USDA Forest Service
U.S. DEPARTMENT OF AGRICULTURE

Rocky Mountain Research Station
Science You Can Use Bulletin
SEPTEMBER / OCTOBER 2023 | Issue 63

Eyes in the Sky: Using drones for forest monitoring

Imagine being able to take a bird's eye view of the forest: you could see the forest structure, how the trees are grouped, the height and size of each tree in a matter of moments as you cruise over. You could fly over the stand today, then again next year and examine the effects of a treatment or a wildfire or an insect outbreak. Uncrewed aerial systems (UAS - aka drones) are starting to allow managers to do just that.

In recent decades, forest management objectives and priorities have shifted. Instead of being primarily focused on timber production, forest management plans now promote a wide range of ecosystem services. This includes managing to promote carbon sequestration, habitat quality, and forest resiliency against disturbance and stress. Additionally, there is now an emphasis on restoring forest structural heterogeneity. That is—moving away from even-aged stands, with the trees all looking the same, to stands with a diversity of tree sizes, ages, and groupings. Forests with appropriately sized gaps and variable tree sizes can allow for tree seedling establishment, increase resilience against disease, enhance wildlife habitat, and more. To meet these objectives, managers need a lot of information about forest spatial patterns as well as the ability to monitor a site over time and in response to treatments or disturbances.

As the emphasis on restoring heterogeneous forests has expanded in recent decades, many managers and collaborative groups acknowledged that existing forest monitoring strategies weren't necessarily able to provide the right metrics to inform prescriptions and assess treatments effects. Traditional, field-based monitoring can describe average conditions within a stand but falls short of depicting the spatial distribution

Aerial photo of a dry conifer forest from UAS (uncrewed aerial system) perspective. USDA Forest Service photo by Wade Tinkham.

of forest structure elements. Field-based monitoring can be extremely time and personnel intensive as well as potentially dangerous for field crews monitoring post wildfire or in insect-infested stands. Satellite-based and commercially sourced remote sensing products, such as light detection and ranging (LiDAR) mounted on aircraft, are intended for landscape-scale data acquisitions and may be too expensive or broad for managers to target specific treatment areas, especially for multiple monitoring periods. Using commercially sourced remote sensing data means managers will not necessarily have control over the physical extent of the data or the timing of data collection. Due to the constraints and limitations with field-based monitoring and commercial data, remote sensing technologies have been adapted for on-the-fly stand-level monitoring by small drones/UAS. UAS-based monitoring is gaining interest and capacity for use as an alternative method for collecting data to support local forest management activities—especially to measure forest heterogeneity and monitor ecosystem services.

Wade Tinkham, a Research Forester with Rocky Mountain Research Station, has been working with fellow U.S. Forest Service researchers and colleagues at Colorado State University to bring UAS-based monitoring methods into the hands of managers. UAS-based methods have the potential to significantly increase inventory precision, reduce crew time in the field, and improve the level of data available for management decision making. Data can potentially be taken more frequently, allowing managers to get rapid feedback on the effects of treatments or monitor after natural disturbances and adapt as needed. Professional grade UAS have recently become more accessible to consumers with entry-level equipment costing under $2000. Despite the low price point, UASs typically have highly accurate GPS receivers, automated navigation systems, and sensors capable of very high-resolution remote sensing.

Reducing hazards for field crews

Due to a combination of climate change, increased insect and pest infestations, and severe wildfire events, many forests are becoming more hazardous for field crews to work in than in the past. Hazards include large numbers of standing dead and down trees (snags and logs) and potential for flash flooding. Managers are increasingly considering risk reduction for field crews conducting on-the-ground forest monitoring and post-fire activities. UAS-based monitoring has the potential to augment field inventories and help mitigate risk to field crews.

A U.S. Forest Service field crew member stands near potential hazard trees. USDA Forest Service photo.

So how exactly does UAS-based monitoring work?

