

MAPPING NATURAL FOREST STANDS WITH LOW-COST DRONES

T. WILLIAMS*, B. WILLIAMS, B. SONG, T. L. O'HALLORAN, J. FORSYTHE

Clemson University, Baruch Institute of Coastal Ecology and Forest Science, Georgetown, SC, USA

**Corresponding Author*

ABSTRACT. We used a low-cost hobby drone to produce high resolution aerial photographs of a 12 ha mature longleaf pine (*Pinus palustris*) stand. The photos were combined into orthophoto mosaics and digital surface models to produce repeatable crown maps. Repeated flights allowed the use of tree phenology to separate longleaf from loblolly (*Pinus taeda*) and pond (*Pinus serotina*) pines, as well as some hardwood species. Careful ground control was necessary to produce aerial crown maps that matched field measured stems. However, average crown area/stem basal area ratio of 15 m radius plots produced correlation coefficients comparable to open single tree measures, ground control improved the relationship especially for loblolly and pond pine. With ground control height measurement was comparable to SfM (Surface from Motion) research results but had a positive bias greater than 1m. The most difficult problem was determining individual trees associated with a mapped crown area. Height measures were hampered by our inability to determine a correction for the true ellipsoid height of the camera.

Keywords: Structure from Motion, tree delineation, plot inventory, longleaf pine, southeast US.

1 INTRODUCTION

Over the last few years, research using unmanned aerial vehicles (UAV, or “drone”) to measure forest structure and volume has increased (Torresan et al. 2017, Anderson et al. 2019). Orthomosaics, digital surface models (DSM) and point clouds produced by Structure from Motion (SfM) analysis, are well established techniques for remote sensing of forested land (Dandois et al. 2017). Research projects have demonstrated UAV photography to measure tree heights (Birdal et al. 2017), forest volume and biomass (Bedell et al. 2017), species specific volume estimates (Bohlin et al. 2012), biodiversity and canopy gaps, (Bagman et al. 2018), forest health (Näsi et al. 2015) and fire detection (Yaun et al. 2017). Although most projects have been in Europe (Torresan et al. 2017), projects have been published spanning the tropics (Kachamba et al. 2016) to near the arctic (Pulti et al. 2016).

To achieve such a wide variety uses, UAVs have been equipped with many different types of sensors; ranging from: standard visible RGB camera, RGB camera with near infra-red usually substituted for the blue channel, mid-range infrared, thermal infrared, and multispectral sensors, as well as LiDAR. (Torresan et al. 2017). Air-

frames varied from rotary winged, with four, six, or eight rotors, and fixed wing from 90cm to 2.9m wingspan. Most research studies were on small plots, from less than one (Wallace et al. 2016) to ten hectares (Gitelson et al. 2014), although areas of 40-50 ha have been studied with fixed wing airframes (Aicardi et al. 2016). Most studies used commercial airframes with sensors attached, although some used self-assembled or contracted custom applications. A few used commercial UAVs equipped with visible RGB cameras. The use of a gimbal mounted sensors minimized problems of pitch and roll for SfM analysis on many of the latest systems. Costs of UAV systems vary as widely as the uses and sensors employed. Airframes alone vary from under \$1000 for smaller quadcopters to over \$15000 for fixed wing models (Anderson et al. 2019).

Non-industrial private landowners account for over 48% of American forest land (Smith 2004), management of these lands has been a concern for decades (Skok and Gregersen 1975). Chief among those concerns was the small size, <100 acres (40 ha), of many of these ownerships (Birch 1996) and the lack of financial resources to pursue forest management. An inexpensive method to measure the structure and volume of a small

landowners' woodlot in a timely manner can be a solution to that part of the challenge of non-industrial private landowners to better manage their forest land. Former research clearly shows that UAV technology can accurately measure the volume and structure of small woodlots, but many of these solutions include expensive, custom combinations of airframes and sensors. The goal of this project was to evaluate a simple, inexpensive, UAV project to create stand volume and structure information that would be useful for a small woodlot owner.

With a low-cost drone we produced point clouds that could be manually interpreted to produce satisfactory measures of tree position, height, and crown area for individual trees in a field (Williams et al., 2018). However, measuring widely spaced trees in an open field does not assure that drone photography will be useful in a natural forest setting. In this paper we describe application of low-cost drone photography at a small stand scale (12ha, 40 ac) in a natural 80 year-old longleaf pine (*Pinus palustris*) stand. Preliminary results using the drones' internal sensors for geo-positioning were presented at the 2019 Southern Forest GIS Conference.

