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Past and present individual-tree damage assessments of the US national forest inventory

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Abstract Identifying the signs and symptoms of pathogens, insects, and other biotic and abiotic agents provides valuable information about the absolute and relative impacts of different types of damage across the forest landscape. In the USA, damage collection protocols have been included in various forms since the initiation of state-level forest surveys in the early twentieth century; however, changes in the protocols over time have made it difficult for the data to be used to its full potential. This article outlines differences in protocols across inventory regions, changes in protocols over time, and limitations and utility of the data so that those interested in using the US national forest inventory database will better understand what data are available and how they have been and can be used.

Keywords Abiotic damage · Biotic damage · Forest health monitoring · National forest inventory · Tree damage

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Introduction

The health and condition of trees is a key indicator of vigor and growth, as well as ecological processes and the quantity and quality of wood products. Assessments of individual-tree damages and defects have long been a part of forest inventories. Whether recorded individually or compositely, identifying the signs and symptoms of pathogens, insects, and other biotic and abiotic agents provides valuable information about the absolute and relative impacts of different types of damage across the forest landscape (Morin et al. 2016, Potter and Conkling 2020).

Damage assessments can be made through air- or spaceborne remote sensing techniques and terrestrial inventories. Both approaches have advantages and disadvantages. Remote sensing includes aerial photography, aerial surveys (sketch mapping), airborne laser scanning (lidar), and satellite imaging (Koch 2015). These methods are advantageous in that they provide a visual record of conditions and can capture real-time effects of acute disturbances and long-term, ongoing events (Nelson et al. 2009). Remote sensing is cost-effective for covering large geographic extents and accessing hazardous or remote areas. Satellite imagery, in particular, provides complete (wall-to-wall) geographic coverage and information on biochemical traits, e.g., photosynthetic activity, absorbed radiation, and canopy water loss (Lausch et al. 2016). The primary disadvantage of remote sensing is that it only provides data on conditions that are visible from the air. Thus, species-specific assessments, especially in areas with high biodiversity, and the quantification of stand hazards, damage losses, and other traditional forest estimates are limited (Ciesla 2000; McRoberts et al. 2010). Remote sensing is also limited by weather conditions, e.g., cloud cover, that prohibit the capture and/or usability of the data (Koch 2015; Hall et al. 2016). Despite advances in detecting and mapping broad-scale forest disturbances, e.g., Norman et al. (2013), terrestrial assessments of individual trees are still necessary to correlate remotely sensed data with growth, mortality, and other forest health indicators.

Terrestrial damage assessments are conducted primarily with sample-based forest inventories, though insect trap networks and ad hoc surveys are conducted as well, especially in urban areas. Sample-based terrestrial inventories provide detailed information on floral, faunal, and fungal taxonomy; damage type and severity; and understory conditions (Lausch et al. 2016). Compared to remote sensing techniques, terrestrial methods are less restricted by minor weather events (clouds, wind, rain) and more restricted by hazardous ground conditions, remoteness, and landowner permissions. Though sensors and tools to detect internal damages and defects (primarily decay) have been developed (Garrett 1997; Johnstone et al. 2010), they have limited use in many forest settings due to issues of reliability, portability, complexity, and destructiveness. Minimally invasive methods that can reliably detect pathogens and are appropriate for use on permanent plot locations have been developed (Hoffman et al. 2014), but they can be time-intensive. In situ real-time polymerase chain reaction detection of pests and pathogens shows promise, but the methods are still in the nascent stage (Capron et al. 2020). Thus, information regarding damages and defects collected during terrestrial inventories is typically limited to external signs and symptoms that can be observed in non-destructive ways, i.e., without removing bark, penetrating the wood, or digging away soil.

Terrestrial, sample-based assessments of individual-tree damages are conducted at the national level by several countries around the world (Tomppo et al. 2010; Michel et al. 2019). In some countries, these assessments are conducted via stand-alone forest health monitoring programs; in other places, damage assessments are incorporated with traditional, commodity-focused national forest inventories (NFIs) (Kovač et al. 2014). Examples of the latter include Brazil (Brazilian Forest Service 2019); Canada (National Forest Inventory 2008); USA (Bechtold and Patterson 2005); China (Zeng et al. 2015); Japan (Forestry Agency, Japan 2019); Finland (Finnish Forest Research Institute 2009); Germany, Slovenia, and Sweden (Kovač et al. 2014); and several more European countries (Michel et al. 2019). Primary responsibility for the NFI in the USA falls to the US Department of Agriculture (USDA) Forest Service, Forest Inventory and Analysis (FIA) Program. In operation since the early twentieth century, FIA data collection protocols have varied regionally and undergone revisions over time as information needs and technologies for data collection, storage, and analysis have evolved. Such changes have been documented in field guides; however, many older (pre- 1999) field guides are not readily accessible.

Difficulty in interpreting FIA protocols and codes has been noted (Kromroy et al. 2008), and a call to provide improved user manuals has been made (Tinkham et al. 2018). Thus, this article describes the iterations of individual-tree damage assessment protocols implemented regionally and nationally by FIA 1936 through 2019. We also discuss the expectations and utility of such data so that researchers, forest managers, policymakers, and others can make effective use of the FIA database (FIADB).

History of FIA damage assessment protocols

The FIA Program can be characterized by two survey frameworks known as the periodic inventory and the annual inventory, respectively implemented before and after passage of the Agricultural Research, Extension, and Education Reform Act of 1998 (US Public Law 105-185) (1998 Farm Bill). To describe the history of the FIA damage assessment protocols, we divided these frameworks into four eras: (1) the periodic historic era beginning c. 1930, (2) the periodic modern era beginning in the late 1960s, (3) field guide versions 1 to 5 of the annual era beginning c. 1998, and (4) field guide versions 6 to 8 of the annual era beginning in 2012.

Periodic inventory beginning c. 1930

The FIA Program, originally known as "Forest Survey," was established by the McSweeney-McNary Act of 1928. The USDA was tasked with conducting a national forest survey to track the nation's timber supply and reporting results to Congress every 10 years. In practice, inventories were conducted state-by-state on a periodic basis such that all plots within a state were measured within 1 to 4 years and then returned to on a cyclical basis with remeasurement intervals ranging between 6 and 18 years (Gillespie 1999). A variety of sampling procedures were implemented over the years. Designs and measurement techniques varied among regions (Fig. 1), among states within regions, and within states over time (Frayer and Furnival 1999, LaBau et al. 2007). Partly because of their size and diverse ownership, some states, particularly those in the western USA, were never inventoried comprehensively. Therefore, the periodic inventories are a patchwork of different designs and sampling intensities, e.g., O'Brien (2002, 2003). A description of the plot designs in use between 1966 and 2004 is provided by O'Connell et al. (2017).