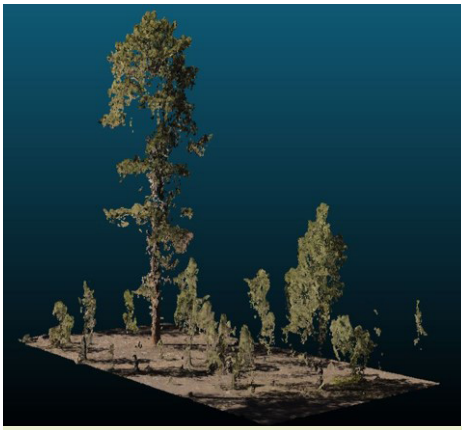
Although there are multiple ways to use drones for data collection, Tinkham and colleagues primarily study UAS photogrammetry methods. Typically, this involves mounting a high-resolution camera on a drone to capture imagery as it flies. It captures overlapping photographs from different angles, which can be processed to estimate three-dimensional structures from two-dimensional photographs using a technique called Structure from Motion (SfM). The imagery is developed into point clouds where each point is a coordinate with a known X, Y, and Z location on the ground or on a tree in our case. Putting the collection of points together creates a representation of the tree and forest structures. The higher the point density, the more defined the features are, resulting in better representations of the trees. Structure from Motion (SfM) photogrammetry with UAS acquired high-resolution imagery can produce point cloud data densities exceeding 1,000 points/m^2—which is an approximately 10X higher point cloud density than most plane-based LiDAR! Using the point cloud data, analysts and researchers can extract common forest monitoring measurements, including tree location, height, DBH, tree groupings, and forest biomass estimates.

Best practices for UAS-based monitoring and data processing

There are many exciting uses for UAS-based monitoring, but as with every emerging technology, there is a need to understand the best methods and limitations before managers can implement it. Validated workflow strategies and data processing steps are needed to accurately translate the data into information that managers can use. Tinkham and colleagues are currently taking a deep dive examining the best methods for collecting, cleaning, and preparing the data collected from UAS. They compare their results to field-based inventories of 100% tree census coverage to ground-truth the accuracy of their products. Tinkham says of this work: “Expanding, re-envisioning, and validating techniques for UAS-based monitoring has required understanding how data acquisition and processing impact the efficiency and quality of the forest inventory metrics being produced.”

“Expanding, re-envisioning, and validating techniques for UAS-based monitoring has required understanding how data acquisition and processing impact the efficiency and quality of the forest inventory metrics being produced.”

– Wade Tinkham,
RMRS Research Forester



High density point clouds show details of individual trees as well as forest structure. USDA Forest Service photo by Wade Tinkham.

MANAGEMENT IMPLICATIONS

- UAS technology is currently best used for monitoring tree to stand-level metrics in low to moderately dense conifer forests. Field inventories may be better in denser forest types or for monitoring understory plant communities, while commercially sourced remote sensing data is best for larger, landscape-scale monitoring efforts.
- The near census quality inventory data that can be derived from UAS observations allows silvicultural treatment plans to go beyond monitoring averages. Prescriptions can be developed to include tree-level variation and stand structural diversity to meet objectives around forest heterogeneity and ecosystem services.
- Implementing UAS technology has potential to substantially reduce or eliminate the need to place field crews in hazardous, post-disturbance environments. UAS data acquisitions begin with a GIS exercise in the office and can often be completed with limited time in the stand.
- Having spatially explicit tree-level observations from UAS monitoring will allow for metrics that have only been considered in research to be implemented in management, such as using infrared sensors for early disease detection and describing the spatial arrangement of trees.

How to use UAS for monitoring:

1 ID your monitoring goals, data needs, & ecosystem constraints: UAS-based monitoring is not always the best option, depending on the ecosystem type, the scale of the project, and the data needs. What is the target ecosystem for monitoring? Tinkham and colleagues have found that UAS technology can accurately inventory tree metrics in low to moderate density forests (<60% canopy coverage). Most of their studies have taken place in ponderosa pine dominated dry conifer forests. UAS-based monitoring does not do as well at tracking individual trees in more dense and productive forest types. UAS-technology is primed for use in low-density forests and woodlands, where carbon storage, habitat quality, and disease or wildfire effects need to be monitored. Additionally, UAS photogrammetry methods are best at characterizing dominant overstory trees (~97% of overstory trees are detected), but not as good at detecting the smaller understory trees (only ~67% understory

