

Northern Research Station

Rooted in Research

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Monitoring Fuel Loads and Prescribed Fire Effects with Terrestrial Laser Scanning

Monitoring fuel loads and treatment effects are critical in planning and evaluating prescribed fire and wildfire operations, but gathering data is difficult at management scales. Monitoring data allow managers to quantify fuel hazards, run fire behavior simulations that inform how prescribed fires and wildfires may progress under different weather and forests, and evaluate ecological impacts of different management decisions.

New monitoring approaches with terrestrial laser scanning (TLS) developed by Northern Research Station scientists and partners are revolutionizing vegetation monitoring and helping managers collect better monitoring data faster and more easily than ever. This issue of *Rooted in Research* summarizes four recent papers on advances in TLS.

KEY MANAGEMENT CONSIDERATIONS

- Terrestrial laser scanning can provide fuel structure and biomass estimates to describe forest conditions and management outcomes and gather fuel inputs for fire behavior models.
- Terrestrial laser scanning can scan a plot in under a minute—a fraction of the time it would take a person to collect data using traditional means—and can be done with the push of a single button.
- As field methods and data analysis procedures improve, Northern Research Station scientists are developing clear and open-access protocols describing how to use TLS technology with field data to optimize the monitoring of forest condition and management outcomes, especially those related to wildland fire. The protocols will enable managers to adopt the TLS approach and increase their ability to document and describe management needs and outcomes.

Scientists at the Silas Little Experimental Forest conduct field experiments in conjunction with laboratory experiments to improve our understanding of fire behavior. USDA Forest Service photo by Michael Gallagher.

What Is Terrestrial Laser Scanning?

Terrestrial Laser Scanning (TLS), also called terrestrial LiDAR (Light Detection and Ranging), is a ground-based type of LiDAR. TLS is a remote sensing technology that uses laser pulses to collect detailed data that describes vegetation structure in three dimensions. A laser range finder placed on a tripod sends out laser pulses in all directions. When these pulses hit an object and bounce back, the laser range finder records the three-dimensional coordinates of these points in space. TLS is particularly useful for capturing high-resolution data used to detect the location and physical structure of forest biomass such as available fuels along with their type and arrangement.

TLS data are useful for describing the dimensions of “hard features” like tree trunks or downed woody debris and the density of “soft features” like shrubs and forest canopies. Its high resolution (exceeding 10 to 100 times the point density of airborne LiDAR) and understory perspective make TLS far superior for identifying and measuring vegetation beneath the canopy where fuel treatments are typically focused but is poorly measured by other remote sensing techniques (e.g. airborne LiDAR, multi-spectral data).

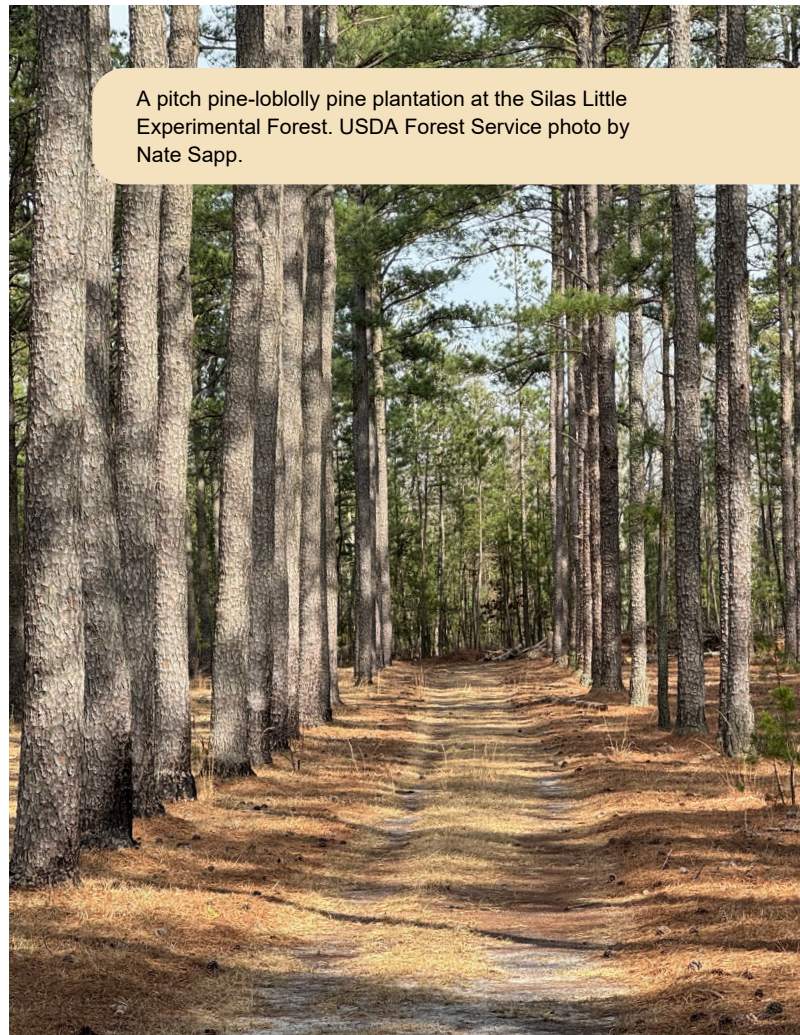
Technological advances have reduced the cost of a TLS laser range finder to an operationally reasonable price (i.e., less than \$30,000), while skill level for use has been simplified to pressing a single button, making it more feasible for managers to use TLS to inform management decisions. Advances have also improved the speed; some versions can scan a plot in under a minute, greatly increasing the number of plots that can be visited in a day.