In keeping with the timber supply focus of the Forest Survey, accounting for damages of various kinds was part of the earliest periodic inventories. However, rather than being coded as specific damages on individual trees, damages were typically integrated cull percentages or product classifications. This was consistent with the design of many of the early inventories. Forest area and size and stocking class distributions were determined primarily through aerial photo interpretation with terrestrial plots established on a subsample of the photo plots for the purpose of scaling gross volume and cull percentages to the area estimates (USDA Forest Service 1936). The practice of integrating defect and damages as cull percentages and log grade deductions continued through the 1960s, although statewide inventories were becoming increasingly plot-based and less reliant on aerial photo interpretation for area estimates.

The inclusion of individual defects and damages during the earliest periodic inventories were often species- and product-specific. For example, documentation of the first Inland Empire (Supplementary information 1) inventory noted that "any white fir (*Abies concolor*) or hemlock (*Tsuga heterophylla*) tree which contains a "conk"…will not be tallied [as a merchantable tree], since such trees as a rule are entirely worthless" (USDA Forest Service 1936). Similarly, given its high potential value for pole timber, defects and damages of western redcedar (*Thuja plicata*) were given special attention, with mention of dead tops and limbs, woodpecker holes, worm attack (wood borers and possibly bark beetles), dead and dry streaks, and curvature of the main stem, i.e., sweep, included in field procedures (USDA Forest Service 1936). To promote consistent data collection, the Forest Survey staff was encouraged to consult the state-of-the-art tree grading guidelines of the day such as Knouf and Weir (1922) and Hubert (1926).

Implementation of damage agent codes during the periodic inventory (1960s–1990s) The periodic modern era began in the late 1960s with the recording of specific damaging biotic and abiotic agents in addition to the more traditional product-oriented defects and damages such as broken tops and limbiness. The types of damage and damage agents recorded during this era fell into nine general categories: animal, disease, fire, human, insect, tree form, vegetation, weather, and other (Table 1). With each state operating under its own field guide during this time period, damage collection protocols were highly variable across the country regarding which damage types and damage agents were collected, when they were to be recorded (severity thresholds), how they were recorded, how they were prioritized for coding, and how damage severity was recorded, if it was recorded at all. In some inventories, damage codes served a dual purpose: when coded on live trees, they indicated damage and when coded on dead trees they indicated cause of death.

Prior to the 1980s, only one damage type or damage agent per tree was typically recorded; however, by the 1980s, the list of recordable damaging agents had expanded in some states, particularly in the western USA where two causes of death could be recorded for each dead tree and up to three damage types for each live tree. During the 1980s, new variables also began to be added to some inventories. For example, in addition to the general damage agent, the 1982 field manual for the Utah-Nevada[1] inventory (USDA Forest Service 1982) allowed two types of "insect and disease incidence" with 7 general (bark beetles, defoliators, terminal-feeding insects, stem rusts, needle diseases, stem rots, and root diseases) and 42 specific agents from which to

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[1] The location of specific US states referenced in this article is shown in Supplementary information 1.

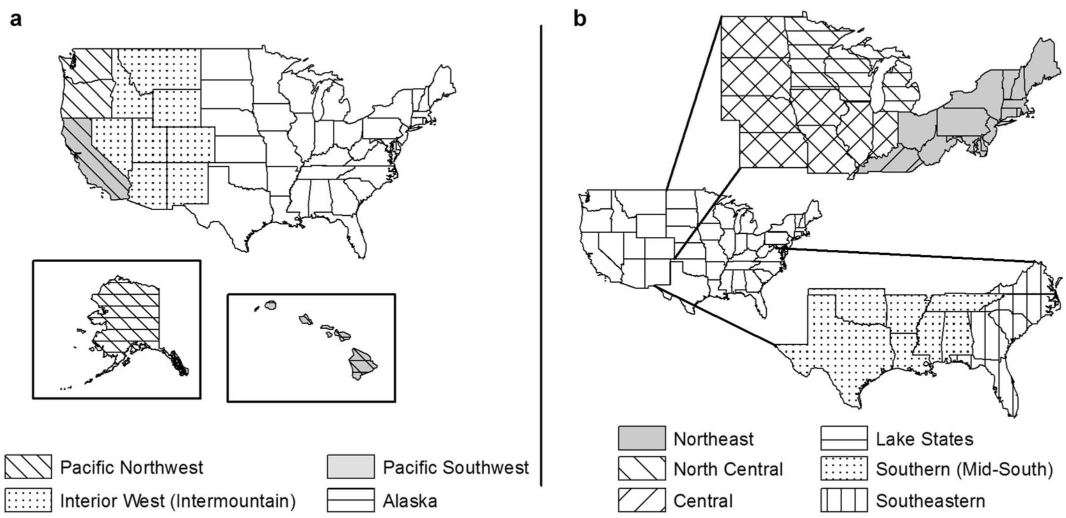

Fig. 1 FIA regions providing oversight for forest inventories in the (**a**) western and (**b**) eastern USA during the modern era of the periodic inventory. The Pacific Northwest, Pacific Southwest, and Alaska units merged in 1966 to form the Pacific Northwest region. The Central and Lake States regions merged in 1966 to form the North Central region. The Southern (Mid-South) and Southeastern regions merged in 1997 to form the Southern region

choose. By the mid- to late-1990s, inventories in the Intermountain region (Fig. 1), hereafter referred to as the Interior West (IW), and southeast Alaska were recording up to two damage agents; Oregon and Washington were recording up to three damage agents; and the previously separate "insect and disease incidence" types had largely been integrated into the main list of possible damage agents. Throughout the periodic inventory modern era, dwarf mistletoe (*Arceuthobium* spp.) was of such great importance in the 11 coterminous western states that the Hawksworth dwarf mistletoe rating (values 0 to 6) (Hawksworth 1977) was recorded as a separate variable in addition to being included in the damage agent list when the rating was 4 or higher.

In some of the periodic inventories, any presence of damage was recorded. In other instances, damages were recorded only when present at "serious" threshold levels defined for each damage type/damage agent or when the damage met general criteria such as cause mortality before maturity, or cause mortality within 10 years in the case of mature trees, reduce tree quality (marketability), or significantly reduce growth and productivity. When multiple damages were collected, they were not necessarily required to be recorded in any hierarchical order. However, for trees with more damages present than were allowed to be recorded, field crews were typically instructed to record the "most severe" or "most serious" damage. Sometimes, the most serious damages were prioritized in the field guide. When individual agents were not prioritized, some states included general guidelines for prioritization, e.g.:

1. If the damage will cause the death of the tree, code it first.
2. In the absence of (1), record the damage that will cause the most degrade.
3. In the absence of (1) or (2), record the damage that will cause the most growth loss.
4. In the absence of (1), (2), or (3), record the most common damage type (USDA Forest Service 1993).