UAS-based forest monitoring is currently best used in open canopy dry conifer forest stands, such as the ponderosa pine forests found in the Black Hills Experimental Forest, where some of the group's research has been conducted. USDA Forest Service photo by Mike Battaglia.

trees are detected). There is a need for future work to investigate how UAS methods could transfer to denser, more species diverse forest types. What is the scale of monitoring needed? UAS-based monitoring is great for tree to stand level measurements, but there are still issues around collecting landscape-scale data. "I see managers opting for UAS to target specific treatment units of limited spatial extents, when broader scale coverage (such as airborne LiDAR is better suited to provide) is not needed or cost effective. Commercial LiDAR collections are very expensive at the small scale but make sense for baseline inventories or for larger regional planning.", explains Andy Hudak, Research Forester at RMRS.

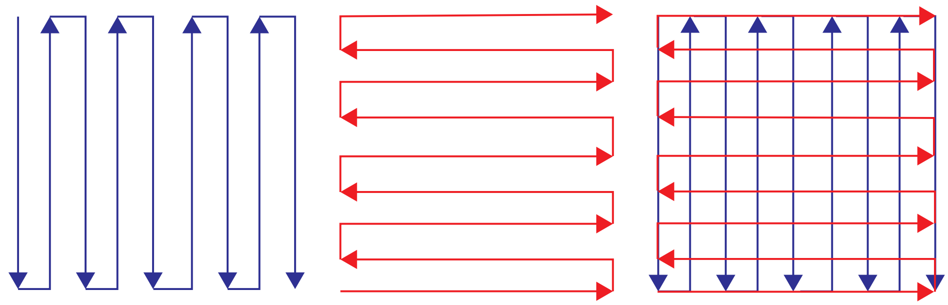
2 **Understand drone regulations:** The United States Federal Aviation Administration (FAA) regulates drone activity and licensing. There are specific regulations that impact UAS-based monitoring—for example, the remote pilot in command of the system must maintain a line of sight with the aircraft throughout each flight. All drones must be registered with the FAA and after March 2024 must be compliant with the FAA remote identification requirements. Drone flying can also be impacted by variations in airspace restrictions (e.g., airports and military installations) and land ownership. Drones are prohibited in National Parks and other sensitive areas. Individual agencies, landowners, or companies may have their own requirements to consider. For the USDA Forest Service, additional requirements are laid out in the Forest Service Standards for UAS Operations guide. When asked about barriers to implementing UAS-based monitoring in forest management and planning, Colorado State Forest Service's Geospatial Data and Analyst Program Manager, Nic Kotlinski, replied, "Getting permission to fly on the landscapes we work in can be difficult. Despite good connections locally and regionally with partners, the bureaucracy is difficult to get through. We need better communication and agreements across boundaries and agencies to build partnerships and trust when using these technologies.".

3 **Define and map your site boundaries:** Once you have determined that UAS-based monitoring is a good fit for your needs, there is some office work that needs to happen to prepare and map the UAS flight. First, users will need to define their site's boundaries and flight extent in a GIS mapping environment. The flight extent should be ~100 ft larger in each direction than the necessary site boundaries to ensure good data coverage. Understanding the terrain within the site boundaries will help inform the UAS flight path options. Users will also need to determine if ground control points are needed for the flight based on the spatial accuracy needed for the resulting data or images. These distinct markers are collocated with a survey-grade GPS and deployed during the UAS flight so they can be used to anchor the data in space.

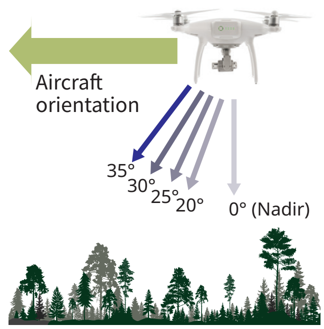
To prepare for monitoring in the field, UAS users will first need to define the site boundaries, flight extent, and possibly control points in a GIS mapping environment. USDA Forest Service photo by Wade Tinkham.