When TLS measurements are made in conjunction with existing field measurements of vegetation and fuel structure, it is possible for TLS measurements alone to impart information about vegetation and fuel structure without managers needing to make additional measurements themselves. For this to be done, though, it is important to fully understand how TLS metrics relate to traditional fuel data and to develop the best statistical protocols for relating TLS measurements to traditional fuels data.

For instance, traditional fuels monitoring approaches use sampling and estimation techniques across a small subset of vegetation to infer fuel load properties about the rest of the fuels that are not measured. TLS works similarly, collecting a vast amount of information about the location, arrangement, and color of vegetation that comprises fuel and fire effects. However, where traditional methods typically use tallies of fuels observed, height and diameter data for trees, and limited information about canopies and ladder fuels, TLS scan data can be distilled into hundreds of statistical properties about the quantity, three-dimensional distribution, patterning, and coloring of vegetation from the surface up to through the forest canopy. Relationships between these statistical descriptors of a plot and standard fuel load metrics are then used to convert TLS data outputs to fuels and fire effects information.



Terrestrial laser scanning, also known as terrestrial LiDAR, is a remote sensing technology that uses laser pulses to collect detailed topographical data and vegetation structure. Airborne LiDAR often misses structures beneath the forest canopy, but terrestrial laser scanning can measure small trees and shrubs, making fuel load measurements more accurate and improving fire treatment plans and firefighter safety. USDA Forest Service photo by Nate Sapp.



A pitch pine-loblolly pine plantation at the Silas Little Experimental Forest. USDA Forest Service photo by Nate Sapp.

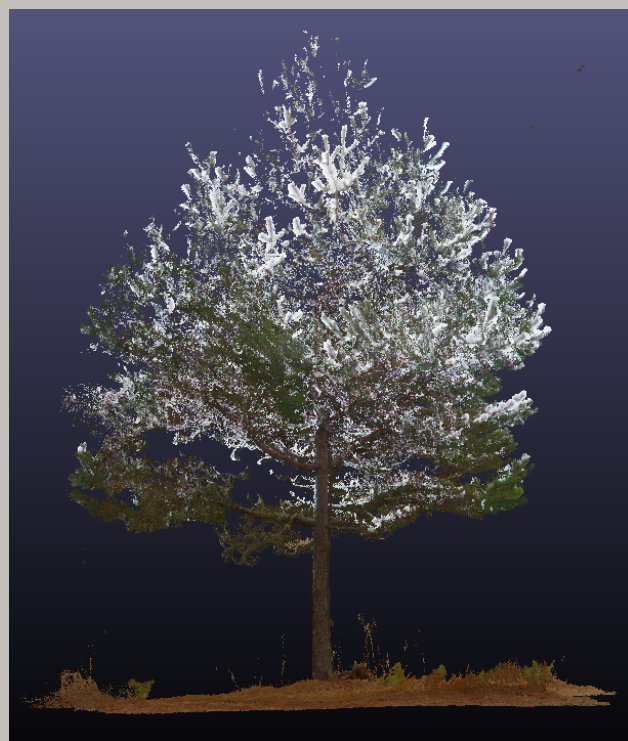
This section summarizes [A simplified and affordable approach to forest monitoring using single terrestrial laser scans and transect sampling](#).

