Sources of Auxiliary Variables for Annual FIA Estimates

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Introduction

For over a century, the task of inventorying a nation's forests has been fundamental to its economic and ecological stewardship. What began as a laborious, ground-based effort involving field crews with clipboards and compasses has transformed into a highly technical, data-driven science. This evolution has been propelled by the integration of remote sensing—the science of obtaining information about objects from a distance, typically from aircraft or satellites. The story of the U.S. Forest Inventory and Analysis (FIA) program and its international counterparts is one of continuous innovation, marked by pivotal pilot studies that tested and proved the value of new technologies. This report traces that evolution, from the first grainy aerial photographs to the modern vision of a near real-time, globally connected forest monitoring system.

1. Early Foundations: The Age of Aerial Photography (1930s-1970s)

The concept of using remote sensing for forestry is nearly as old as aviation itself. By the 1930s, foresters like H.E. Seely in Canada were pioneering methods to identify tree species and estimate timber volume from black-and-white aerial photographs. This was a revolutionary leap, offering a synoptic view that was impossible from the ground. For decades, photointerpretation was the cornerstone of remote sensing in forestry. It was used primarily for stratification: dividing the landscape into homogenous units (e.g., softwood, hardwood, non-forest) to make ground sampling more efficient. While it saved time and money, this approach was still heavily reliant on manual interpretation and periodic, large-scale acquisitions, meaning inventories were only updated every 10-20 years.

2. The Push for Modernization: Annual Inventories and Multi-Phase Sampling (1980s-1990s)

By the 1980s, the need for more timely data became critical. In response, a series of groundbreaking concepts and pilot studies laid the groundwork for the modern inventory system.

- **Czaplewski, Raymond L., et al. (1987):** This work championed the idea of using permanent photo plots as a consistent, repeatable method for monitoring land cover change, providing a crucial bridge between intensive ground plots and broad-scale satellite data.
- **Schreuder, H. T., et al. (1995):** The Alaska four-phase inventory was a prime example of a sophisticated, multi-stage design. It strategically combined satellite imagery (Phase 1), high- and low-altitude photography (Phases 2 & 3), and ground sampling (Phase 4). This demonstrated how to efficiently tackle immense, inaccessible landscapes by progressively focusing resources.

- **Cost, Noel D. (1995):** The North Carolina pilot study was arguably one of the most influential, as it tested the operational feasibility of an *annual* inventory system. By measuring a fraction of plots each year in a panel design, it proved that timely, continuous data could be produced, leading to the eventual mandate for an annual national inventory in the 1998 Farm Bill.
- **Goebel, J. Jeffery, et al. (1998):** The Oregon Demonstration Project expanded the vision beyond just forests, exploring how to integrate surveys of various natural resources. This highlighted a move toward a more holistic, ecosystem-based monitoring framework.

3. The Annual Inventory Era: Expansion and Refinement (2000s)

The 2000s saw the institutionalization of the annual inventory system and its expansion into new domains.

- **McRoberts, Ronald E. (2000):** McRoberts articulated the strategic rationale and structure for the Annual Forest Inventory System (AFIS), which became the new standard for the FIA program, emphasizing national consistency and timeliness.
- **Nowak, David J., et al. (2008):** Demonstrating the flexibility of the FIA framework, pilot studies began adapting the protocols for urban environments. This was a pivotal expansion of scope, recognizing the importance of urban forests and proving the system could answer new ecological questions.
- **Frescino, Tracey S., et al. (2009) & Lister, Tonya, et al. (2009):** With the annual system in place, researchers focused on refining techniques. The Nevada Photo-based Inventory Pilot (NPIP) established detailed procedures for photo-sampling in arid, challenging environments, while other work developed "expedient" methods for rapidly estimating land-use change from photos.