4 **Set up the UAS flight and camera parameters:** How the UAS gets programmed to fly over the site (e.g. flight speed, direction, pattern, altitude, etc.) will have major implications on how long it takes to collect data and the quality of the resulting images and data. Tinkham and colleagues systematically tested different flight patterns, flight altitudes, and camera orientations. **Flight pattern:** The research group found that flying the UAS using a crosshatch ("crisscross") flight pattern, increased data accuracy (~30% increase in DBH accuracy, for example). However, flying this pattern nearly doubles time in the field, internal hard-drive storage, and processing time, compared with flying a more basic serpentine ("side-to-side") pattern. Additionally, it is best

to program the flight pattern to parallel elevational contour lines as much as possible. This saved battery life when trying to maintain an altitude above the ground and keeps the imagery at a constant resolution. **Flight altitude:** Researchers studied the best and most efficient flight height. The best data quality and model performance was when the UAS was flying at altitudes greater than 4 times a stand's Lorey's Height (the average tree height weighted by tree basal area). Images taken from higher altitudes provide more efficient flight times as each image covers a larger area. However, the FAA limits the maximum flight altitude at 400 feet above ground level without specific waivers. **Flight speed:** Increasing the UAS speed will allow data to be collected more quickly, but will it negatively impact data quality. Tinkham and colleagues found that flying the UAS moderately faster, at speeds up to 4 m per second (~9 mph) could further improve the rate of data acquisition without compromising data quality. **Camera orientation:** The angle of the camera as the UAS flies over a stand impacts the perspective of how we see the forest. Using off-nadir camera angles (adjusting the camera angle to 2-40%; not shooting the camera straight down from above) resulted in small improvements in plot- and stand-level metrics but posed data processing challenges. In most platforms, users can get away with using the "auto" setting for most other camera operations. Overall, research has found that there will always be trade-offs between collecting the highest quality data vs. being able to efficiently process data to meet realistic time and computational constraints.



A. North-South Serpentine B. East-West Serpentine C. Crosshatch



D. Off-Nadir Camera Angle

Researchers tested 3 flight pattern options (panels A-C) and multiple camera angles (panel D). They found that using a crosshatch flight pattern (panel C) and off-nadir camera angles (angling the camera to not be directly down) can slightly improve results.

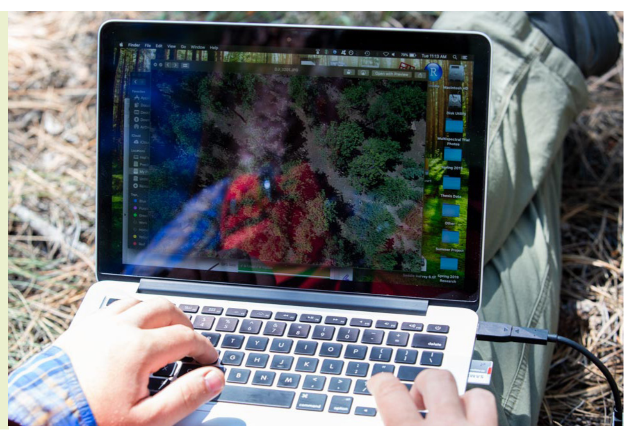


Image quality and resulting data from UAS monitoring depends on the flight and camera parameters. Wade Tinkham inspects the UAS images to ensure quality and accuracy while in the field. USDA Forest Service photo by Wade Tinkham