In that presentation we had assumed the cost of surveying highly accurate ground control points would defeat the advantages of a low-cost drone. Those results were soundly criticized for lack of ground control. That criticism led to re-analyzing the data after a set of surveyed ground control points were added and the drone mosaics and DSMs were geo-referenced to accurate ground positions. This paper will compare the results of data collected using the drone internal sensors and the data collected from carefully ground controlled photography

2 METHODS

A 40-meter-tall eddy –covariance flux tower (Dabberdt et al., 1993) has been located on Hobcaw Forest in eastern Georgetown County, SC (Figure 1) to examine carbon and water exchange between the atmosphere and a mature stand of longleaf pine on sandy coastal soils. As part of the Ameriflux network (Novick et al., 2018), the tower measures turbulent gas and energy exchange between the forest and the atmosphere in a region around the tower known as the flux footprint. In our case, we estimate that 90% of the flux footprint is contained within a 200 m radius around the tower. The standard protocol to characterize forest conditions associated with the tower data is to locate FIA level 2 plots (Bechtold and Patterson, 2005) within the footprint area, and six level 2 plots were located within the footprint area of this tower.

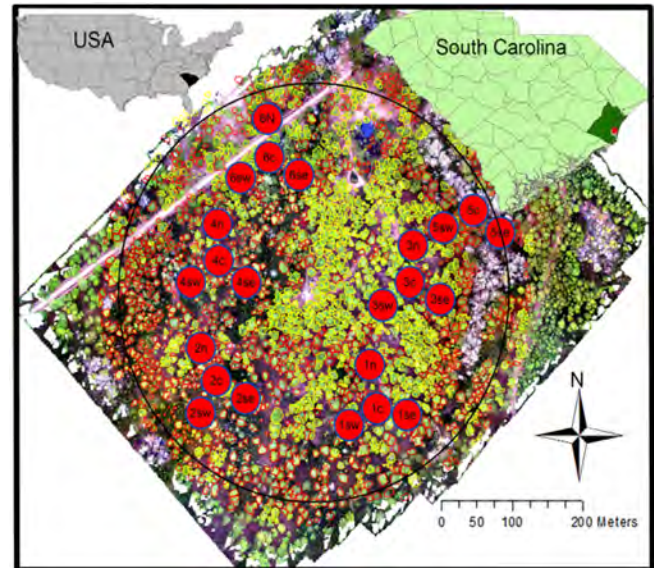


Figure 1: Distribution of pine species within a 200 m radius of a tower located in eastern Georgetown County SC, based on visual classification of orthomosaic. Yellow polygons were classified as longleaf pine crowns and red polygons as loblolly or pond pine crowns. The February 2019 orthomosaic is shown. Location of the six, FIA-Level 2 style inventory plots are larger red circles.

The primary application of the flux tower is to examine the processes associated with carbon assimilation and evapotranspiration of the sensed footprint area. Rather than the lumped statistics needed for the regional synthesis, distributed values of leaf area by tree species were needed to characterize carbon assimilation and water balance in the local stand. The goal of the drone project was to map the stem and crown distribution within the 12.6 ha circle around the tower.

The tower is located near the center of Hobcaw Forest (79°14.7'W, 33° 19.4'N) on a site primarily on Leon soil, a sandy soil with high water table. Traditional biometric data were measured in six FIA level 2 style plots (Figure 1). Overall average density was 302 tree/ha and 21.45 m²/ha basal area. Longleaf pines were 50% of the stems and 56.8% of total basal area with average diameter at breast height (DBH) of 30.4 cm and height of 15.1m. Loblolly pines were 28.3% of stems and 25% of basal area with an average DBH of 26.5 cm and height of 14.5m. Pond pines were 21.7% of stems and 14.8% of total basal area with an average DBH of 22.7 cm and height of 12.9m.

