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Advancing forest inventory science for enhanced insights into tomorrow's forests

1. Introduction

Forest inventory and monitoring is critically important to the long-term success of forest ecosystems, particularly given increasing levels of disturbance from wildfire, insects, disease, and human activity. Since its inception under the McSweeney-McNary Forest Research Act of 1928, and following revisions in the 1998 Agricultural Research, Extension, and Education Reform Act and 2014 Agricultural Act ("Farm Bills"), the U.S. Department of Agriculture (USDA) Forest Service Forest Inventory and Analysis (FIA) program has conducted continuous monitoring of the Nation's forest resources, growing to become an essential and trusted source of information by land managers, international researchers, policymakers, and various nongovernmental organizations (NGOs) worldwide. The FIA program is comprised of four broad focus areas. The Nationwide Forest Inventory (NFI) is a network of plots installed across all land ownerships and remeasured every 5–10 years, consisting of detailed information about tree status, damages, down woody material, and understory vegetation. The National Resource Use Monitoring (NRUM) quantifies harvested wood products manufacturing across various facilities nationwide. The National Woodland Owners Survey (NWOS) aims to better understand how private landowners plan and utilize forest resources over time. Finally, the Urban Inventory provides information on how green spaces are used in urban settings. Together, each component of FIA collects and analyzes forest resource data on an annualized schedule to deliver the congressionally mandated goal to "inventory and analyze, in a timely manner, public and private forests and their resources in the United States" (16 U.S.C. §1642(e)(1)).

Research is a fundamental component of the FIA program, leading to refined statistical inference (Affleck and Gaines, 2025; Roesch et al., 2012; Westfall et al., 2022), integration with emerging technologies (Khatri-Chhetri et al., 2025; Wiener et al., 2021), and improved insights into trends in forest health and attributes (e.g. growth, volume, biomass and carbon) (Chisholm and Gray, 2025; Quirion et al., 2021; Smith et al., 2019), among other novel data uses (e.g. Shaw, 2008; Tinkham et al., 2018). To highlight the growing and dynamic body of inventory-based research, the biennial FIA Science Symposium seeks to convene researchers, managers, and policymakers to showcase the most recent advancements in monitoring and inventory science through presentations, posters, and plenary discussions. Held virtually November 19–21, 2024, the most recent conference attracted over 700 registrants and consisted of 233 sessions spanning a wide variety of topics. This special issue highlights the expansive capacity and relevance of research arising from forest inventory data. Papers herein underscore the benefits of partnerships to enhance the diversity and applicability of FIA data, evaluate multidimensional approaches to forest stewardship, and emphasize the capacity of data analytics to enhance forest inventory science and data delivery. In addition, we include several studies that were not presented at the Symposium but highlight the global importance of NFI-based research.

2. Leveraging partnerships to advance forest inventory-based science

The success of the FIA program is due, in large part, to the productive partnerships among local, State, private, and Federal entities. From co-production of research to contracted data collection, FIA's partners contribute substantially to inventory-based science. For instance, following the adoption of National Scale Volume and Biomass (NSVB) models, an examination of the effects of model implementation identified an overall increase in biomass and carbon estimates (consistent with FIA findings by Westfall et al., 2024) due to the inclusion of treetops and limbs, which could have important implications for revaluation of timber and carbon resources (Restrepo et al., 2025). In a related study, Johnson et al. (2025a) found that existing methods, models, and maps based on FIA data are insufficient at predicting aboveground biomass using the new NSVB estimates and recommended updating current workflows to improve spatial analyses of carbon and biomass. At a finer scale, researchers from the University of Maine (Zhao et al., 2025) used FIA remeasurement data and detailed harvest information from across the state of Maine to demonstrate how ownership, soil characteristics, and climate can alter forest diversity, providing managers with important insights to achieve sustainable forest management goals.