Annual inventory beginning c. 1998

With the passage of the 1998 Farm Bill, the FIA Program transitioned to an inventory system in which a portion of plots distributed at an intensity of 1 plot per approximately 2400 ha would be measured annually in each state beginning in 1999 (Bechtold and Patterson 2005). This new system known as the Enhanced FIA Program, or more commonly as the "annual inventory," was implemented gradually across the USA. Under this system, all plots within each state were divided into spatially balanced panels. Each panel of plots is measured on a rotating basis so that, under ideal conditions, data for each panel are collected once every 5 or 7 years in the eastern USA and once every 10 years in the

Table 1 Generalized summary of damage agents collected during the FIA periodic inventories, by region

Damage category	Region[a] and damage agents[b]			
	Interior West (Intermountain)	NE, NC, C, LS	PNW, PSW, Alaska	S and SE
Animal	Big game, browse, domestic animals, hare/rabbit, pocket gopher, porcupine, sapsucker, small rodents	Beaver, browse, buffalo, deer, domestic animals, elk, hare/rabbit, livestock (cattle), mice, moose, porcupine, sapsucker, squirrel	Bear, beaver, browse, deer, elk, hare/rabbit, livestock, mice, moose, mountain beaver, pocket gopher, porcupine, sapsucker, squirrel, vole	Beaver, sapsucker
Disease[c]	Blights; cankers; dwarf mistletoe; foliage disease; root, stem and butt rots (conks); root/butt disease; rusts (broom, stem); true mistletoe	Blights; cankers; declines; foliage disease; heart and root rots; needle casts; root/butt disease; rusts (broom, gall, needle, stem); stem decay; wilts; yellows	Cankers, declines, dwarf mistletoes, foliage disease, needle casts, stem decays, root/butt disease, root rots, rusts (needle, gall, broom, stem)	Cankers, root disease, root rots, rusts (stem)
Fire	Fire	Fire	Fire	Fire
Human	Chemical injury, land clearing, logging, timber stand improvement, woodland cutting	Air pollution, chemical injury, imbedded objects, logging, land clearing, mechanical damage, oil and salt damage, pesticide, soil compaction, timber stand improvement, vehicle damage	Imbedded objects, improper planting, logging	Land clearing, logging, timber stand improvement, turpentining
Insect[d]	Defoliators, phloem borers (bark beetles, engraver beetles), terminal and shoot feeders (weevils)	Bud, terminal, tip, and shoot feeders; cone insects; defoliators; gall makers; phloem borers (*Agrilus bilineatus*, *Dendroctonus* spp., *Ips* spp.); root collar insects; sap suckers; shoot borers; wood borers	Defoliators; phloem borers (*Dendroctonus* spp., *Ips* spp., *Scolytus ventralis*, *Pseudohylesinus sericeus*), sap suckers (*Adelges piceae*); terminal, tip, and shoot feeders	Phloem borers (bark beetles, *Dendroctonus frontalis*); sap suckers (*Adelges piceae*); terminal, shoot, and stemborers; twig borers and girdlers
Tree form	Broken and dead top, crook, forking, heartwood scar, lean, limbiness, sweep, taper, unhealthy foliage, wolf tree	Form defect (culling); broken, dead, flat, missing, and spike top; burl; checks/bole cracks; crook; dieback; forking; lean; physical defect; sweep; unhealthy foliage	Broken, dead, missing, and spike top; burl; checks/bole cracks; crooks; fluting (on hemlock); forking; heartwood scar/catface; lean; limbiness; physical defect; product/fiber damage; seam; sweep; sucker limb bayonet top; taper; wolf tree	Basal defects, branch stubs, broken top, crook, forking, form defect (culling), rot, sweep
Vegetation	*Arceuthobium* spp., *Phoradendron* spp., suppression	*Arceuthobium* spp., *Arceuthobium tsugense*, *Phoradendron* spp., suppression, vines	*Arceuthobium* spp., *Arceuthobium tsugense*, knocked down by other tree, parasitic/epiphytic plants, suppression	Inhibiting vegetation, stagnation, suppression
Weather	Drought, flooding, frost, lightning, snow, sun scald, wind, winter desiccation	Drought, flooding, frost or frost cracks, hail, ice, lightning, snow, sun scald, wind breakage, windthrow, winter desiccation, winter injury	Drought, flooding, frost, ice, landslides, lightning, moisture deficiency, mudflows, rockfall, snow, sun scald, wind breakage, windthrow, winter desiccation	Erosion, flooding, hurricane, ice, lightning, tornado
Other	Air pollution	Off-site trees	Air pollution, chemical injury, knocked down by other tree, lack of drainage, unhealthy foliage	Dieback, off-site trees

[a] *NE* Northeast, *NC* North Central, *C* Central, *LS* lake states, *PNW* Pacific Northwest, *PSW* Pacific Southwest, *S* Southern, *SE* Southeastern

[b] The same damage agent may appear in multiple damage categories due to regional classification differences

[c] For brevity, specific pathogens are listed only by type, e.g., rusts, rather than scientific name

[d] For ease of comparison across regions, insects are listed by feeding guild. The specific insects and insect categories included within each guild are provided in parentheses

western USA (Fig. 2). Under the annual inventory, all FIA regions began operating under one national field guide (Supplementary information 2). Protocols are consistent and uniform across all regions, though some regional differences in data collection are allowed including within the protocols for observing tree damage.

Field guide versions 1 to 5 of the annual inventory (1998–2012) Tree damage under field guide versions 1 to 5 was characterized by a set of three attributes: damage location, damage type, and damage severity (USDA Forest Service 2000), a method similar to that of the International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests (ICP Forests) in Europe and beyond under the United Nations Economic Commission for Europe (UNECE) Air Convention (Eichhorn et al. 2016). Damage location described the tree part affected, e.g., roots, bole, and branches. Damage type described the kind of damage, e.g., canker or broken bole. Damage severity described the extent of the damage, e.g., percent of branches affected. Only damages meeting established severity thresholds were recorded. A maximum of two damages were recorded per tree. If more than two damages were present, damages lower on the tree were given priority. If more than two damages were observed within the same location, priority was given to the most significant damage type. Damage location and damage type were logically related such that only certain combinations of damage location and damage type could be recorded together. The agent causing the damage identified with this protocol was recorded under a separate, regionally specific variable in the Pacific Islands and states in the IW and North Central regions (Fig. 2). Details of the damage location, damage type, and damage severity attributes are provided in Supplementary information 3.

The shift from the damage agent protocol of the periodic inventories to the location-type-severity protocol in field guide v1 coincided with the integration of detection monitoring (DM) plots from the USDA Forest Service, Forest Health Monitoring (FHM) Program into FIA (McRoberts 2005, Riitters and Tkacz 2004). Within the tiered framework of FHM, DM was intended to capture the status and trends in forest health with detected anomalies triggering intensive evaluation monitoring (EM) projects to further understand identified conditions. Given this framework, the DM damage assessments were to be combined with standard mensuration data, summaries of other indicators, and auxiliary data so causes could be deduced or further investigated with EM. However, it became evident over time that the location-type-severity protocol failed to satisfy the informational and programmatic needs of FIA in terms of specificity, efficiency, and consistency. Therefore, beginning with field guide v2, damage collection shifted from being required nationally to regionally optional (Table 2) while new protocols were developed.