All photography was captured with a DJI Phantom 4 Pro drone flying at a height of 80m. At that altitude, the 20 mP (megapixel) scene was roughly 100 m x 50 m with a pixel of slightly over 2 cm. All photography was

captured as vertical photos during autonomous flights, using the Litchi flight control software (Litchi, 2018) running on an Android system tablet. Digital photographs were saved and processed as JPEGs. Parallel flight lines were placed 25 m apart and the drone flew at 13.8 km/h (3.6 m/s) capturing images every 2 seconds. The drone was oriented to capture images with the photo long axis perpendicular to the flight line. That spacing and airspeed resulted in 80% overlap and 75% sidelap. Sixteen flight lines, averaging 350 m long, covered an area slightly larger than the tower footprint. Photography was flown as two missions, each 3.2 km long, lasting approximately 20 minutes. Roughly 400 photos were captured in each mission. Successful missions were flown May 18, Sep. 20, Oct. 9, Nov. 8, Dec. 6, 2018; and Feb. 27, 2019.

Photographs were processed (both missions in a single batch) using Photoscan and later renamed Metascape SFM software (Agisoft, 2019). Photo locations were transformed into a projected coordinate system (NAD 83 UTM Zone 17N) prior to point matching. For all missions, a dense point cloud was created and used for orthomosaic and digital surface model (DSM) creation. Uncorrected orthomosaics were treated in two ways. Originally the May 18, 2018 was rectified to match a 1:6000 ortho rectified aerial photograph, flown in 2009, and all subsequent orthomosaics were rectified to that image. The image had roughly the same resolution and positional accuracy that a landowner might derive from Google Earth images in this region.

For the comparative analysis RTK (Real-time kinematic) surveyed reference ground control points were located at 22 vegetation plot centers, described below, two concrete monuments, and 16 well locations. Each well was a 5cm PVC pipe 3m into the ground with a concrete pad and reinforcing bar in the concrete to measure water table elevation. Surveying was done in RTK mode with Trimble R8 dual phase receivers. Reference was to a local benchmark located by static survey using three, >2-hour occupations, corrected by OPUS (NGS Online Positioning User Service). The local benchmark was located in a forest opening <500 m from the tower. At each RTK surveyed point a 30 x30 cm black and white target was located over the point. On February 27, 2019, another set of photographs were taken. The orthomosaic from these photographs was geo rectified to the RTK survey points that were visible. The rectification matrix created during geo-referencing the orthomosaic was used to geo-reference the DSM for that mission.

Six FIA level 2 measurement plots were randomly located within the tower footprint area (Figure 1). Each plot consisted of four 15 m radius subplots, one at the plot center and three others located 25 m from the plot center at 0°, 120°, and 240°. Plot centers were surveyed

with the same RTK system used for ground control points. Trees on each subplot were located by azimuth and distance from the sub-plot center with a Suunto azimuth compass and laser rangefinder. Trees were tallied by species, DBH, and height. An RTK fix could not be obtained for one subplot in dense hardwood. That subplot was not used in subsequent comparisons to drone photography.

3 RESULTS

3.1 Analysis based on mosaics from drone internal GPS rectified to May 11, 2018 mosaic.

A GIS layer was created from the table of FIA surveyed trees using coordinate geometry with the azimuth and distance to the plot center to add X, Y coordinate locations of each tree stem. A second layer, crown projected areas for longleaf and loblolly+pond pine, was digitized using the appearance in the May 18, 2018 orthophoto. At that time the white buds and new growth of longleaf pine made that species distinguishable from other pines. While pines could be distinguished from hardwoods, loblolly and pond pines were indistinguishable and grouped for further analysis. The footprint area had very little hardwood (Figure 1) and some species could be separated by phenology of leaf drop and fall colors.

Accuracy of the crown polygons was evaluated in a manner like Wang et al. (2008). A 15 m buffer layer was created around each of the 23 located subplot centers. The May rectified DSM and crown polygon layers were clipped with the plot center buffer to create a layer of only the FIA measured plots. Those layers were overlaid with a color-coded layer of the measured tree stems in the FIA plots. The crown overlay was color-coded by pine species and the DSM was gray scaled with white as highest point. A *hit* consisted of a single crown cloud surrounded by a colored crown polygon that matched one stem point in that polygon. A cloud with a single stem of a non-pine species was also a *hit*. A *hit species error* was a single cloud with a single polygon and single stem that did not match the species of the crown. A *split* was a cloud and polygon with multiple stems. A *split species error* was a cloud and polygon with several stems and none match the species of the polygon. A *miss* consisted of a cloud and polygon without a stem or stem and cloud without a polygon. An *error* consisted of a cloud without stem or polygon, or a stem without cloud or polygon, or a polygon without cloud or stem.