Demonstrating the international importance of NFIs, Zhang et al. (2025) examined carbon stock models in China to reveal an average increase in ecosystem carbon of 0.166 Pg C year^{-1} between 2003 and 2021 that was largely attributed to afforestation efforts. Using remeasurement data from the Spanish Forest Inventory, Cruz-Alonso et al. (2025) showed that oak and pine recruitment depended on shrub volume and stand origin (i.e., planted or secondary), and recommended land managers consider historical land use and the facilitative function of neighboring shrubs to maximize tree recruitment. In North America, Lamping et al. (2025) unified FIA data with Forest Analysis Inventory Branch (FAIB) data from British Columbia to create 30-meter resolution maps of forest structure and carbon throughout southeast Alaska and Canada, home of the world's largest intact coastal temperate rainforest. In the diverse forests of the Caribbean, Yang et al. (2025) used a novel combination of a machine learning algorithm and mixed-models to improve predictions of diameter growth for hundreds of species in Puerto Rico and the U.S. Virgin Islands, an area regularly impacted by

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hurricanes.

3. Multidimensional approaches to forest stewardship

One of the original purposes of the U.S. NFI was to estimate timber volume and improve growth and yield models used in land management strategies. Advancements in this field continue today, as Swann et al. (2025) demonstrated by providing short-term, locally relevant calibration datasets to improve the accuracy and reduce error of the popular stand growth model Forest Vegetation Simulator (FVS). Relatedly, Itter et al. (2025) incorporated continuous forest inventory data into a Bayesian dynamical model to improve management strategies aimed at maintaining sustainable forest yields. Meanwhile, Ogana et al. (2025) used a series of differential equations to predict stand productivity and other forest attributes among the most common hardwood forest types in the southeast US. Using FIA data from the same region Fatunsin and Naka (2025) detected a strong relationship between structural diversity and ecosystem carbon storage, which could have important lessons for management strategies aimed at maximizing forest carbon uptake. Finally, Subedi et al. (2024) created a novel composite site index (CSI) that normalized species-specific site index (SI) models by the common loblolly pine (*Pinus taeda*) SI, then used random forest algorithms to create maps of CSI across the US state of Georgia to be used in conservation and timber management strategies.

Over time, the FIA program has grown beyond timber resource estimation to include a broad range of forest ecology and management research subdisciplines (Shaw, 2008). For example, Harris et al. (2025) used FIA data to model the impact of white-tailed deer (*Odocoileus virginianus*) browsing on seedling abundance, demonstrating the strong and often underappreciated effect herbivory can have on shaping forest regeneration. Recognizing that a complete carbon inventory should include assessments of belowground attributes, Pastore et al. (2025) provided numerous case studies demonstrating the strength of combining above- and belowground research from the FIA plot network, while Vickery et al. (2025) examined the statistical power needed to detect change in soil carbon from southeastern US loblolly pine forests. While reforestation has been offered as a powerful natural solution to mitigate impacts from climate warming by expanding carbon sequestration, Johnson et al. (2025b) considered the potential offset of reducing surface albedo through increased forest cover, providing managers with a joint carbon-albedo index to assess overall climate mitigation potential across forest types. Meanwhile, Wei et al. (2025) demonstrated that warming could alter forest composition in the northeast US to favor hardwood dominance, thus leading to a decline in plot-level aboveground biomass and potentially reducing the carbon sequestration capacity in the region.

The spatially balanced and panelized sampling design used in the US NFI (Westfall et al., 2022) provides a unique platform to examine disturbance patterns over space and time. Through estimation of annual areal extent of wind disturbances in the Great Lakes region, Edgar and Westfall (2025) demonstrated the importance of evaluating temporal mismatches between a disturbance event (disturbance year) and its observation (inventory year), especially for a rotating panel design like the one implemented by FIA. Using repeated measurements of plots along the western side of the Cascade Range, Chafe and Fried (2025) showed that fire severity drives variation in snag and dead wood recruitment, with important implications for wildlife management and fire reburn potential. The multidimensional nature of FIA data contributed to novel analyses of site-tree information beyond the standard estimates of capturing potential productivity of a particular plot or condition. For instance, Lu et al. (2025) recognized that age information from a subset of surveyed trees (i.e., site trees) can limit insights into stand structure and biomass change over time. To address this shortcoming, the authors developed a modeling framework that combined site-tree age information with topographic, climatic, and other environmental variables to predict tree age for every live tree in the US NFI, revealing regional differences that likely reflect disparities in land use history, disturbance, and long-term environmental conditions. In a similar study, Giebink et al. (2025) compared tree attributes (diameter and height) among all live trees and dominant/codominant trees, with trees selected for assessing site index, age, and growth (i.e., site trees, age trees, and growth increment trees; termed "indicator trees"). The authors also used a subset of trees from the northeastern US to compare growth rates among the same tree categories. Although attributes of all live tally trees and dominant/codominant individuals were rarely equivalent to those of indicator trees, differences were minor across regions, suggesting the latter adequately represent population-level characteristics.