With the exception of the Caribbean and Pacific islands and states in the Northern region (Fig. 2), the national location-type-severity system of recording damages effectively fell into disuse after the protocol was changed from required to optional, and the regional FIA programs took different approaches to covering the potential data gap (Supplementary information 4). States in the IW went back to the system of recording the presence of damage agents that had been in use for many years during the periodic inventories. In the Pacific Northwest (PNW) region (Fig. 2), Alaska discontinued damage data collection; however, California, Oregon, and Washington instituted a protocol of recording the location, agent, and severity of damage.

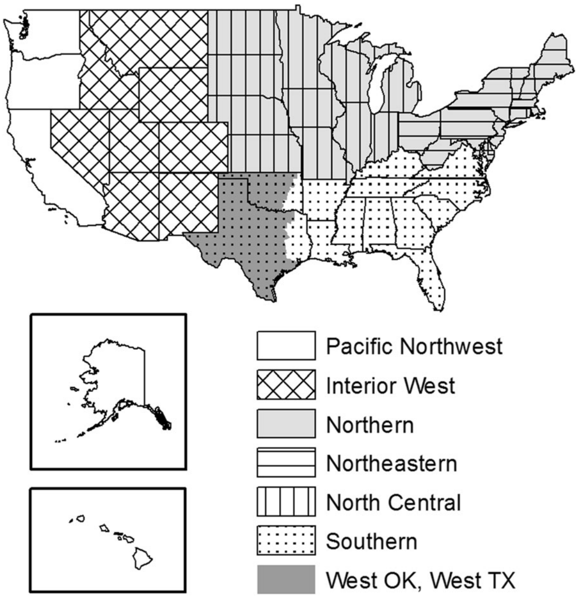

Fig. 2 FIA regions providing oversight for forest inventories in the USA during the annual inventory era. The North Central and Northeastern regions merged in 2007 to form the Northern region. Plots in west Oklahoma (OK), west Texas (TX), and the Pacific Northwest and Interior West regions are measured on a 10-year cycle. Plots in the Northern region and other parts of the Southern region are measured on a 5- or 7-year cycle. Territories and island nations in the Caribbean Sea and Pacific Ocean (not shown) are inventoried under the auspices of the Southern region and Pacific Northwest region, respectively

Damage collection in the Southern region continued for three agents that had been collected concurrently with the national protocol: dieback on hardwood species and fusiform rust (*Cronartium quercuum* f. sp. *fusiforme*) and Comandra rust (*Cronartium comandrae*) on pines (*Pinus* spp.). Similarly, protocols for identifying damage from mistletoes and epiphytes also continued in the western regions (IW and PNW, excluding Alaska) and the Pacific Islands, respectively.

Field guide versions 6 to 8 of the annual inventory (2012–2019) Because of the lack of national consistency as of 2012, the National (Washington, DC) FIA Office directed a task team to develop a new national damage protocol. This task team included representatives from each of the FIA regions and from the national FHM Program. Regional FHM staff and others within the Forest Health Protection (FHP) program were consulted on an ad hoc basis.[2] While some advocated for a very short list of possible agents, FIA analysts in general wanted to (1) include agents that were deemed locally important and (2) have the flexibility to add and remove agents relatively easily as circumstances warranted, e.g., upon the appearance of an exotic insect of high concern. The latter was desired because the existing national change management process within FIA was considered insufficiently agile to respond to emerging issues and customer demands.

The contrasting needs for both regional flexibility and national consistency were met through the adoption of the two-tiered Pest Trend-Impact Plot System (PTIPS) as the comprehensive list of potential damage agents. The PTIPS agent list is maintained by the FHP Forest Health Assessment and Applied Sciences Team (FHAAST) (née Forest Health Technology Enterprise Team) and serves as the standard list of codes used by federal and state forest health specialists in terrestrial and aerial forest health surveys. Like the protocols of the periodic inventories, the specific damage agents in PTIPS are organized in a hierarchical system with relatively few general agent categories (Table 3) and a large number of specific agents under the general categories. Within a regional FIA program or state, damages may be recorded with either a general or a specific code in such a way that the specific codes can be "rolled up" into general categories (Fig. 3), allowing for cross-regional or national comparisons. The resulting system satisfied needs that were expressed during the task team process: (1) a relatively short list of general agents, (2) a list of specific agents that was much greater than FIA analysts would likely need, and (3) congruence with an existing national standard that was already in use by forest health specialists. Furthermore, because the list was being maintained by forest health specialists, new agents of concern would be expected to be added to the list quickly. The seemingly conflicting goals of regional flexibility and national consistency were achieved by making the collection of the generic codes mandatory and placing the collection of specific PTIPS codes as either optional or mandatory under regional purview. Moreover, potential future regional/national conflicts were addressed by granting each FIA region the flexibility to add or remove a specific agent from their required regional list at any time without consulting other regions. However, changes to the required general categories would only occur through concurrence of all regions. In practice, the addition or removal of specific agents and general categories is made when field guides are updated, typically October of any given year. The Supplementary information 2 provides a timeline of field guide updates.

After the main task team settled on the general damage framework, the task of refining thresholds for when damages were to be recorded fell to a sub-team composed primarily of members of each regional data collection team. Using existing documentation of different thresholding systems, the sub-team developed instructions for use in national and regional field guides. This system, which dropped the damage location and damage severity variables, came into effect with the implementation of field guide version 6.0 (USDA Forest Service 2012) in October 2012.

Nationwide, there are 965 possible damage agents; the most any state has opted to collect is 101. Damage agents are observed on all live trees ≥ 12.7 cm diameter at breast height or root collar (d.b.h./d.r.c.), with some locations (state or region) opting to collect damages on all live trees ≥ 2.54 cm d.b.h./d.r.c. (Table 2). Up to three damage agents are recorded per tree. Agents are prioritized by impact if more than three are present. For example, damage that threatens survival is given priority

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[2] The USDA Forest Service is organized into five deputy areas: National Forest System, State and Private Forestry, Research and Development, Business Operations, and Finance. The Forest Health Monitoring Program is under the administration of the Forest Health Protection program within State and Private Forestry. In contrast, the Forest Inventory and Analysis Program is under the administration of Research and Development.