4. The Lidar Revolution: Entering the Third Dimension (2010s)

The next great leap was the operational adoption of Light Detection and Ranging (Lidar). Unlike passive optical sensors that capture a 2D image, lidar is an active sensor that sends out laser pulses and measures their return. This provides a direct, highly accurate 3D measurement of the forest's vertical structure.

- **Andersen, H-E., et al. (2011):** The Interior West Lidar Pilot Project was a landmark study that demonstrated how airborne lidar data, when combined with FIA ground plots, could be used to create highly accurate, spatially explicit maps of forest attributes like height, volume, and biomass. This ushered in the era of "enhanced forest inventories," where the output is not just a statistical summary for a county, but a detailed map of forest conditions across the landscape.
- **Watts, Andrea, et al. (2019):** Later work in Alaska showcased the maturation of these technologies. The combination of lidar and digital photogrammetry (which also creates 3D data from overlapping photos) became the state-of-the-art solution for inventorying the vast and remote Alaskan interior.

5. Towards Real-Time Monitoring (2020s and Beyond)

The current era is defined by an explosion in data availability and processing power, pushing the goal from annual updates to continuous monitoring.

- **Coops, Nicholas C., et al. (2023):** This work outlines the conceptual framework for a near real-time inventory. The idea is to fuse the high temporal resolution of satellite constellations like Landsat and Sentinel (which revisit every few days) with the high spatial detail of lidar and the ground truth of field plots to constantly update inventory estimates as new data arrives.
- **Mulverhill, Christopher, et al. (2024):** This research provides the empirical evidence for the real-time concept, evaluating how effectively optical satellite data can track changes in forest attributes between more intensive measurements.
- **White, Joanne C., et al. (2025):** Looking at parallel efforts in Canada, this paper confirms that the push for Enhanced Forest Inventories (EFI) is an international trend. It highlights shared research needs, such as better species classification and integrating data from diverse sensors.

6. Bridging Data Gaps: The Role of Deterministic Models

While remote sensing provides a powerful spatial overview, the annual inventory system faces a temporal challenge: in any given year, only a fraction of ground plots (a "panel") are physically re-measured. To create a complete, current estimate, the data for the unmeasured plots must be updated. This is accomplished using deterministic growth and yield models, most notably the **Forest Vegetation Simulator (FVS)**.

FVS is an individual-tree, distance-independent growth and yield model that projects forest stand dynamics through time. By inputting the tree list from a plot's last measurement, FVS simulates biological processes like growth and mortality, effectively "growing" the forest forward to the current reporting year. This creates a synthetic, updated dataset for the majority of plots that were not visited.

The synergy between FVS and remote sensing is critical. While FVS can model predictable growth, it cannot account for sudden, stochastic events like fires, harvests, or insect outbreaks. This is where remote sensing provides essential information. Satellite-based change detection systems are used to identify which plots have been disturbed since their last measurement. Undisturbed plots are updated with FVS, while disturbed plots are treated differently, preventing the model from making erroneous projections. This powerful combination—using models for predictable change (growth) and remote sensing for unpredictable change (disturbance)—is fundamental to the accuracy of modern annual inventories.

7. Ongoing Challenges and Future Directions

Despite incredible progress, several challenges remain:

- **Data Fusion and Model Integration:** Integrating disparate datasets (lidar, radar, optical, ground plots) and linking them seamlessly with growth models like FVS remains a complex technical and statistical challenge.

- **High Costs and Data Processing:** While satellite data is often free, acquiring and processing high-resolution lidar or commercial imagery remains expensive and computationally intensive.
- **Cloud Cover and Saturation:** In many parts of the world, optical satellite imagery is plagued by clouds. Furthermore, in dense forests, optical and even radar sensors can "saturate," becoming insensitive to variations in high-biomass conditions.

The future of forest monitoring will likely involve a synergistic combination of technologies, including **Artificial Intelligence (AI)** for automated feature extraction, **drones (UAS)** for highly detailed local monitoring, and the continued fusion of public and commercial satellite data with sophisticated simulation models.