Accuracy was also assessed on a plot basis. For each plot, statistics were calculated for longleaf pine and loblolly-pond pines combined. Stem count and basal area of each plot was calculated from the measured trees. Also, total crown projected area was calculated with the

spatial analyst tool on the crown layer for each plot and species group. The tallest tree of each species group and overall tallest tree were calculated for each plot from the stem data and with the identify tool on the DSM. Identification of species on the DSM was done considering the species of the crown polygon surrounding the cloud rather than any stem that may have occurred within the crown polygon. Linear regressions were calculated for number of stems versus number of crown polygons, stem basal area versus crown projected area, tallest tree by species group versus tallest DSM point by species group and overall tallest stem versus highest overall DSM point. Highest DSM point was compared to the DSM value of three ground points within the plot area.

3.2 Analysis based on surveyed ground control points

During rectification of mosaics to that of May 11, 2018, RMSE values of matched points were in the range of 2–3 m which was similar to the performance of this drone in our previous work in an open field (Williams et al. 2018). Using the surveyed ground control RMSE was reduced to under 1 m for the Feb 27, 2019, mosaic. This mosaic has been used as ground truth for all subsequent analyses. The crown polygon layers of longleaf and loblolly+pond were manually edited to match outlines of crowns on the Feb. 27th mosaic. Only the *move* command was used and no polygons were altered with the *edit vertex* command. Overall crown polygon shapes were surprisingly similar between the seasons, and it was easy to match polygons to the February crown shapes.

Once the crown layers were edited and polygons corresponded to the corrected mosaic, analysis of tree position, number of trees per plot, and plot crown projected area vs stem basal area were done as outlined above. However, a much better result of tree position allowed a better method to be applied to tree height assessment. Assessment of tree height accuracy was done on a tree by tree basis rather than the tallest tree in a plot. For the 110 trees that were *hits*, the ground measured height was compared to the highest DSM point in the matching polygon. For each sub-plot, an average of five minimum DSM points was used as the base elevation for all height measurements of that sub plot

4 RESULTS

4.1 General UAV flying issues and recommendations

We discovered several factors that were needed to produce a series of photographs that could be processed by Metascape into an orthomosaic. By far the most critical aspect was wind speed. Wind gusts above 13 kph (8

mph) produced crown motion that resulted in failure to find match points on photo pairs, resulting in distortion or missing holes in the resulting orthomosaic. Shadows tended to make both point matching and interpretation of the final orthomosaic more difficult. Since this site is near the coast, sea breezes precluded high sun angle photos in the summer. Summer photos were especially difficult to collect as there was only a period of 2 hours of optimal flying time after the land breeze subsided in mid-morning and the sea breeze began in the late morning. In general, ideal photography was confined to overcast days with light winds.

We found several adaptations to the Litchi app were needed to take vertical aerial photographs that worked well for point matching in Metascape. Several default settings appeared to favor smooth videography rather than uniform still vertical photos. The drone orientation must remain uniform on all flight lines and transitions. If the orientation is changed to follow the flight lines, as would be done with using fixed winged aircraft flights, the application would smoothly turn the drone as it approached the waypoint at the end of each flight line, resulting in increasingly crabbed photos near the ends of the line. This occurred even when each waypoint turn was specified to be exactly 90° with no turning radius. The only way to get uniformly oriented photographs was to specify the flight orientation as constant azimuth, in our specific case that was 320°. Flying at 80 m above ground, we found that a fixed focus at infinity and automatic aperture resulted in the most uniform exposure without unwanted changes in depth of field. That may not always be the case flying at different altitudes.

4.2 Accuracy of crown polygons

As noted in the methods, pine crowns were hand digitized into longleaf and pond+loblolly groups, based in the appearance of the new flush of needles seen on the May 18, 2018, mission. A qualitative check on the pine-hardwood separation and assessment of our ability to identify hardwood species were done with missions in September, November, December of 2018 and February 2019. A single area of interest was chosen near the riparian hardwoods along the small streams in the footprint area, containing both pines and hardwoods (Figure 2).

In general, pine crowns were well distinguished from hardwood as most of the crowns without pine polygons had lost their leaves in the February photo. Hardwood species can also be distinguished on the different photos taken at different times; water tupelo (*Nyssa aquatica*) lose leaves early, as seen in the September photo, and oaks (*Quercus* spp.) lose leaves much later as seen by the reddish hue of the tree in the upper center of the December photo that lost leaves in the February photo.