Table 2 Measurement years and summary of when the national damage assessment protocol was required (R), optional (O), or not collected (NC) during the FIA annual inventory era for trees and saplings, by national field guide version (v)

	Region					
Field guide version, years, and tree size[a]	Caribbean Islands	Interior West	Northern	Pacific Islands	Pacific Northwest	Southern
v1						
Years	2001–2004	2000–2003	1998–2004	2001–2006	1999–2006	1998–2004
Trees	R	R	R	R	R	R
Saplings	NC	NC	NC	R	NC	NC
v2 to v5						
Years	2006–2015	2004–2014	2003–2013	2012–2014	2004–2015	2003–2013
Trees	R	NC	R	R	NC	NC
Saplings	R	NC	NC	R	NC	NC
v6 to v8						
Years	2014–2019	2012–2019	2012–2019	2015–2016	2013–2019	2012–2019
Trees	R	R	R	R	R	R
Saplings	NC	O	NC	R	R	NC

[a] Trees are ≥ 12.7-cm diameter at breast height or root collar. Saplings are ≥ 2.54 cm and < 12.7-cm diameter at breast height or root collar

over damage that only reduces merchantability. There are no time constraints on damages collected, meaning that damages once incurred are recorded in successive inventories as long as the damage is still evident. Data have shown that for most tree species, coding three damage agents is relatively rare. Many species exhibit a relatively consistent pattern in which about 25 percent of live trees ≥ 12.7 cm d.b.h./d.r.c. have at least one damage recorded, about 5 to 7% have two damages, and around 1 to 2% have three (Table 4). Some species, such as sugar maple (*Acer saccharum*), can be prone to higher rates of damage, but the sharp decline in number of trees having two or three damages recorded is similar across species.

Data availability and usage

Data availability in the FIADB for the periodic inventory era varies widely, but the latest modern survey, typically from the 1990s, is available for most states. The earliest survey data available in FIADB is South Carolina 1968. Damage data collected during the periodic inventory were briefly noted in some state-level reports, e.g., in Wisconsin as acres damaged (Spencer et al. 1988) or volume killed (Schmidt 1998), but in other instances were comprehensively detailed in supplemental reports, e.g., Huber et al. (1987). Included in these supplemental "incidence and impact" reports were tables or figures describing the percentage of trees damaged by size class and species; estimated volumes of mortality, cull, and quality loss for major species groups; and quantification of economic impact. Damage trends were not included due to the addition of new damage codes that prevented direct comparisons with earlier inventories.

Damage data collected by FIA during the annual inventory era are available in the FIADB for all states. The primary outlet for reporting this information is the quinquennial report mandated for each state by the 1998 Farm Bill. Results have been presented in these reports in a variety of ways. For example, using data collected under the former location-type-severity protocol, Rose (2007) described the most frequently observed damage types (conks, vines in the crown, etc.), percentage of trees with at least one damage by species, and percentage of trees damaged by plot in Virginia. In a similar fashion, McWilliams et al. (2005) described the percentage of basal area with damage for select species in Maine. For data collected under later regional or national damage agent protocols, results typically have been presented as the proportion of trees, volume, or basal area, usually by species or genus, that were observed in each general damage category, e.g., DeBlander et al. (2010), Dooley and Randolph (2017), Morin et al. (2015a), and Palmer et al. (2019).

Table 3 General damage agents included in the national field guide versions 6 to 8 of the FIA annual inventory era. These general agents are recorded unless regions opt to collect a more specific agent within each category

General agent	Description
General insects	Insect damage that cannot be placed in any of the other insect categories
Bark beetles	Phloem feeding insects that bore through the bark and create extensive galleries between the bark and the wood
Defoliators	Foliage-feeding insects
Chewing insects[a]	Non-defoliating insects that chew on trees, e.g., grasshoppers and cicadas
Sucking insects	Adelgids, scales, and aphids that feed on all parts of the tree
Boring insects	Boring insects with larval galleries in the wood or phloem
Gallmaker insects[b]	Insects whose feeding or egg-laying results in galls on branches, leaves, or other tree parts
General diseases	Diseases that cannot be placed in any of the other disease categories
Root/butt diseases	Pathogenic fungi that kill all or a portion of the tree's roots or stump
Cankers	Sunken lesions on the stem caused by the death of the cambium, most often caused by fungi
Stem decays	Rot occurring in the bole/stems above the roots and stump
Parasitic/epiphytic plants	Parasitic and epiphytic plants, including vines, excluding benign epiphytes such as lichens and mosses
Decline complexes/dieback/wilts	Tree disease which results from an interacting set of factors
Foliage diseases	Foliage diseases caused by fungi, including needle casts, blights, and needle rusts
Stem rusts	Disease caused by fungi that deform or kill all or a portion of the stem or branches of a tree
Broom rusts	Disease caused by fungi that deform or kill all or a portion of the branches of a tree
Fire	Temporary or permanent damage resulting from fire
Wild animals	Damage from wild birds and mammals
Domestic animals	Damage from domestic animals such as horses and cattle
Abiotic	Damages not caused by organisms, e.g., wind, snow, and ice
Competition	Suppression of overtopped shade-intolerant species
Human activities	Damages from human activities, e.g., logging, poor pruning, and vandalism
Harvest	Only recorded for woodland species that have had part of their crowns removed
Other damage	Form defects and damages that reduce merchantability but do not typically reduce the probability of survival
Unknown damage	Used only when damage cannot be attributed to a general or specific agent

[a] Only collected by the Interior West and Southern FIA regions

[b] Only balsam gall midge (*Paradiplosis tumifex*) in the Northern region

Nationally, Coulston et al. (2005a, 2005b) used a Damage Severity Index to describe the extent of damage at the plot and ecoregion section levels. Regionally, Morin et al. (2016) summarized the percentage of damaged trees at each plot and county within the Northern FIA region for the top 20 tree genera, with additional analyses for individual species with substantial damage. Such summaries provide broad geographic context for the frequency of damage and damage types across the landscape and highlight variations between species and sites. For example, although stem decay is the most frequently recorded damage overall (Fig. 3), it is recorded more often on eastern tree species than western tree species (Table 5). Similarly, vegetation and the other/unknown damage categories, the latter of which includes form defects and damages that affect merchantability but do not typically reduce the probability of tree survival, are more often recorded on western tree species than eastern tree species (Table 5). Damage from fire, animals, human activity, and abiotic agents are recorded relatively infrequently. These results contrast those recently collected in Europe, where insects and abiotic agents