8. Conclusion

The evolution of remote sensing in national forest inventories is a story of moving from static, periodic snapshots to a dynamic, continuous understanding of forest ecosystems. Each pilot study and research initiative built upon the last, progressively integrating new technologies to answer questions with greater precision, timeliness, and scope. What began with interpreting shadows on a photograph has become a system that fuses 3D point clouds with satellite time-series data and sophisticated growth models to provide the foundation for sustainable forest management in an era of rapid environmental change. Czaplewski's 1999 vision of a multistage, remote sensing-driven annual inventory has not only been realized but has become the launching point for the next ambition: to monitor the pulse of the world's forests in near real-time.

References

Andersen, H. E., Strunk, J., & Temesgen, H. (2011). "The Interior West Forest Inventory and Analysis Lidar Pilot Project." In: Strunk, J., & Temesgen, H., eds. Fusing remote sensing and field data for forest inventory. Gen. Tech. Rep. PNW-GTR-851. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 1-14.

Coops, Nicholas C., et al. (2023). "Framework for near real-time forest inventory using multi source remote sensing data." *Forestry* 96(1): 1-19.

Cost, Noel D. (1995). "The North Carolina pilot study for a new annual forest inventory system." In: *Proceedings of the IUFRO XX World Congress*, 6–12 August 1995, Tampere, Finland. Vienna, Austria: IUFRO: 1-12.

Czaplewski, Raymond L., et al. (1987). "National land cover monitoring using large, permanent photo plots." In *Proceedings of International Conference on Land and Resource Evaluation for National Planning in the Tropics*, pp. 197-202.

Frescino, Tracey S., et al. (2009). "Nevada photo-based inventory pilot (NPIP) photo sampling procedures." Gen. Tech. Rep. RMRS-GTR-222. Fort Collins, CO: US Department of Agriculture, Forest Service, Rocky Mountain Research Station. 30 p.

Goebel, J. Jeffery, et al. (1998). "A study on integrating surveys of terrestrial natural resources: The Oregon Demonstration Project." EPA/600/R-98/032. Corvallis, OR: U.S. Environmental Protection Agency.

Lister, Tonya, et al. (2009). "Estimating fine-scale land use change dynamics using an expedient photointerpretation-based method." In: *Forest Inventory and Analysis (FIA) Symposium 2008*. Proc. RMRS-P-56CD. Fort Collins, CO: US Department of Agriculture, Forest Service.

McRoberts, Ronald E. (2000). "Background for AFIS, the Annual Forrest Inventory System." In: *Proceedings of the First Annual Forest Inventory and Analysis Symposium*. Gen. Tech. Rep. NC-213. St. Paul, MN: US Department of Agriculture, Forest Service.

Mulverhill, Christopher, et al. (2024). "Evaluating the potential for continuous update of enhanced forest inventory attributes using optical satellite data." *Forestry: An International Journal of Forest Research*: cpae029.

Nowak, David J., et al. (2008). "Urban forest health monitoring: large-scale assessments in the United States." *Arboriculture & Urban Forestry* 34(6): 341-345.

Schreuder, H. T., et al. (1995). "The Alaska four-phase forest inventory sampling design using remote sensing and ground sampling." *Photogrammetric Engineering and Remote Sensing* 61(3): 291-297.

Watts, Andrea, et al. (2019). "Innovation in the Interior: How state-of-the-art remote sensing is helping to inventory Alaska's last frontier." Science Findings 222. Portland, OR: US Department of Agriculture, Forest Service, Pacific Northwest Research Station.

White, Joanne C., et al. (2025). "Enhanced forest inventories in Canada: implementation, status, and research needs." *Canadian Journal of Forest Research* 55: 1-37.

