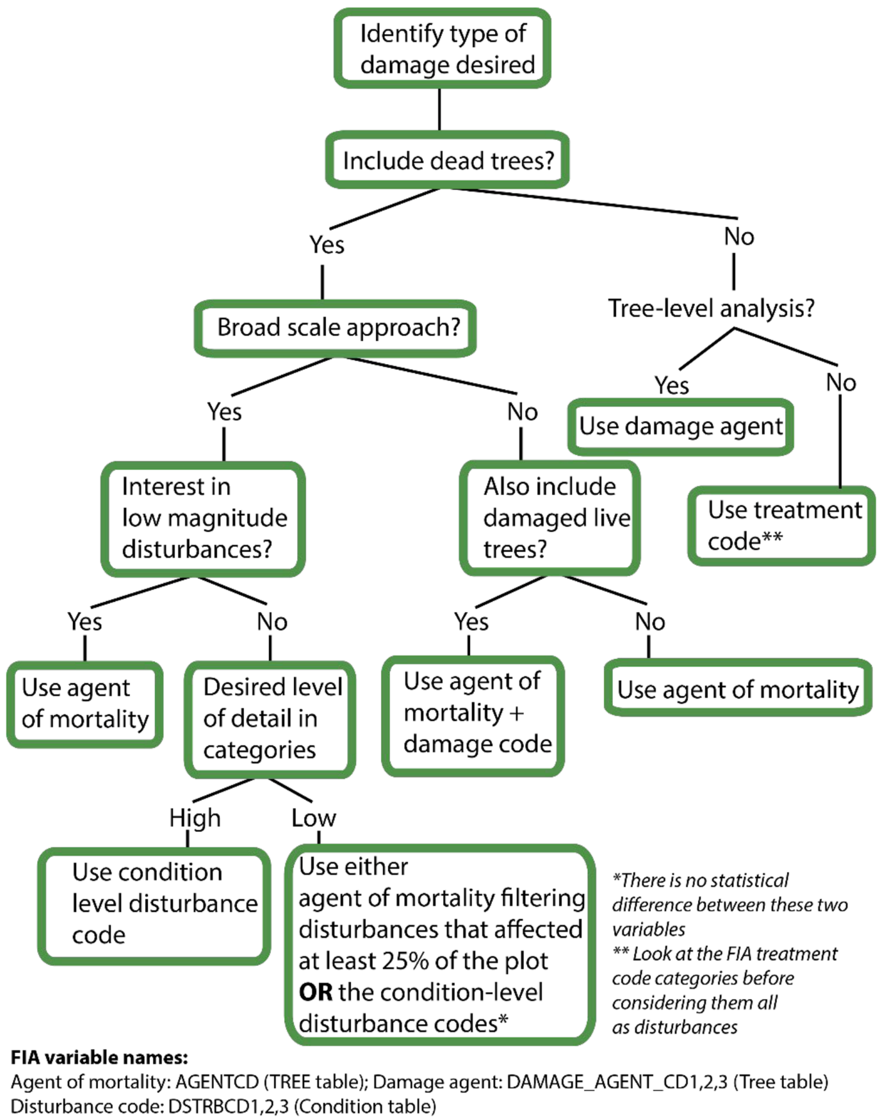

Fig. 5 Decision tree showing the process we suggest for choosing the most appropriate disturbance variable according to specific research objectives

Discussion

This study demonstrates the importance of national forest inventories (NFIs) in capturing the presence and extent of forest disturbances. Despite the advantages of remote sensing techniques in capturing stand replacing disturbances over large areas at a low cost (Masek et al., 2013; Randolph et al., 2021), data collected with NFIs offer on-the-ground disturbance information. NFIs also have the advantage of capturing disturbances underneath the canopy at finer scales. However, most NFIs are not designed to capture rare events due to their sample design and intensity, which are fixed at the national level (Coulston et al., 2020; Masek et al., 2013), as well as their frequency of remeasurement, which makes some disturbances go unnoticed (Coulston et al., 2020; Wilson et al., 2019). Despite these limitations, the US National Forest Inventory has different variables that we can use to calculate disturbances at different levels of detail, such as disturbance at the condition level (DSTRBCD), silvicultural treatment code (TRTCD) at the condition level, agent of mortality of individual trees (AGENTCD), and damage agent at a tree level (DAMAGE_AGENT_CD). Our study clearly demonstrates that the disturbance variable used depends on the research objectives, the scale of the study, the magnitude of disturbance we want to capture, and the type of damage (Fig. 5). We are not advocating for a specific variable to be used in every scenario but raising awareness of the effects of choosing different variables and showing a rationale for deciding on the most appropriate one for a specific study.