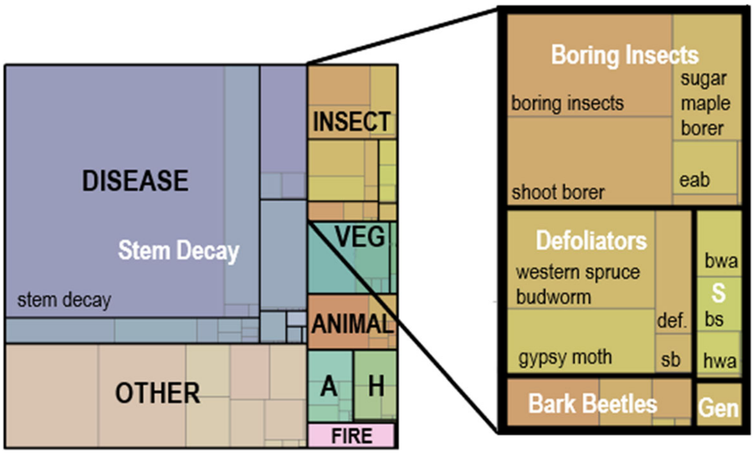

Fig. 3 Visualization of the proportion of damages recorded nationwide in FIA inventory year 2016. The hierarchical nature of the damage agents is represented by text capitalization (uppercase, mixed case, and lowercase). Agents with relatively few observations are not visible. A ABIOTIC, bs beech scale, bwa balsam woolly adelgid, def. defoliators, eab emerald ash borer, Gen general insects, H Human, hwa hemlock woolly adelgid, S sucking insects, sb spruce budworm, VEG vegetation

(drought, snow, ice, etc.) accounted for 27.3% and 16.4% of all recorded damage symptoms, respectively (Michel et al. 2019).

Limitations of the current FIA damage assessments

The FIA inventory is a national, strategic inventory implemented regionally with the goal of providing objective information on key forest ecosystem processes (forest area, tree growth and mortality, harvest removals, etc.). The strengths of the FIA annual inventory include its national scope and consistency of plot design and data collection protocols. However, these very important strengths in some ways constrain the utility of damage assessment data. Although the rotating panel design (Reams et al. 2005) allows even temporal coverage of the country and direct tracking of change over long periods of time, the periodicity of remeasurement limits data collection on new or quickly spreading forest health issues (Nelson et al. 2009). Likewise, the sampling intensity of one plot per approximately 2400 ha hinders the ability to detect acute events or diagnose localized damage. The design of any forest inventory influences how the inventory data can be used and these limitations are characteristic of most, if not all, national forest inventories (Wulff et al. 2013). Although much can be done with FIA data at a local level, the inventory is designed primarily to provide information for large geographic extents (state, region, and nation).

Other characteristics that constrain the utility of damage assessments include the timing and duration of damage signs and symptoms, the cryptic nature of many damage agents, the complexity of interacting agents, and the threshold at which damage occurs (Mistretta and Bylin 1987). Though these characteristics are present in all damage assessments, they are particularly important within the FIA inventory. First, some damage signs and symptoms are seasonal; therefore, the timing of plot visitation, which happens year-round in some FIA regions, influences the accuracy and repeatability of damage assessments. For example, defoliators require attribution based on evident defoliation, but deciduous trees are in a leaf-off state for 4 to 6 months every year across most of the continental USA. The list of damage agents in recent field guides (versions 6 to 8) does not discriminate against specific agents or general damage types that are seasonal in nature. Consequently, population-level estimates of area, number of trees, or volume of trees affected are not feasible for all agents. The duration of signs and symptoms also influences the accuracy and repeatability of damage assessments. With remeasurement intervals of 5 to 10 years, ephemeral signs and symptoms may go unnoticed unless they occur shortly before a plot visit. Contrastingly, longer-lasting signs and symptoms are more likely to be observed throughout the course of the inventory.

Second, FIA field crews are limited to non-destructive sampling and, though they receive extensive training, field crew members are typically

Table 4 Frequency of damages recorded on common species in the USA during FIA inventory year 2016

Species	Region[a]	Live trees measured[b]	Damages recorded One (%)	Two (%)	Three (%)
Balsam fir (*Abies balsamea*)	E	9161	14.6	2.8	0.4
Common pinyon (*Pinus edulis*)	W	3657	22.0	3.5	0.6
Douglas-fir (*Pseudotsuga menziesii*)	W	20,872	23.8	6.5	1.5
Engelmann spruce (*Picea engelmannii*)	W	3715	24.7	6.6	1.2
Loblolly pine (*Pinus taeda*)	E	49,047	11.4	3.6	0.6
Lodgepole pine (*Pinus contorta*)	W	9383	33.9	9.5	1.9
Mountain hemlock (*Tsuga mertensiana*)	W	2810	30.2	10.2	3.0
Northern white-cedar (*Thuja occidentalis*)	E	7310	28.2	7.6	1.5
Ponderosa pine (*Pinus ponderosa*)	W	9514	26.1	5.3	0.9
Quaking aspen (*Populus tremuloides*)	E	9238	28.0	7.7	2.0
Red maple (*Acer rubrum*)	E	24,077	31.8	8.9	1.8
Slash pine (*Pinus elliotii*)	E	7404	16.8	5.0	0.9
Subalpine fir (*Abies lasiocarpa*)	W	4564	25.1	7.6	1.4
Sugar maple (*Acer saccharum*)	E	12,010	36.7	10.7	1.7
Sweetgum (*Liquidambar styraciflua*)	E	10,708	23.7	8.5	2.2
Utah juniper (*Juniperus osteosperma*)	W	5252	22.1	5.6	0.9
Western hemlock (*Tsuga heterophylla*)	W	6198	25.9	9.3	3.4
White fir (*Abies concolor*)	W	3524	27.3	8.3	1.8
White oak (*Quercus alba*)	E	9209	21.1	5.5	1.3
Yellow-poplar (*Liriodendron tulipifera*)	E	7092	17.0	5.4	1.1

E east, *W* west

[a] Divided by the 100th west meridian

[b] Diameter at breast height or root collar ≥ 12.7 cm

not, nor are they required to be, specialists in entomology and pathology. When destructive sampling is prohibited, identifying damage agents such as insects and pathogens to the species-level can be difficult even for expert observers. With the current damage assessment framework, damages can be attributed to a specific agent, e.g., black turpentine beetle (*Dendroctonus terebrans*), if the agent can be identified and if the region has elected to record it. If the specific agent cannot be identified, or if the region has not elected to record it, damages are attributed to a general category, e.g., bark beetles. Given the varied experience levels of field crews and cryptic nature of some damage agents, this flexibility is an advantage of the damage assessment protocol, but it can yield unexpected results. For example, Dooley (2017) noted a discontinuity in the assessment of damage from boring insects in Arkansas and Missouri (Fig. 4), an area with known red oak borer (*Enaphalodes rufulus*) outbreaks (Jones et al. 2014, Starkey et al. 2004). Querying FIADB for locations of the red oak borer (specific code 15026) yielded approximately the same number of locations in Arkansas as in Missouri (Fig. 4a). However, querying FIADB for locations of boring insects (general code 15000) on oak trees (*Quercus* spp.) yielded far more locations in Missouri than in Arkansas (Fig. 4b). It is unknown what proportion of the boring insect (code 15000) locations in Missouri, if any, represent damage from the red oak borer. Nevertheless, the disparity between the two states suggests variations in field crew expertise and training, i.e., in identifying borer damage and distinguishing red oak borer damage from other borer damage, or regional training regarding the usage of general codes versus specific codes, or a combination of both.