Read more about setting up UAS parameters

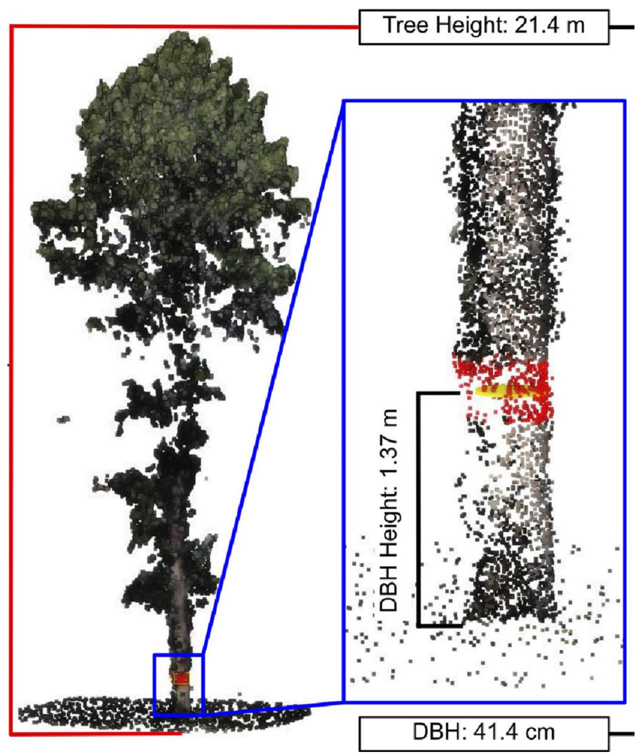
- Influence of flight parameters on UAS-based monitoring of tree height, diameter, and density
- Influence of UAS flight altitude and speed on aboveground biomass prediction

5 **Fly the drone out at the site:** It is best practice to thoroughly inspect the area surrounding your flight for any obstacles that might pose an aerial hazard before flying. If being used, the ground control point locations visually established using GIS imagery at the office should be placed in matching locations in the field in a way that maximizes visibility from the air (e.g., small canopy openings distributed across the site). Typically, it is best to fly within a couple of hours of solar noon to minimize shadowing and ideally when there are either no clouds or continuous cloud cover to achieve consistent illumination conditions. Additionally, most UAS cannot operate in rain and better results will be achieved when winds are calm. Finally, when you are comfortable with the site conditions, users can launch the UAS and initiate the pre-programmed flight mission. Most UAS only offer 15-30 minutes of flight time per battery, so it is good practice to land the UAS with 20% battery remaining, even if this means you need to use multiple flights to complete a project. It is best practice to inspect the images for accuracy and to make any corrections while out at the site.

Colorado State University Ph.D. student Lauren Lad launches the UAS for its pre-programmed monitoring flight mission. USDA Forest Service photo by Wade Tinkham.

6 **Process & filter the data, fill in the data gaps:** UAS-collected data needs to be processed and cleaned to turn it into metrics that can be used by managers. First, the raw images need to be turned into 3D spatial data point clouds that represent the trees and forest. To do this, Tinkham and colleagues have codified a Structure from Motion (SfM) photogrammetric survey workflow using Agrisoft Metashape software. The point clouds then need to be filtered to remove faulty points below ground and above the canopy.

Once the point clouds have been generated and filtered, forest inventory metrics can be extracted. There are many data processing packages and algorithm options available for extracting tree metrics. The resulting data quality will be influenced by the software packages that the researcher or analyst chooses to use. Tinkham and colleagues evaluated several different R software packages to be able to recommend the best data-processing codes for extracting individual tree location and crown area. They found that, in general, individual tree detection rates were highest when using models with adaptive variable window detection (a method that allows analysts to extract trees of all sizes). Tree crown area estimates were most accurate



Researchers and analysts can use a mix of UAS-derived data and Forest Service Forest Inventory and Analysis (FIA) data to model tree DBH and other metrics that are difficult for the UAS to measure directly. USDA Forest Service image by Wade Tinkham.