How Is TLS Used to Measure Fuel Characteristics?

Developing and testing the relationships to convert TLS output metrics to standard fuel load terms is an ongoing focus of Michael Gallagher and Nicholas Skowronski, research scientists with the USDA Forest Service Northern Research Station, who have partnered with Louise Loudermilk of the USDA Forest Service Southern Research Station and collaborators at West Virginia University and the New Mexico Consortium. The team initially developed a simple transect-based method by physically estimating a limited range of surface fuel conditions in tandem with TLS scans, which provided a starting point for developing and testing these relationships across vegetation types. Currently the team is refining these methods to better understand the importance of phenology (i.e., seasonal changes in vegetation, such as leaf presence or absence) and to develop best practices for efficiently collecting adequate physical measurements for driving TLS data conversion processes. For example, the team has found that fewer random samples may be sufficient for estimating certain shrub-layer characteristics in either dormant or growing season conditions.

Acknowledging that many management agencies may not have in-house TLS data storage or analysis capabilities, the USDA Forest Service, the US Fish and Wildlife Service, and the New Mexico Consortium have partnered with the US Geological Survey to host a web-based data repository and processing hub called IntELiMon (Interagency Ecosystem Lidar Monitoring).

A pitch pine-loblolly pine plantation at the Silas Little Experimental Forest. USDA Forest Service photo by Nate Sapp.



Terrestrial laser scanning uses laser pulses to collect detailed information such as topographical data and vegetation structure. The top image is of a pitch pine tree. The bottom image is of the same tree, recorded using TLS. This image demonstrates the high resolution and precision TLS offers in recording forest structure. USDA Forest Service photos by Michael Gallagher.

This section summarizes [Terrestrial laser scan metrics predict surface vegetation biomass and consumption in a frequently burned southeastern U.S. ecosystem.](#)

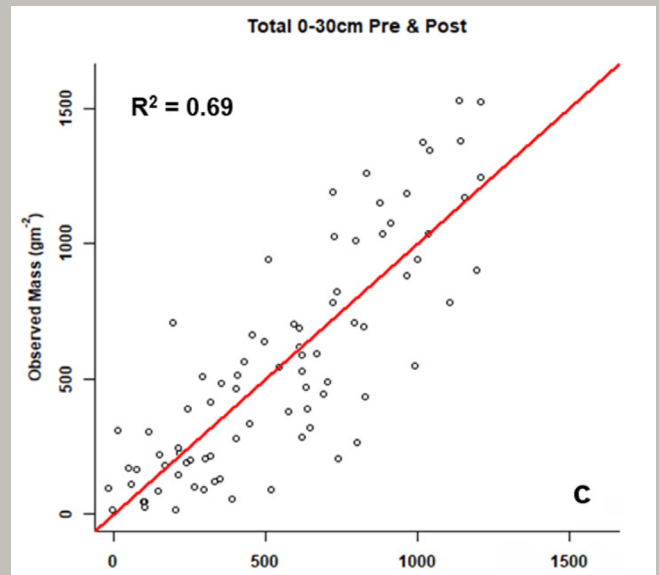
How Well Does TLS Predict Fuel Biomass?

Estimating fuel biomass and its location in the forest are among the most time-consuming components of fire modeling used to evaluate fuel hazard, potential fire behavior, and carbon tradeoffs of wildfire and fuels management. Biomass is often estimated by harvesting fuel in the field and bringing it into the lab to be sorted, dried, and weighed, which is very time consuming, or via visual means, which are much faster but prone to error. Louise Loudermilk and other scientists at the Southern Research Station are leading a cross-station effort to evaluate how well TLS can estimate fuel biomass quickly and accurately.