Appendix: Summary of Relevant Research

Czaplewski, Raymond L., Glenn P. Catts, and Paul W. Snook. (1987)

Czaplewski, Raymond L., Glenn P. Catts, and Paul W. Snook. "National land cover monitoring using large, permanent photo plots." In Proceedings of International Conference on Land and Resource Evaluation for National Planning in the Tropics, pp. 197-202. 1987.

This paper, a precursor to much of the later work, advocated for the use of large, permanent photo plots as a tool for monitoring national land cover. The authors proposed that regular interpretation of these aerial photo plots could provide consistent, large-scale data on land cover and land use change over time. This method was presented as a practical way to bridge the gap between detailed ground surveys and broad-scale satellite remote sensing, offering a balance of detail and coverage.

Schreuder, H. T., V. J. LaBau, and J. W. Hazard. (1995)

Schreuder, H. T., V. J. LaBau, and J. W. Hazard. "The Alaska four-phase forest inventory sampling design using remote sensing and ground sampling." Photogrammetric Engineering and Remote Sensing 61, no. 3 (1995): 291-297.

This study details a four-phase sampling design implemented for the Alaska forest inventory. The approach integrated various levels of remote sensing with ground sampling to create an efficient and cost-effective inventory system. The first phase involved satellite imagery for initial stratification. Subsequent phases used high- and low-altitude photography to refine classifications and select areas for ground plots, which constituted the final phase. This multi-phase approach was designed to optimize the allocation of resources by concentrating expensive fieldwork on pre-selected, representative areas.

Cost, Noel D. (1995) "The North Carolina pilot study for a new annual forest inventory system."

Cost, Noel D. "The North Carolina pilot study for a new annual forest inventory system." In: Proceedings of the IUFRO XX World Congress, 6–12 August 1995, Tampere, Finland. Vienna, Austria: IUFRO: 1-12.

This study was one of the foundational pilot projects that tested the feasibility of shifting from a periodic to an annual inventory system. It implemented an interpenetrating panel design, where a fraction of the plots were measured each year. The pilot was crucial for developing and validating the statistical estimators and operational workflows required for a continuous inventory, demonstrating that an annual system could provide more timely data on forest trends without a prohibitive increase in cost.

Goebel, J. Jeffery, et al. (1998)

Goebel, J. Jeffery, Hans T. Schreuder, Carol C. House, Paul H. Geissler, Anthony R. Olsen, and William Williams. "A study on integrating surveys of terrestrial natural resources: The Oregon Demonstration Project." EPA/600/R-98/032. Corvallis, OR: U.S. Environmental Protection Agency, Office of Research and Development, National Health and Environmental Effects Research Laboratory. 44 p. 1998.

The Oregon Demonstration Project was a study focused on the feasibility of integrating different terrestrial natural resource surveys. The research explored methods to combine data from various agencies and monitoring programs (e.g., forestry, agriculture, environmental quality) to create a more holistic and efficient monitoring framework. The key takeaway was that while integration is complex, it offers significant benefits in reducing redundant efforts and providing a more comprehensive understanding of the landscape.

McRoberts, Ronald E. (2000)

McRoberts, Ronald E. "Background for AFIS, the Annual Forrest Inventory System." In: McRoberts, Ronald E.; Reams, Gregory A.; Van Deusen, Paul C., eds. Proceedings of the First Annual Forest Inventory and Analysis Symposium; Gen. Tech. Rep. NC-213. St. Paul, MN: US Department of Agriculture, Forest Service, North Central Research Station: 1-4. 2000.

This article provides the foundational context for the shift from periodic to annual forest inventories with the introduction of the Annual Forest Inventory System (AFIS). Building on the success of pilots like the North Carolina study, McRoberts outlines the strategic reasons for this change, emphasizing the need for more timely and consistent data to support policy and management decisions. The paper explains how an annual system allows for continuous monitoring and more rapid detection of trends.

Nowak, David J., et al. (2008) "Urban Forest Health Monitoring: Large-Scale Assessments in the United States."