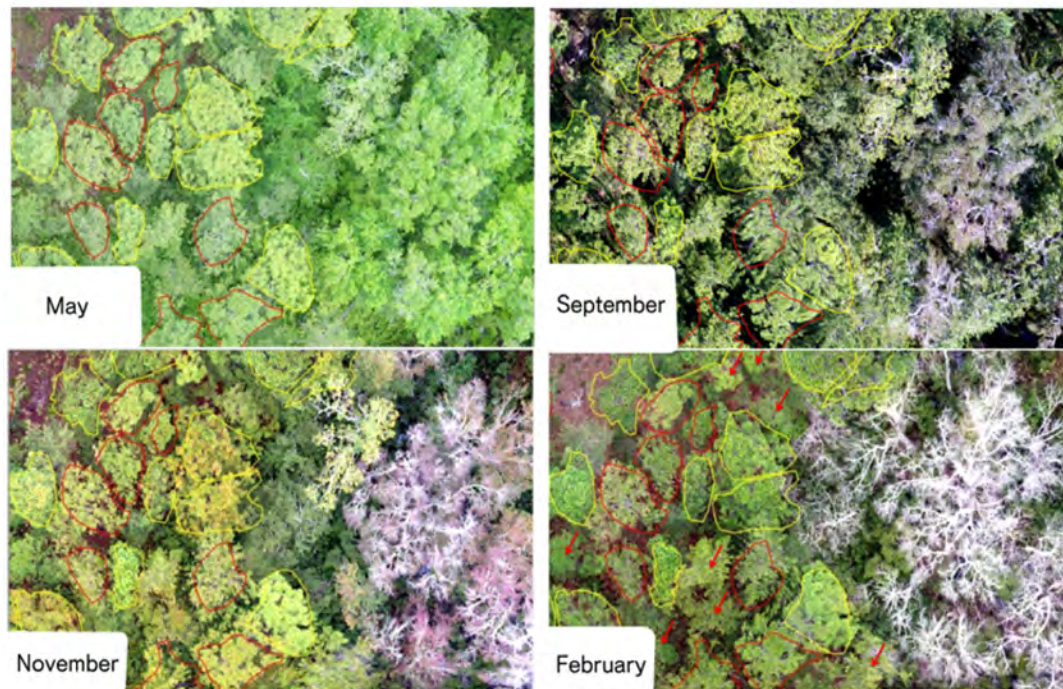


Figure 2: Screen grabs of ARC-GIS georeferenced scenes of an area of interest in May 2018, September 2018, December 2018, and February 2019. Arrows on the February photo indicate trees that are evergreen trees, probably pine, missed during crown digitization.

However, there were eight evergreen trees missed, with four of those resembling crowns labeled as longleaf pine. Note also the thick evergreen shrubs along the riparian area that consisted primarily of fetterbush (*Lyonia* spp.) and gall berry (*Ilex glabra*).

The accuracy of crown digitization was quantitatively assessed in the 23 subplots of the six FIA style plots where traditional biometric data had been collected. The plot overlays (Figure 3) revealed that our digitized crowns were not as consistent as those measured by Wang et al. (2008). In only 57 of 322 cases were the stem and crown correctly matched (Table 1a). In 175 of the 322 cases one or two of the three elements were missing. Plots with more longleaf pine tended to have a few more *hits* than those with fewer longleaf trees. These results indicated that further analysis could only be done on a plot basis.

Analysis of data obtained with ground control (Table 1b, Figure 4) revealed that lack of ground control was responsible for a large part of the poor performance in matching tree positions. The largest change was a decrease in the number of *errors* and an increase in the number of *hits*. There was an increase in the number of polygons with the wrong species, either as individuals or as *splits*. The number of *misses* was the only consistent category. Many of the misses were simply crowns

that were not identified in the digitizing of crown shapes. Others were stem locations near the edge of a polygon that may have been leaning trees. Although the RMSE of the mosaic done without ground control was less than a crown width it appears the actual errors in tree position were often more than a crown width. The use of ground control also resulted in enough correct tree locations to allow tree by tree comparisons of tree height.

If the crown maps made without ground control could not be used to identify characteristic of individual trees, could data collected from the crown maps be used to quantify the characteristics of each of the FIA subplots? Would aggregating an area of 0.07 ha compensate for spatial errors in locating trees? Finally, how much did careful ground control add to accuracy of data for each plot? Three criteria were used to evaluate the relationship of the crown maps to the field collected data.