In one investigation, scientists paired TLS measurements with biomass measurements made in a lab. They conducted this research in two burn units on the Fort Stewart-Hunter Army airfield, a longleaf pineland in the Coastal Plain region of southeastern Georgia. From 41 plots, they harvested fuel from “clip plots” of $0.5 \times 0.5 \times 1$ m. They clipped and removed all the fuel from the clip plots and brought it to a lab to be sorted, dried, and weighed. They established one clip plot before burning and one after burning in each plot. Fuels clipped in these plots were separated by layer (ground to 30 cm and 30 to 100 cm) and then into 10 categories based on the type of fuel (e.g., woody live vegetation, conifer litter, pinecones, and so on). In these same plots, the researchers also ran TLS scans, making TLS measurements before and after prescribed burning. With these TLS data, they ran linear regression models to see how well they could predict different fuel biomass categories using TLS data.

Overall, the researchers were able to predict pre- and post-burn biomass well. Their best predictions were of pre-fire total fuel biomass measured from the ground to 30 cm, where there are a lot of different fuels to capture (live grasses, tall shrubs, leaf litter) that have not burned yet. Explicit categories of fuels were also captured in their predictions, including fine woody debris (dead tree branches) and fine fuels (small sticks, grasses, forbs, dead leaves). These predictions explained more than half of the variability in biomass measurements (61 to 71 percent, respectively). Predictions of both pre- and post-burn biomass from the scanner provided accurate estimates of variable surface biomass consumption, which are important for prescribed fire management reporting of fuel treatment effectiveness.

These promising results could reduce the need to harvest fuels in the field and the labor associated with making biomass measurements, which in turn could increase managers’ ability to nondestructively estimate pre-burn biomass. These biomass measurements could then be used as inputs in simulation models that predict fire behavior. Additional research is needed to evaluate how well TLS measurements can be used to predict biomass in other ecosystems.



Observed vs. predicted surface biomass for the total 0-30 cm vegetation and fuel mass class using pre- and post-burn ($n=82$) linear model. This graph illustrates that structural measurements from terrestrial laser scans predict 69 percent of the variable surface biomass (shrubs, grasses, dead leaves) using pre- and post-fire data ($n=82$) and statistical linear modeling. Source: Loudermilk et al. 2023.

Interagency LiDAR Monitoring and Research Applications

Monitoring programs are critical for managing natural resources because they provide ways to quantify current and changing land conditions. Results can help to guide the decision-making process.

The LiDAR Monitoring Project consists of partners from federal agencies and the New Mexico Consortium working together to develop efficient methods for monitoring natural and cultural resources and to provide effective decision-support tools for land managers. This multidisciplinary project seeks to integrate LiDAR and modeling techniques to monitor fuels and ecosystems and link fire modeling for land management decision support. The goal is to standardize monitoring across agencies with uniform language, methods, and data analysis.

This section provides an overview on [Estimation of plot-level burn severity using terrestrial laser scanning](#).

How Well Does TLS Predict Burn Severity?

Burn severity is the magnitude of ecological change caused by fire and is commonly used to describe heterogeneity in fire effects and ecological consequences of wildfires. Monitoring wildland fire burn severity is important for assessing ecological outcomes and fire patterns, and for guiding efforts to mitigate or restore areas where ecological outcomes are negative. Products that map burn severity are typically created using satellite reflectance data, but these products need to be calibrated to field data to be useful. The composite burn index (CBI) is the most widely used field-based method used to calibrate satellite-based burn severity data; however, limitations of CBI need to be resolved.

CBI is a visual assessment of fire effects made in the field that complements two-dimensional fire effects captured by remote sensing; it integrates understory and midstory effects of fire with two-dimensional burn severity measurements. CBI measurements typically pertain to substrates (e.g., soil and rocks), low shrubs and herbs, tall shrubs and herbs, pole-size trees, and tall trees. Because CBI measurements are visual assessments, they tend to be subjective and prone to human error.

In a recent study, USDA Forest Service scientists Gallagher, Skowronski, and Loudermilk collaborated with researchers at West Virginia University, the New Jersey Department of Environmental Protection, and Swedish University of Agricultural Science to leverage TLS as a tool for evaluating burn severity following a prescribed fire in New Jersey, further testing the potential benefits of TLS as a fast, consistent, and repeatable approach that requires minimal field expertise and training.