Nowak, David J., Daniel E. Crane, and Jack C. Stevens. "Urban forest health monitoring: large-scale assessments in the United States." Arboriculture & Urban Forestry 34, no. 6 (2008): 341-345.

This paper describes a series of pilot studies that adapted the national Forest Inventory and Analysis (FIA) and Forest Health Monitoring (FHM) protocols for urban environments. Initiated in states like Indiana and Wisconsin, these pilots tested the feasibility of using the FIA grid to sample urban areas and collect data on tree health, species composition, and ecosystem services. This work was pivotal in expanding the scope of national inventory efforts beyond traditional forests to include critical urban ecosystems.

Frescino, Tracey S., et al. (2009)

Frescino, Tracey S., Gretchen G. Moisen, Kevin A. Megown, Val J. Nelson, Elizabeth A. Freeman, Paul L. Patterson, Mark Finco, and James Menlove. "Nevada photo-based inventory pilot (NPIP) photo sampling procedures." Gen. Tech. Rep. RMRS-GTR-222. Fort Collins, CO: US Department of Agriculture, Forest Service, Rocky Mountain Research Station. 30 p. 2009.

The Nevada Photo-based Inventory Pilot (NPIP) focused on establishing detailed procedures for a photo-sampling inventory. This report documents the methodologies for selecting, interpreting, and managing a large number of photo plots. It highlights the practical challenges and solutions in implementing a photo-based inventory, including interpreter training, quality control, and the integration of photo data with existing ground-plot information to improve the precision of estimates across large, often inaccessible, landscapes.

Lister, Tonya, Andrew Lister, and Eunice Alexander. (2009)

Lister, Tonya, Andrew Lister, and Eunice Alexander. "Estimating fine-scale land use change dynamics using an expedient photointerpretation-based method." In: McWilliams, Will; Moisen, Gretchen; Czaplewski, Ray, comps. Forest Inventory and Analysis (FIA) Symposium 2008; October 21-23, 2008; Park City, UT. Proc. RMRS-P-56CD. Fort Collins, CO: US Department of Agriculture, Forest Service, Rocky Mountain Research Station. 10 p. 2009.

This research presents a streamlined, "expedient" method using photointerpretation to estimate fine-scale land use change. The authors developed a practical approach that could be implemented quickly to generate timely estimates of change dynamics, which is crucial for monitoring things like deforestation, urbanization, or agricultural expansion. This work underscores the value of photointerpretation as a flexible tool for specific monitoring objectives.

Andersen, H-E., et al. (2011) "The Interior West Forest Inventory and Analysis Lidar Pilot Project."

Andersen, H. E., Strunk, J., & Temesgen, H. "The Interior West Forest Inventory and Analysis Lidar Pilot Project." In: Strunk, J., & Temesgen, H., eds. Fusing remote sensing and field data for forest inventory. Gen. Tech. Rep. PNW-GTR-851. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 1-14. 2011.

This large-scale pilot project tested the integration of airborne lidar data with FIA ground plots to improve forest inventory estimates across vast areas of the Interior West. The study focused on developing methods to use wall-to-wall lidar data to create precise, high-resolution maps of forest attributes like biomass and canopy structure. It was a key step in demonstrating the operational utility of lidar for creating "enhanced" forest inventories and moving beyond traditional plot-based statistical estimates.

Watts, Andrea, et al. (2019)

Watts, Andrea, Hans-Erik Andersen, Bruce Cook, and Mike Alonzo. "Innovation in the Interior: How state-of-the-art remote sensing is helping to inventory Alaska's last frontier." Science Findings 222. Portland, OR: US Department of Agriculture, Forest Service, Pacific Northwest Research Station. 5 p. 2019.