The first criterion was simply comparing the number of stems to the number of crowns by species group. Both species groups showed crown mapping underestimated the number of trees in a plot, although the relationship showed r^2 of 0.58 and 0.63 for longleaf and pond+loblolly groups, respectively. The relationship varied further from the predicted 1:1 relationship for plots with more than 15 trees in the 0.07 ha plot, or 214 trees/ha. (87 trees/ac) (Figure 5 A and B). Careful ground control

Table 1: Summary of position accuracy analysis on the six FIA plots. Categories are explained in the methods but briefly: a Hit was a correctly identified crown, a Hit Spp. was a crown correctly identified but to the wrong species, a Split were multiple stems in a crown polygon, a Split Spp. were multiple stems in a crown polygon some of the wrong species, a Miss was only two of the three elements present, and an Error was 2 of the three elements missing. A are data from the mosaic made without ground control while B is an identical analysis done on the ground-controlled mosaic.

A Plot	Hit	Hit spp.	Split	Split spp.	Miss	Error
1	6	3	8	7	12	18
2	14	4	10	1	19	18
3	12	4	14	0	23	4
4	10	3	8	3	21	11
5	5	2	3	1	7	5
6	10	3	16	0	22	15
Total	57	19	59	12	104	71

B Plot	Hit	Hit spp.	Split	Split spp.	Miss	Error
1	11	6	9	7	12	8
2	26	3	6	0	19	4
3	33	3	11	4	23	3
4	12	10	3	5	24	2
5	13	1	3	2	6	0
6	15	5	10	7	16	0
Total	110	28	42	25	100	17

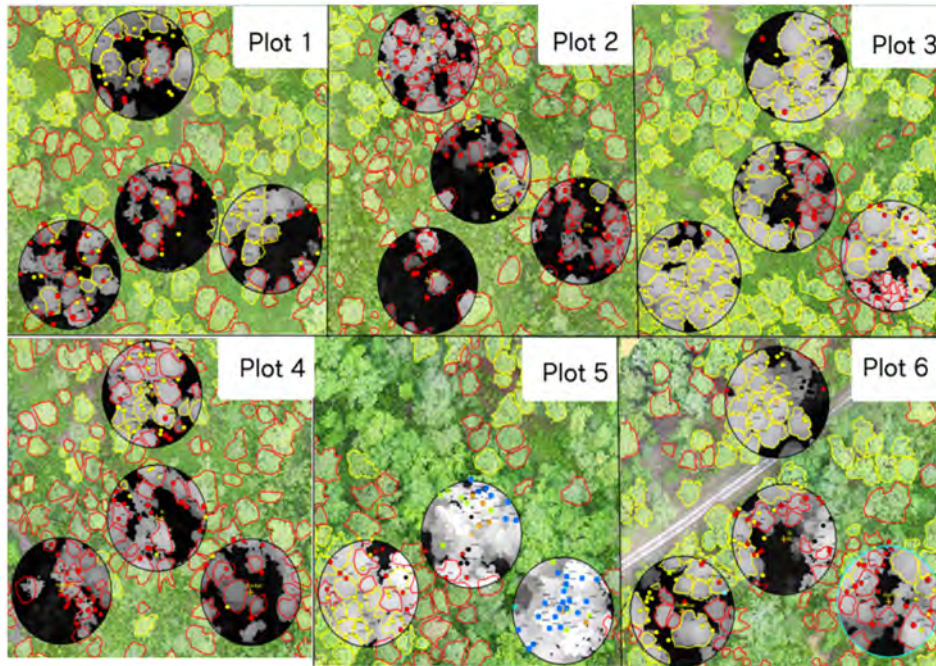


Figure 3: Representation of the six FIA style plots. Each sub-plot center is an orange cross and the black border is edge of the 15 m radius plot. Within each plot the DSM is a gray scale with white representing higher elevations. A tree crown on the DSM should resemble a small cloud with a bright spot somewhere within. Interpreted longleaf crowns are represented by yellow polygons and loblolly or pond pines as red polygons. Location of measured stems are represented by dots, color coded like the crown polygons. Colored dots other than red or yellow represent hardwood species where crowns have not been mapped.

Table 2: Regression equations of measured values (x) and UAV estimated values (y) of number of trees, basal area vs crown area, height. Basal Area (BA) and Crown Intercepted Area (CA) are m² and height is m.