The researchers used TLS data to create metrics of change based on the loss of organic matter, which provided a detailed characterization of forest structure before and after the prescribed burns.

To evaluate how well TLS data estimate burn severity, researchers delineated 43 plots in the New Jersey Pinelands National Reserve and measured CBI in the plots before and after they were burned. They also took TLS measurements and visible-spectrum camera (RGB) measurements before and after burning. In relating these TLS and RGB measurements to their CBI measurements, they tried three different statistical approaches: traditional linear regression and two machine learning algorithms (random forest and support vector machines).

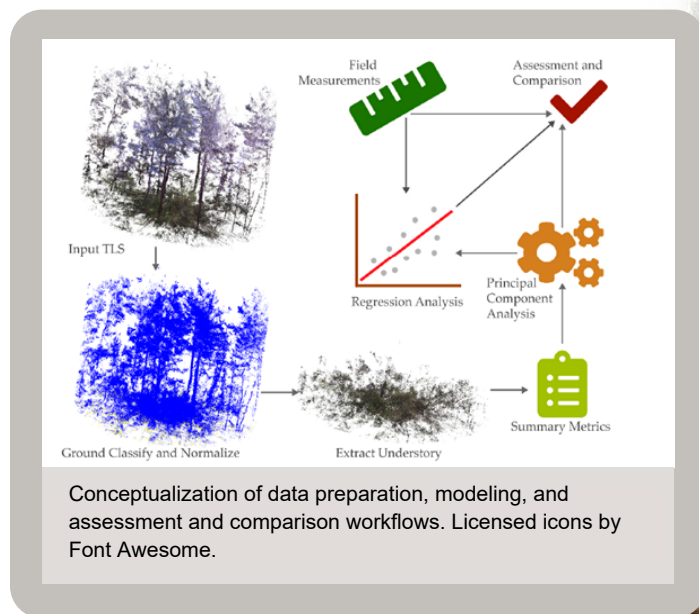
The findings indicate that the random forest machine learning algorithm outperforms multiple linear regression and is more effective at predicting burn severity. The study introduces

various metrics, including 70 TLS-based variables and 10 RGB-based variables, offering a comprehensive understanding of forest structure and spectral conditions. This extensive set of variables allows a more nuanced and accurate prediction of burn severity, surpassing the limitations of traditional methods like the CBI.

Crucially, the study identifies inconsistencies in the correlation between CBI data and the loss of organic matter across different forest layers. Canopy CBI and TLS burn severity exhibit the highest correlation, suggesting that TLS provides a more consistent and tractable method for assessing burn severity. This insight is particularly relevant for forest resource managers because it highlights the potential for TLS to redefine burn severity metrics at prescribed burns with a focus on specific layers.

Moreover, the study addresses challenges associated with TLS, such as merging multiple TLS and RGB scan collections, shading inconsistencies, occlusion issues, and limitations of exporting TLS data in certain formats. It underscores the importance of considering these factors for a more accurate estimation of burn severity.

In summary, the results support the efficacy of TLS coupled with machine learning algorithms in providing a more sophisticated and reliable assessment of burn severity. The approach improves the quality and pace of burn severity observations and presents an opportunity to redefine how forest resource managers monitor fire effects and integrate data into their management strategies.



This section summarizes [Impact of reference data sampling density for estimating plot-level average shrub heights using terrestrial laser scanning data](#).

How Much Reference Data Are Needed for TLS?

When evaluating TLS for estimating fuel structure, it is important to know how much reference data are needed to match TLS measurements with fuel data. Gallagher, Skowronski, and Loudermilk recently partnered with scientists at West Virginia University, Tall Timbers Research Station, and the New Mexico Consortium to evaluate the sensitivity of TLS measurements to reference data in pinelands, specifically to determine how many shrubs were necessary to measure in a plot for TLS to accurately estimate shrub height.