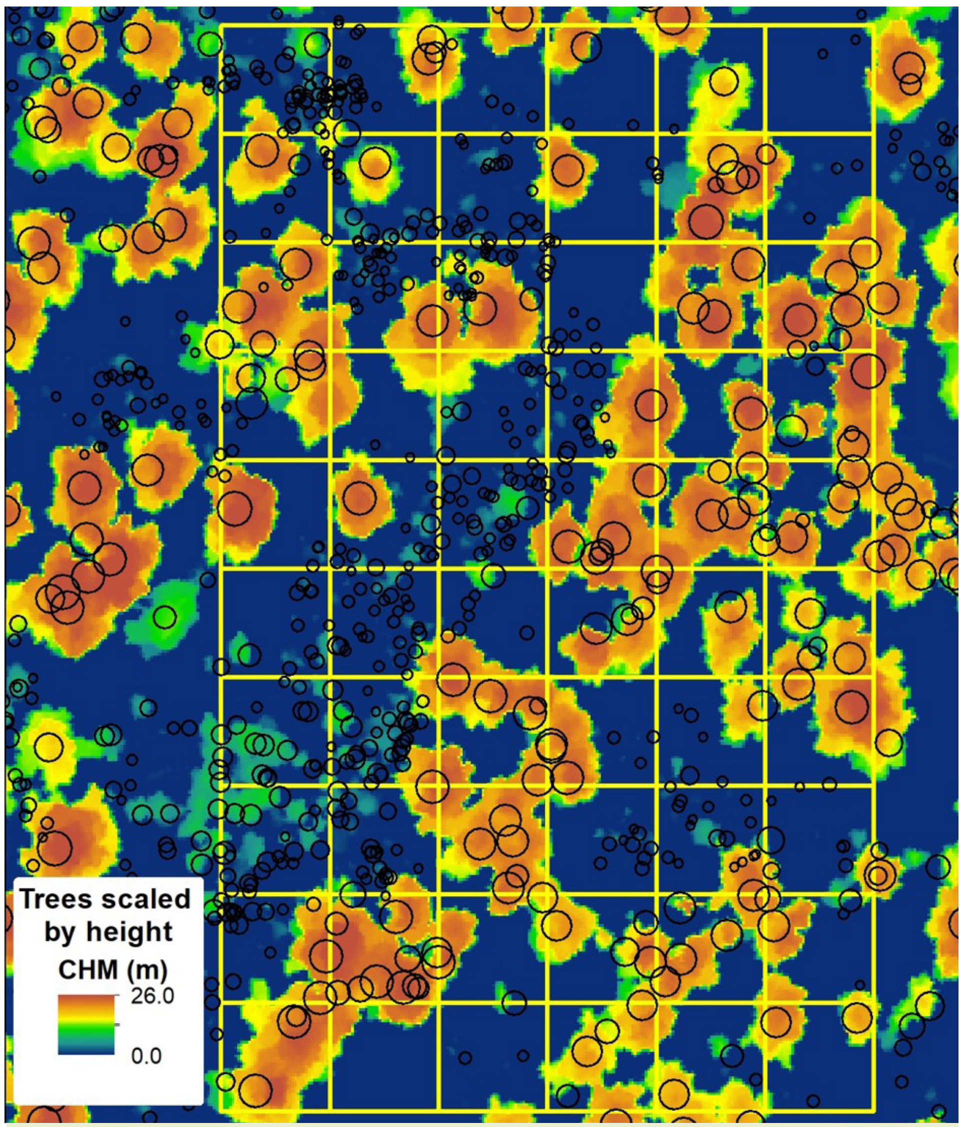
Read more about data processing and filling in the data gaps

- Influence of Agisoft Metashape Parameters on UAS Structure from Motion Individual Tree Detection from Canopy Height Models
- Application of unmanned aerial system structure from motion point cloud detected tree heights and stem diameters to model missing stem diameters
- Modeling the Missing DBHs: Influence of Model Form on UAV DBH Characterization
- Potential for individual tree monitoring in ponderosa pine dominated forests using unmanned aerial system structure from motion point clouds

7 Create meaningful results and products: From the resulting data, there is still some translation that needs to happen to create meaningful results for land managers and owners. The data outputs can be processed to provide maps, graphs, and other visualizations of the stand density, stand or tree structural patterns, or to estimate stand

and representative of on the true crown dimensions when using an R software package that processes data at higher resolution (specifically, they recommend the lidR watershed method, which processes at the pixel-level).

Because the original images were collected from above the canopy, UAS-collected data will always have trouble "seeing" or capturing some of the understory plants, small trees, and horizontal branch structure. Tinkham and colleagues have figured out how to model some of that missing data to get more complete forest structure monitoring using regionally specific data from the Forest Service's Forest Inventory and Analysis (FIA) program to create an expected relationship between tree height and DBH. Developing these models and recommended workflow has been a key part of the group's research to help managers apply new techniques.