Many studies on forest dynamics in the USA have shown that rates of disturbance and mortality in forest stands range between 0.5 and 4.5% of forest area per year, averaging about 1% per year (Cohen et al., 2016; Masek et al., 2013; Runkle, 2000; Stephenson & Van Mantgem, 2005). These estimates do not reflect recent phenomena such as disturbance by invasive species and climate change effects on the frequency and severity of disturbances (Turner, 2010). Therefore, if we assume a 1% disturbance rate, the turnover rate of a stand would be 100 years. Assuming this disturbance rate with the US FIA design, 5% of the stand would be disturbed in the eastern states (5-year remeasurement period), and 10% in the western states (10-year period) by the time the field crew samples the plot. These diffuse disturbances would not be captured with the condition-level variable (DSTRBCD) because of the 25% of disturbed trees threshold. However, the tree-level variables (AGENTCD and DAMAGE_AGENT_CD) recorded by the FIA program would be a good alternative to register these disturbances and would allow their early detection and trigger a timely management action. Even if we assume a 3% yearly disturbance rate, we would still be below the threshold to detect disturbances in the eastern states and it would be difficult to capture some of the disturbances in the western states (around 30% of the plot would be disturbed).

Prior disturbance studies in the USA have used the FIA data differently. Coulston et al. (2020) used the condition-level variable (DSTRBCD) for estimating the timing and extent of forest disturbances by taking advantage of the panelized nature of the FIA inventory incorporating weights adjustments. However, given our findings with the Chi-square tests, by using tree-level data, the results from Coulston et al. (2020) would have likely found a greater extent of disturbed area. Other studies have looked at individual-tree data including Ward et al. (2021), who performed an emerald ash borer (*Agrilus planipennis*) study using the agent of mortality. The authors highlight the importance of early disturbance detection, which is not always possible with the frequency of plot remeasurements. By the time a plot shows signs of invasion, forest insects and diseases might have already spread to other areas. Other authors looked at the damage agent variable in FIA to analyze the effects of insect and disease in the forest (Fei et al., 2019; Randolph et al., 2021). Fei et al. (2019) estimated that about 41.1% of the total live biomass in forests of the conterminous USA is at risk from invasion of currently established insects and diseases.

Many countries have NFIs that estimate disturbances using different approaches including field plots, photo-interpreted plots, and satellite images (Tomppo et al., 2010). For example, Canada uses photo plots (with a 2km cell size) to identify disturbances with ground plot validation in 8% of these photo plots (Canadian Forest Service, 2008; National Forest Inventory, 2021). With their permanent field plots (25m radius), they collect information on natural disturbance agents (including its species), as well as the extent and approximate time of the disturbance (Canadian Forest Service, 2008). Spain uses a 10-year cycle for their forest inventory, recording information on biotic and abiotic damage agents through geographic information systems (GIS) and field plots (MMA - DGB, 2007). Denmark records information on forest health at both landscape level (general status of forest health through GIS and 16km grids) and at tree-level (through field plots) on a 5-year inventory cycle (Tomppo et al., 2010). China does a two-stage stratified sampling with remote sensing and field plots, where information on state of forest health, tree mortality and disturbance agents are recorded (Tomppo et al., 2010). Brazil's NFI is based on satellite-imaging interpretation with a 20x20, 20x50, and 10x10 km grid for landscape level variables and field plots measured every 5 years (Freitas et al., 2006) where individual-tree health state is recorded (Serviço Florestal Brasileiro, 2017). Similar to other countries, the US FIA program collects, analyzes, and reports information on the status and trends of forest disturbances with a 5- to 10-year inventory cycle. Even though the US FIA program has some photo-interpreted plots and satellite-based observations, this program's strength relies on its solid on-the-ground plot system, its broad extent, and the frequency at which plots are evaluated. In addition, the protocols to capture disturbance are very explicit and the field crew has an extensive list of possible damage or disturbed agents to help identify the agent.