The researchers ran TLS scans in 27 plots that represented a broad range of fire history and burning intensity throughout the New Jersey Pinelands National Reserve. Researchers first measured the height of 40 randomly selected shrubs. Next, they created regression models to predict mean shrub height from a combination of TLS variables; using multivariate statistical techniques, they reduced the 54 variables that TLS could measure down to 8 combinations of these variables. To see how the number of shrubs measured would influence the ability of TLS measurements to predict shrub height, they randomly selected 2 to 40 shrubs from each plot and used them to calculate mean shrub height in each regression model.

From these analyses, they determined that TLS was not able to accurately predict shrub height when fewer than 10 shrubs per plot were measured. The accuracy of TLS predictions of shrub height increased with each additional shrub measured from 10 to 20 shrubs per plot, but there was no substantial benefit to measuring more than 20 shrubs. These results help refine the type and amount of reference data needed to use TLS to predict shrub height.

These results best pertain to pinelands in New Jersey; ecosystems with more homogenous shrubs might require fewer shrubs to reach the same level of accuracy. Repeating studies like this one in other ecosystems used in prescribed burning will help scientists and managers know how much reference data to collect to effectively pair TLS and fuel measurements to inform fire behavior models in other areas.



Research ecologist Michael Gallagher using a terrestrial laser scanner at the Silas Little Experimental Forest. USDA Forest Service photo by Nate Sapp.

Silas Little Experimental Forest

Nearly 100 years ago, the State of New Jersey and the USDA Forest Service signed a cooperative agreement to form the Silas Little Experimental Forest. The core themes of research at Silas Little include wildland fire and forest restoration. Using a coproduction model, scientists and managers continue to work together to define science and application needs, conduct experiments, and disseminate the results of their work through workshops, trainings, and demonstrations. Today, the Silas Little Experimental Forest produces and facilitates significant contributions to prescribed fire research, drawing scientists from across the country and the world. Terrestrial laser scanning is one of the emerging technologies being researched at Silas Little for monitoring fuels distributions in forests.

A pitch pine lowland in Stafford Forge Wildlife Management Area that was burned in a 2023 wildfire. USDA Forest Service photo by Nate Sapp.

Outlook and Future Directions

Much of the research conducted by Northern Research Station scientists on the use of TLS in fire modeling pertains to frequently burned pinelands, primarily in New Jersey. Future research in other frequently burned ecosystems would help evaluate the use of TLS beyond the scope of research presented here and further facilitate the use of this technology by managers. Coupling TLS measurements with insights derived from airborne LiDAR is also another future avenue for innovation.

In addition, new studies focus on using TLS to improve forest carbon estimation and carbon tradeoffs of fires and fire management and using LiDAR to build libraries of digital plant structure information that can be used to develop realistic wildland fire simulations in a virtual environment for fire research, planning, and firefighter training.

TLS is a promising tool that, with further refinement and testing, can improve the accuracy of model inputs used to predict fire behavior. As scientists at the USDA Forest Service and elsewhere conduct this research, the use of TLS will continue to become more feasible and operational for managers, enabling more accurate predictions of fire behavior. More accurate predictions will help managers plan safe and effective prescribed burns and integrate potential wildfire effects into forest management decisions.



Mike Gallagher (Northern Research Station) and Louise Loudermilk (Southern Research Station) demonstrate TLS after a wildfire for Latonya Williams (Bahamas Forestry Department) and Brittany Harris (Florida International University). USDA Forest Service photo by Joe O'Brien.

PROJECT LEADS

[Michael Gallagher](#) is a research ecologist with the Physical and Ecological Fire Processes, Interactions, and Applications research unit of the Northern Research Station.

[Nick Skowronski](#) is a project leader and research forester with the Physical and Ecological Fire Processes, Interactions, and Applications research unit of the Northern Research Station.

[Louise Loudermilk](#) is a research ecologist with the Athens Prescribed Fire Science Laboratory, Center for Forest Health and Disturbance, Southern Research Station.

FURTHER READING

Gallagher, Michael R.; Maxwell, Aaron E.; Guillén, Luis Andrés; Everland, Alexis; Loudermilk, E. Louise; Skowronski, Nicholas S. 2021. [Estimation of plot-level burn severity using terrestrial laser scanning](#). Remote Sensing. 13(20): 4168. <https://doi.org/10.3390/rs13204168>.

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