The UAS collected monitoring data can be displayed as maps or figures, such as the tree canopy height figure above, to provide managers and researchers with relevant information. USDA Forest Service image by Wade Tinkham.

biomass. Currently, processing the data to developing user-friendly, meaningful metrics and maps can take a long time and a lot of technical expertise. However, there are forthcoming data visualization applications and workflows that will produce sharable, stand-alone products and maps to reduce data processing turnaround times. For example, Colorado State University PhD student Lauren Lad is addressing this challenge by adapting existing tree extraction algorithms into sharable, stand-alone products and maps that can be used to quickly process data collected from UAS. The goal is to allow land managers to monitor their sites and adjust their management plans all in the same week. Another advancement on the horizon is a way to connect drone augmented inventory data with the Forest Service's Forest Vegetation Simulator software for projecting and comparing various silvicultural alternatives in the same way managers currently do with traditional forest inventory data.

Colorado State Forest Service expands the use of UAS in their monitoring program

Colorado State Forest Service FAA licensed drone operators and visual observers in the field. Photo courtesy of Nic Kotlinski, Colorado State Forest Service.

The Colorado State Forest Service (CSFS) provides technical forestry assistance, wildfire mitigation expertise, and outreach and education to help landowners and communities achieve their forest management goals. Additionally, under agreements with the Colorado State Land Board, multiple agencies including the Colorado State Forest Service, Colorado Parks & Wildlife and Jackson County concessionaires and private individuals cooperatively manage the Colorado State Forest, a 71,000-acre state trust property in north-central Colorado. The CSFS currently has over 10 foresters and staff members spread across the state who are FAA Part 107 licensed. They use drones to gather photos and videos of pre and post management treatments to share with landowners and other managers interested in seeing a bird's eye view of their property. CSFS is working with Wade Tinkham on developing technical workflows for implementing UAS-based technology in their forest monitoring program. Amanda West Fordham, Associate Director of CSFS's Science and Data Division, says that they are "excited about the ability to monitor change over time at a localized scale" using UAS-based monitoring. Looking forward, Tinkham and CSFS colleagues are working to expand the relevance of UAS technology into different ecosystem types. For example, they want to validate a workflow and process for monitoring in pinyon-juniper woodlands, where the tree structure is very different from the ponderosa pine forests where much of the existing research has been conducted.

How are managers using UAS for forest monitoring?

Managers and foresters are currently using UAS-based inventories for a variety of purposes. Some examples include: tracking change over time for silvicultural prescriptions, measuring changes pre vs. post treatment, assessing wildfire risk, generating spatially referenced locations to inform management plans, producing aerial photography or video footage to share with land owners when discussing fuel reduction treatments, and planning fuel management treatments. Ultimately, UAS technology could allow organizations to receive feedback and monitoring data more rapidly about forest treatments, allowing for more flexible and responsive adaptive management.

KEY RESEARCH FINDINGS

- Monitoring of pre- and post-treatment ponderosa pine stands found that greater than 90% of individual trees could be extracted from UAS data, with tree heights and DBHs having mean errors less than 0.5 m and 3 cm, respectively.
- Field collection of UAS data requires less than 2 minutes per acre and results in stand-level basal area estimates within 4–15% of field censused values, with the largest errors in characterizing small, suppressed trees.
- UAS were able to derive metrics of groupy-clumpy forest structure (e.g., number of trees per clump, within clump height variation, opening size, etc.) with no statistical difference compared to field-derived values.
- UAS observations can provide a map of tree locations with associated height and DBH values in low to moderate (< 60%) canopy closure conditions, providing the necessary tree attribute data for precise prescription development and treatment effectiveness assessment.

What does the future of UAS-based forest inventory and monitoring look like?

UAS-based monitoring has emerging technologies and applications on the horizon. Using a drone outfitted with infrared and multispectral sensors may be able to assess tree health and forest conditions in new ways. For example, Colorado State University PhD student Lauren Lad is studying the use of UAS imagery to estimate conifer drought stress to inform management and thinning operations. Infrared stress signals given off by trees may be used to identify drought stressed trees or detection of insect outbreaks before they are even visible on the ground. Lad comments on the future applications of her research: “With the ongoing mega drought in the Western US, being able to assess the drought status of individual trees will help managers identify trees that can be removed to improve the health of remaining trees and to lower crown fire risk.”. Additionally, we may soon be able to better monitor the recovery of a landscape post wildfire—for example by being able to estimate slope stability. Sophisticated methods for managers to measure the results of prescribed fire or restoration efforts on landscape-scale forest structure, heterogeneity, and successional patterns are emerging because of UAS forest monitoring efforts.