Broader impacts of our research include volume and productivity estimations and carbon sequestration potential. How disturbances are recorded for these estimations and potential will greatly impact reports and likely management actions. For example, forest productivity may be overestimated by using condition-level disturbance variables since we are not accounting for the many trees that are actually disturbed but would otherwise be considered healthy according to the inventory data. This would then overestimate the commercial volume in the stand. Moreover, with climate change increasing the frequency and severity of disturbances (Turner, 2010) and facilitating compound disturbances, changes in the carbon stored in tree biomass is receiving more attention in the research community. This increased attention is also due to the role of forests as the largest terrestrial sink of carbon (Pan et al., 2011; Sleeter et al., 2018; Woodall et al., 2015). Disturbances cause this carbon to cycle through the ecosystem causing it to move between different pools (i.e., aboveground and belowground biomass, dead wood, litter, organic soil) (Domke et al., 2019). Therefore, our ability to detect any evidence of disturbance by using tree-level data would help in attribution of carbon fluxes to particular disturbances across scales and thus improve attribution in greenhouse gas estimation at national scales. Furthermore, disturbances affect the allocation of the carbon in the ecosystem and the capacity of trees to sequester carbon (Fei et al., 2019). Dead trees store the carbon in dead wood biomass, but this pool represents carbon emissions as trees decay (Russell et al., 2014). In addition, looking at a short temporal scale, the growing space is already occupied by those dead trees and new regeneration would not occur. Therefore, the carbon sequestration potential of the whole plot is affected. Future work should investigate how forest productivity or carbon sequestration potential varies over time by using the different disturbance variables found in NFIs. In summary, in a changing climate, where disturbances are increasing in frequency and severity and more interactions among disturbances are seen, we need to be careful to capture not only stand replacing disturbances but also all evidence of disturbances, which can be better accomplished by using individual-tree data when available.

Conclusions

Through this study, we have described different methods of classifying disturbed plots by exploring understudied FIA variables that represent forest disturbances both individually and, when applicable, combined. The number of plots that are considered disturbed varies greatly depending on the disturbance variable used, changing the patterns and frequency of disturbances represented in the maps.

The selection of the disturbance variable to use depends on specific research objectives. The inclusion of dead or damaged live trees (residual trees) and the scale and magnitude of the disturbance to capture are important factors that influence our decision-making regarding which variable to use. Another important factor is the desired level of detail of the disturbance agent. The disturbance variable selected will likely significantly impact estimates of forest productivity at national scales. For example, the health of individual trees and the impact of small-scale disturbances when estimating growth potential are essential in understanding forest carbon stocks and sequestration patterns. Another application is individual tree growth, which has a significant economic value when forecasting stand volume and determining future composition. This information will aid management of the stands to mitigate the effects of disturbances on forests in a changing climate.

Overall, our results will be a useful tool for researchers using national forest inventories to inform the magnitude and scale of the disturbances being evaluated. The method in which disturbances are categorized has an important application in the policy and management of natural resources. Disturbances will impact national and international estimates of forest carbon stocks and sequestration potential under future global change scenarios as well as climate change mitigation and adaptation strategies.

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Author contribution LAF, MBR, and GMD conceived and designed the study. LAF conducted the analyses and wrote a first draft of the work. MBR and GMD provided input on the analysis and interpretation of results. All authors read and approved the final manuscript.

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Availability of data and material The data that support the findings of this study are openly available in the USDA Forest Service FIA Datamart public data repository at: https://apps.fs.usda.gov/fia/datamart/.

Code availability Code is available upon request

Declarations

Competing interests The authors declare no competing interests.

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