Table 5 Percentage of live trees with damage, by species and damage type during FIA inventory year 2016

			Disease								
Species	Region[a]	Insects	Cankers	Decay	Other diseases	Fire	Animal	Abiotic	Veg[b]	Human activity	Other[c] or unknown
		%[d]									
Balsam fir	E	6.1	0.0	5.2	0.1	0.0	1.6	0.6	0.1	0.5	3.5
Common pinyon	W	1.8	0.1	2.2	0.7	0.1	2.4	0.6	5.7	0.2	12.4
Douglas-fir	W	7.0	0.8	3.1	0.3	1.3	0.7	0.2	3.1	0.2	15.0
Engelmann spruce	W	15.9	0.7	1.5	0.6	0.2	0.5	0.3	0.8	0.0	12.0
Loblolly pine	E	0.4	0.1	5.5	7.9	0.1	0.3	0.2	0.1	0.9	0.4
Lodgepole pine	W	4.0	2.8	1.5	6.3	0.8	0.8	0.3	10.3	0.1	18.5
Mountain hemlock	W	0.1	0.2	8.6	0.2	0.7	1.1	2.5	4.0	0.0	25.9
Northern white-cedar	E	0.2	0.1	20.9	0.1	0.0	2.0	3.4	0.0	0.2	10.5
Ponderosa pine	W	3.2	0.2	1.2	0.8	2.2	1.5	0.5	4.9	0.3	17.6
Quaking aspen	E	7.7	6.0	18.3	0.1	0.1	1.0	1.0	0.0	0.3	3.4
Red maple	E	1.5	1.0	29.6	0.2	0.3	1.2	0.8	0.6	1.0	6.3
Slash pine	E	0.3	0.2	7.8	11.5	1.4	0.1	0.3	0.2	0.5	0.5
Subalpine fir	W	9.5	1.2	2.4	0.9	0.3	0.4	0.9	0.4	0.1	18.0
Sugar maple	E	11.1	2.4	22.6	0.2	0.0	2.8	0.8	1.4	1.7	6.1
Sweetgum	E	0.1	0.0	25.8	0.5	0.4	1.0	0.5	0.3	1.1	4.6
Utah juniper	W	0.1	0.0	7.2	0.4	0.1	0.3	2.1	1.6	1.0	15.7
Western hemlock	W	0.1	0.5	8.3	0.2	0.0	1.6	0.3	8.3	0.3	18.9
White fir	W	4.9	1.4	3.8	0.8	1.2	0.1	0.4	2.3	0.4	22.0
White oak	E	5.1	0.3	14.9	0.2	0.6	0.7	0.7	0.6	1.5	3.3
Yellow-poplar	E	1.1	0.0	15.8	0.2	0.2	0.8	0.8	1.3	0.5	2.7

E east, *W* west

[a] Divided by the 100th west meridian

[b] Vegetation

[c] This category includes several types of form defects and damages that do not typically reduce the probability of a tree's survival, but instead are intended to assess the number of trees with reduced merchantability

[d] Sum of damages for a species may differ from Table 4 due to rounding

Third, the attribution of damage to specific causal agents is complicated, and in some cases confounded, by the fact that many times, there are multiple agents at work. In some cases, these interactions have been formally termed declines or diebacks and can be recorded as such by the field crews; however, in other cases, field crews must determine which single agent to code. This issue is not particular to the FIA inventory, but is present in all assessments in which damages are attributed to specific causal agents. The conundrum is explained by Manion (1991), who described forest or tree decline as a three-stage process in which predisposing, inciting, and contributing factors operate in succession. Predisposing factors are recognized as the underlying issue, and include factors such as tree age, site or soil quality (nutrients, moisture holding capacity, etc.), aspect, elevation, and vegetative competition. Inciting factors can be single or multiple disturbances, e.g., extreme weather events or defoliation from insects, that further weaken trees already predisposed to stress. Contributing factors include insects and fungi that act opportunistically by invading or colonizing trees in a weakened state, ultimately resulting in tree mortality. Such contributing agents are typically described by entomologists and

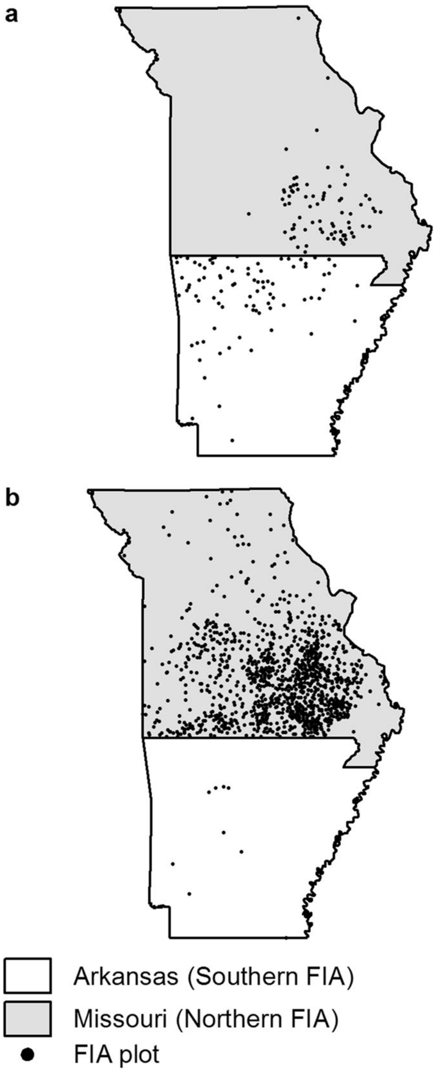

Fig. 4 Approximate FIA plot locations in Arkansas and Missouri where (**a**) the specific damage "red oak borer" (code 15026) was recorded compared to where (**b**) the general damage "boring insects" (code 15000) was recorded during FIA inventory years 2013–2017. Adapted from Dooley (2017)

pathologists as secondary or non-aggressive factors. Thus, determining an actual causal agent can be a challenge when multiple biotic and abiotic agents or conditions are present—which is more typical than not.

Fourth, the threshold at which particular agents are considered damaging is an additional factor to consider when evaluating the damage data collected by FIA. To be considered a "damaging agent," agents must generally be likely to prevent the tree from surviving more than 1 to 2 years, reduce the growth of the tree in the near term, or negatively affect a tree's marketable products (USDA Forest Service 2018). To refine these general guidelines, each causal agent (whether coded specifically or generally) has a threshold of occurrence that must be met before its presence is recorded. Some agents are coded if any evidence of damage is present, whereas other agents are recorded only when a certain proportion of the tree is damaged. For example, the generic damage "stem decay" and specific pathogens within this category are recorded when there is any visual evidence of decay, i.e., no minimum amount of damage. This may partly explain why stem decay is the most frequently recorded damage (Fig. 3). Alternatively, fire is recorded as a causal agent only when at least 20% of the bole circumference (single-stemmed species), stem count (multi-stemmed species), or crown is affected (USDA Forest Service 2018). Thus, the absence of recorded damage does not necessarily mean the absence of a damage agent. Overall, the frequency with which a damage agent is recorded is related to its probability of occurrence and the probability that it is causing damage when it occurs. Consequently, careful consideration must be given to the thresholds when summarizing the FIA data.