Tinkham is often asked whether he expects UAS-based monitoring to replace traditional field-based inventories—he does NOT think this will be the case. Instead, he envisions that—“We are headed towards a system of augmented inventories”—where field and UAS techniques will be used together to get the best possible information.

RESEARCHER AND MANAGER PROFILES

The following individuals were instrumental in the creation of this Bulletin.

WADE TINKHAM, Ph.D. is a research forester with the Rocky Mountain Research Station. Wade's research focuses on improving the reliability of data and tools available to support land managers. He and collaborators are working to make UAS-derived forest inventory data accessible for forest management and planning.

ANDY HUDAK, Ph.D. is a researcher with the Rocky Mountain Research Station who studies a variety of remote sensing applications for land management. Andy works to provide managers with better tools and information for measuring vegetation patterns, forest fuels, and ecosystem carbon/biomass.

MIKE BATTAGLIA, Ph.D. is a research forester with the Rocky Mountain Research Station. Mike's research centers around developing and implementing innovative management strategies to enhance forest resiliency to disturbances and evaluating the ecological impacts of these activities.

LAUREN LAD is a Ph.D. student in Colorado State University's Forest Biometrics Lab. Her research is focused on the use of drones for high resolution fire effects monitoring to help inform land managers on the risk and impact of fires.

AMANDA WEST FORDHAM, Ph.D., is the Associate Director of the Science and Data Division for the Colorado State Forest Service. Amanda coordinates Forest Health, Forest Monitoring, Geospatial Data and Analysis, Experiential Learning, and Applied Research programs, as well as the Forest Inventory and Analysis Program at CSFS through a cost-reimbursable agreement with RMRS. Amanda can be reached at Amanda.West@colostate.edu

NIC KOTLINSKI is the Geospatial Data and Analysis Program Manager for the Colorado State Forest Service. Nic manages the Colorado Forest Atlas, Colorado Wildfire Risk Assessment project, and the CSFS GIS team. Nic has a background in geospatial applications for conservation and scientific research including remote sensing and hydro-geomorphic modeling in the U.S. Mountain West and tropical South America. Nic can be reached at Nicholas.Kotlinski@colostate.edu

ETHAN BUCHOLZ, Ph.D. is the Forest Monitoring Program Manager for the Colorado State Forest Service. Ethan can be reached at Ethan.Bucholz@colostate.edu

WRITER'S PROFILE

HANNAH FARRELL, Ph.D., is a Science Delivery Specialist in the Rocky Mountain Research Station's Forest and Woodland Ecosystem Program. Hannah is excited about science synthesis and co-production of science between land managers and researchers.

About the
Science You Can Use Bulletin

The purpose of SYCU is to provide scientific information to people who make and influence decisions about managing land.

Nehalem Clark: Bulletin Editor / Science Delivery Specialist
nehalem.clark@usda.gov

Jessica Brewen: Bulletin Editor / Science Delivery Specialist
jessica.brewen@usda.gov

To subscribe online to future Bulletins via email, click here. Previously published Bulletins are posted on our website at: https://www.fs.usda.gov/research/rmrs/products/sycu.

You may also be interested in regular science delivery bulletins similar to Science You Can Use, produced by the Pacific Northwest, Northern, and Southern Research Stations, as well as Forest Service Research and Development: PNW Science Findings, NRS Rooted in Research, SRS CompassLive and R&D newsletter.

The Rocky Mountain Research Station is one of 7 Forest Service Research & Development units nationwide. Within the 12 state RMRS footprint, we maintain 14 research locations; conduct long-term ecological research on 14 experimental forests, ranges and watersheds; and work in hundreds of research natural areas.

https://www.fs.usda.gov/research/rmrs

X (formerly twitter): @usfs_rmrs

facebook: @fsresearch

flickr

vimeo