Returning to Alaska, this publication showcases how modern, state-of-the-art remote sensing technologies are being used to tackle the immense challenge of inventorying the state's remote forests. It highlights the use of technologies like lidar and digital photogrammetry to derive detailed forest structure information that was previously impossible to obtain at scale. This represents a significant leap forward from the earlier multi-phase sampling designs, driven by technological innovation.

Coops, Nicholas C., et al. (2023)

Coops, Nicholas C., Piotr Tompalski, Tristan RH Goodbody, Alexis Achim, and Christopher Mulverhill. "Framework for near real-time forest inventory using multi source remote sensing data." Forestry 96, no. 1 (2023): 1-19.

This paper proposes a conceptual framework for achieving a near real-time forest inventory. The authors describe a system that leverages the high temporal resolution of modern satellite constellations (e.g., Sentinel, Landsat) and integrates them with various other data sources (e.g., lidar, ground plots) and advanced modeling techniques. The goal is to move from periodic or even annual updates to a system where inventory attributes are updated continuously as new remote sensing data becomes available.

Mulverhill, Christopher, et al. (2024)

Mulverhill, Christopher, Nicholas C. Coops, Joanne C. White, Piotr Tompalski, and Alexis Achim. "Evaluating the potential for continuous update of enhanced forest inventory attributes using optical satellite data." Forestry: An International Journal of Forest Research (2024): cpae029.

Building on the near real-time concept, this research evaluates the practical potential of using optical satellite data to continuously update enhanced forest inventory attributes. The study tests how well changes detected in satellite imagery correlate with changes in key forest metrics, assessing the accuracy and limitations of such an approach. This work provides empirical evidence for the feasibility of the framework proposed by Coops et al. (2023).

White, Joanne C., et al. (2025)

White, Joanne C., Piotr Tompalski, Christopher W. Bater, Michael A. Wulder, Maxime Fortin, Chris Hennigar, Geordie Robere-McGugan, Ian Sinclair, and Robert White. "Enhanced forest inventories in Canada: implementation, status, and research needs." Canadian Journal of Forest Research 55 (2025): 1-37.

This paper provides a comprehensive overview of the status of Enhanced Forest Inventories (EFI) in Canada, which parallels efforts in the United States. It outlines how Canadian agencies are integrating remote sensing data, particularly from lidar and satellites, to produce more detailed and spatially explicit inventory products. The authors also identify key research needs and operational challenges, offering a forward-looking perspective on the future of forest monitoring.

Synthesis of Lessons Learned

Across these studies, several key themes and lessons emerge:

1. **Multi-Stage/Multi-Source Integration is Key:** From the early four-phase design in Alaska (Schreuder et al., 1995) to the modern near real-time frameworks (Coops et al., 2023), it is clear that no single data source is sufficient. Effective forest inventory relies on the strategic integration of satellite data, aerial photography, advanced sensors like lidar (Andersen et al., 2011), and ground plots.
2. **The Enduring Value of Photo Plots:** Photointerpretation remains a critical component of large-area forest inventory. As proposed by Czaplewski et al. (1987) and refined in studies like Frescino et al. (2009) and Lister et al. (2009), photo plots provide a vital link between broad-scale satellite observation and intensive ground measurement, especially for classifying land use and monitoring change.
3. **The Drive for Timeliness and Expanded Scope:** The shift from periodic to annual inventories, tested in pilots like North Carolina (Cost, 1995) and institutionalized by McRoberts (2000), marked a major change. The most recent research pushes this further towards continuous, near real-time updates (Coops et al., 2023). Simultaneously, pilot studies like the Urban FHM work (Nowak et al., 2008) show a successful expansion of the inventory's scope to new and critical ecosystems.
4. **Technology is a Primary Driver of Innovation:** The evolution from the sampling designs of the 1990s to the enhanced inventories of today is directly tied to advancements in remote sensing technology. The operational integration of lidar, as tested in the Interior West pilot (Andersen et al., 2011), and the use of dense satellite time-series data represent major technological leaps that enable far more detailed and current assessments.