Despite the aforementioned caveats, the FIA survey of damage agents can provide a picture of relative incidence and impact, particularly for agents that are easily recognizable and persistent. They also can show where losses are likely to be significant and what future conditions may be if no actions are taken to remedy the causal agent. As states complete full inventory cycles with field guide versions 6 and later, we expect that the damage assessment protocol and subsequent analytical techniques will be refined to address identified shortcomings.

Using auxiliary data to assess damage

Overall, the greatest strengths of the FIA inventory are the statistical sample-based approach and the ability to measure long-term trends in vegetation change. FIA is a more-than-adequate system for documenting the long-term impacts of forest health issues by simply assessing standard forest metrics such as species distributions (trees and invasive plants), tree growth and survival, and disturbances (Vogt and Koch 2016). For example, by calculating the ratio of annual mortality to gross growth (MRATIO) for ecoregions in the USA, Ambrose (2018) identified areas where mortality was outside the range of natural variation and whether or not the mortality represented new phenomena. Then to understand possible causes of mortality, Ambrose (2018) examined the disturbance codes recorded at each plot location. Closely related to damage, disturbances are recorded by FIA field crews when at least 25% of all trees, 50% of an individual species' count, or 25% of the soil surface or understory vegetation in an area of at least 0.405 ha in size has been negatively affected, i.e., damaged or killed. Like damages, disturbances are attributed to specific agents within general categories; however, disturbances are recorded only if they have occurred since the last plot visit (typically 5 to 10 years prior, depending on region) or within the last 5 years when a plot is newly installed. Because disturbance is a stand-level variable and mortality and damage are tree-level variables, there is not always a direct cause-effect relationship. Nevertheless, disturbances provide insight into potential causes of mortality and sublethal damage. Further insight is provided by the estimation of disturbance rotation intervals (Wilson et al. 2019) which can be used to predict how often trees may be damaged by different disturbance types.

A powerful use of FIA data for monitoring forest health is to couple standard forest metrics with complementary datasets collected by federal and state forest health specialists (entomologists, pathologists, etc.) who provide a level of expertise beyond what is typically found among the FIA crews. For example, oak decline in the eastern USA has been documented for decades due to maturing oak-dominated stands growing on poor soils at high elevations with recurring exposure to intense winds, air pollution, and drought. The arrival and spread of the European gypsy moth (*Lymantria dispar dispar*) throughout this region in the 1980s introduced an additional inciting factor to the oak decline process with recurring, severe defoliation events. These defoliation events were well-documented by annual FHP aerial detection surveys (Johnson and Wittwer 2006; USDA Forest Service 2019), but not necessarily so by the FIA damage data for the previously suggested reasons. Coupling information from both sources increased the power of each as demonstrated by Woodall et al. (2010) and Morin and Liebhold (2016), who found correlations between the gypsy moth defoliation events detected by FHM aerial surveys and the growth and mortality measurements of oak trees made on FIA plots. Other examples which demonstrate the complementary nature of the FIA and FHM datasets include the following:

1. Forest pest dashboards developed for emerald ash borer (*Agrilus planipennis*), hemlock woolly adelgid (*Adelges tsugae*), beech bark disease (*Neonectria faginata* and *N. ditissima* vectored by *Cryptococcus fagisuga*), and laurel wilt disease (*Raffaelea lauricola* vectored by *Xyleborus glabratus*), which incorporate growth, mortality, and removal rates for specific hosts (FIA-derived) with the percent of host volume invaded by the pest in question, the pest arrival time, and current distribution of the pest (FHM-derived) to paint a broad picture of pest presence, distribution, and long-term impacts to the resource (https://www.nrs.fs.fed.us/fia/data-tools/data-visualizations/default.asp).
2. The National Insect and Disease Risk Map (NIDRM), which combined historical pest information (FHM-derived), host distribution (FIA-derived), and other data, e.g., elevation and soil moisture, to model and predict host basal area loss over a 15-year period for each major host (Krist et al. 2014).
3. The southern pine beetle (*Dendroctonus frontalis*) (SPB) historical database, which combines annual SPB spot data (FHM-derived) and area (acres) of loblolly-shortleaf and oak-pine forest types (FIA-derived) to describe the ongoing outbreak history of this pest from 1960 forward (Price et al. 1998; Asaro et al. 2017).
4. Summaries reported in the annual FHM National Report, e.g., Potter and Conkling (2020), which quantify trends in, and threats to, US forests using ground-collected and remotely sensed forest information (FIA-derived) and terrestrially and aerially detected insect and disease information (FHM-derived).

In addition to the standard forest metrics, FIA also assesses tree crown conditions. Collected during the summer on a portion of the total FIA plots (Morin 2020), crown condition variables describe the amount, condition, and distribution of foliage, branches, and growing tips of trees, and, like damage, are recorded at the individual tree level (Schomaker et al. 2007). Healthy, full crowns suggest carbon is being stored, the tree is growing, and that there are no serious impacts from pathogens, air pollutants, or insects. Tree crown conditions are correlated with tree survivorship, particularly among hardwood species but less so among some conifers (Morin et al. 2015b, Shaw 2007), and provide additional evidence of biotic and abiotic damage agents, e.g., Randolph (2018) and Randolph and Rose (2009).

Summary

Damage collection protocols have been included in the FIA inventory in various forms since the initiation of forest surveys in the 1930s. Inventory data available on the FIA website (https://www.fia.fs.fed.us/) provide a wealth of information for researchers, forest managers, policymakers, and others; however, changes in the damage collection protocols over time have made it difficult for the data to be used to their full potential. In this article, we have outlined these different protocols so that those interested in using the FIADB will better understand what data are available and how they can be used.

The FIA inventory is a broad, strategic inventory designed to make statistically sound estimates of forest area, tree volume, and other attributes at multi-county, state, territory, and national scales. Current data collection protocols produce temporally and spatially balanced data on a regular basis for all 50 US states, as well as some islands in the Caribbean Sea and Pacific Ocean. Year-round data collection in some areas of the country and a restriction on destructive sampling make it difficult to attribute damage to causal agents when signs and symptoms are cryptic or seasonally dependent, and the sampling intensity of the FIA inventory may be insufficient for documenting acute events and localized damage. Therefore, incorporating auxiliary FIA data, e.g., disturbance and crown condition, and ancillary datasets, such as the aerial and terrestrial detection surveys conducted by FHP, strengthens the conclusions that can be drawn.

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Data availability Not applicable

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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