4. Big data methods to enhance forest science and data delivery

After decades of effort to inventory forests across the US and affiliated islands, FIA data are ideally suited for novel analyses that harness enhanced computing power and statistical innovation to better inform management decisions and reveal fresh insights into forest dynamics. This is especially the case when forest inventory data are combined with complex and large remote sensing products, as Frank et al. (2025) demonstrated in their comparison of LiDAR and digital aerial photogrammetric (DAP) point clouds to predict post-fire stem density and aboveground biomass. The authors reported that although LiDAR remains the gold standard in forest structure mapping, augmenting DAP-driven models with readily available Sentinel-2 imagery is a cost-effective and accurate method that could be used by a wide range of organizations faced with post-fire management decisions.

The FIA sample design provides adequately precise estimates of forest population parameters spanning broad geographic regions (e.g., US States) and multiyear time periods (i.e., 5 – 10 years) using traditional, design-based estimators. However, demand for inferences into forest subpopulation parameters spanning sub-State geographic areas (e.g., counties, ecological regions, forest disturbance perimeters, etc.) and narrower time intervals (i.e., annual) is increasing, requiring new techniques to generate reliable estimates for these domains that are typically sparsely observed by the FIA sample network. Small area estimation (SAE) techniques (Rao and Molina, 2015) offer the potential to borrow statistical strength from extra-domain sample information, and to leverage relationships between sample and auxiliary data to improve the performance of domain-specific estimates (Dettmann et al., 2022).

SAE is a vibrant area of research in FIA and forest inventory more broadly. For example, Shannon et al. (2025) developed a unit-level spatiotemporal Bayesian modeling framework that incorporates spatially and temporally varying fixed effects and dependence structures, providing complete domain-level uncertainty quantification. Their model-based estimator achieved improvements in accuracy relative to both traditional direct estimates and other model-based small area estimators, especially when domain sample sizes were small, homogenous, or null. Wilson (2025) compared US county-level estimates of live tree aboveground biomass generated using traditional post-stratified methods (e.g., Bechtold and Patterson, 2005) with two versions of a model-assisted regression estimator, one of which (the tessellated model-assisted regression estimator) demonstrated increased efficiency relative to the direct estimator while reducing the risk of plot location confidentiality exposures. Relatedly, Doser et al. (2025) used a multivariate model that incorporated plot-level FIA tree data with climate and tree canopy cover data to estimate species-specific biomass across the southern US. Their model led to increased precision across all 20 tree species examined and nearly every county where they compared model-assisted estimates to standard design-based estimates. Overall, innovations in the field of SAE continue to provide important detail of forest attributes at scales that are in high demand by researchers and land managers alike, broadening the use of FIA data and supporting critical decision-making steps.

5. Conclusions

The science of inventory and monitoring is inherently a multidisciplinary field, attracting researchers from such diverse fields as statistics, remote sensing, silviculture, entomology, ecology, microbiology, and everything in between. The purpose of the biennial FIA Science Symposium is to highlight the diversity of inventory-based research and disseminate cutting edge insights into the complexity of forest dynamics and the implications for managing sustainable forests across a wide range of forest inventory data users and specialists. This special issue is a sample of the latest advancements in forest inventory and monitoring, demonstrating the innovative and informative uses of high-quality forest data to improve our understanding of changing forest ecosystems and address challenges facing forest ecology and management in the future.

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