Mosaic Type	Criterion	Longleaf		Loblolly + pond		Combined	
		Equation	r ²	Equation	r ²	Equation	r ²
No Ground Control Points	Number	$y = .58x + 0.5$	0.6	$y = .55x + 2.2$	0.6		
	BA vs CA	$y = 240x - 24$	0.5	$y = 175x + 99$	0.3		
	Height	$y = 1.18x - 0.15$	0.2	$y = 1.31x$	0.2	$y = 1.41x - 4.6$	0.5
Ground Control Points	Number	$y = .63x + 0.6$	0.6	$y = .61x + 2.3$	0.6	$y = .58x + 3.8$	0.7
	BA vs CA	$y = 248x - 8$	0.7	$y = 220x + 67$	0.5	$y = 226x + 74$	0.8
	Height					$y = 1.36x - 1.4$	0.7

changed the relationships within the species slightly and showed a slight improvement in the number of crowns per plot from 0.55 to 0.68 in longleaf and from 0.55 to 0.61 for loblolly+pond (Table 2). Accurate crown positions justified combining the analysis of all trees on the plot regardless of species. The percentage of stems identified did not improve but the r^2 of the relationship improved to 0.68.

The second criterion was comparing the plot basal area to the crown projected area by species group. This analysis showed much larger differences in accuracy of the species groups. The r^2 for longleaf pine trees was 0.64 while that for loblolly and pond pine only 0.26 (Table 2). The r^2 for longleaf pine in this study was higher than the value we measured on individual sawtooth oak (*Quercus acutissima*) in an open field (Williams et al., 2018). Longleaf pine tended to be larger trees, showing both more basal area and projected crown area, although the number of trees was nearly identical. Longleaf pine also appeared to carry more crown area than loblolly+pond pine; 240 m² projected crown/m² basal area and 176 m² projected crown/m² basal area respectively. However, when the analysis was done on ground controlled data the relationship of basal area to crown projected area was closer, with 248 m² projected crown/m² basal area for longleaf and 220 for m² projected crown/m² basal area for loblolly+pond. r^2 also rose considerably with ground control for both species and was 0.78 if species were combined.

Unlike DBH tree height can be directly measured from SfM photography. Accurate measurement of height is also vital to estimating merchantable volume or biomass. Since the mosaic made without ground control resulted in poor identification of individual stems, we tried to compare only the tallest tree of each species to the highest point within a crown polygon. The r^2 of these comparisons were rather dismal at 0.23 for longleaf pine and 0.17 for loblolly+pond pine. Both groups also showed a consistent positive bias of 1-2 m in both regressions. Repeating the analysis considering the tallest tree on

the plot improved the r^2 to 0.54 but the positive bias remained (Table 2).

Table 1. Summary of position accuracy analysis on the six FIA plots. Categories are explained in the methods but briefly: a Hit was a correctly identified crown, a Hit Spp. was a crown correctly identified but to the wrong species, a Split were multiple stems in a crown polygon, a Split Spp. were multiple stems in a crown polygon some of the wrong species, a Miss was only two of the three elements present, and an Error was 2 of the three elements missing. A are data from the mosaic made without ground control while B is an identical analysis done on the ground-controlled mosaic.

With ground control we were able to compare measured height to the DSM on 102 trees that represented from 3 to 9 trees on each individual plots. Tree by tree comparisons resulted in a much better representation of true height with an r^2 of 0.67 and an intercept of -1.4m. However, the slope of the regression of 1.36 represents a 36% increase in error with increasing height. One interesting result occurred if the regression was required to pass through the origin resulted in a r^2 of 0.99 with a slope of 1.28, suggesting much of the error in height measurement was in determining an accurate DTM

5 DISCUSSION

In this project we evaluated the use of low-cost drone photography to examine forest structure in the footprint area of an eddy-covariance flux tower as a proxy for a small woodlot. This work was done with a \$2,000 drone and controller, \$2,500 desktop computer and \$3,500 software package. We found a low cost drone could take vertical aerial photos precisely when the drone flew autonomously. Multiple flights could be combined into a single mission to cover the entire 12.6 hectares, resulting in a complete dense point cloud that yielded high resolution orthophotos and DSMs. Species differences could be determined from repeated flights timed to accentuate differing phenology of the dominant species. Using only the GPS of the drone stamped on the individual photos,

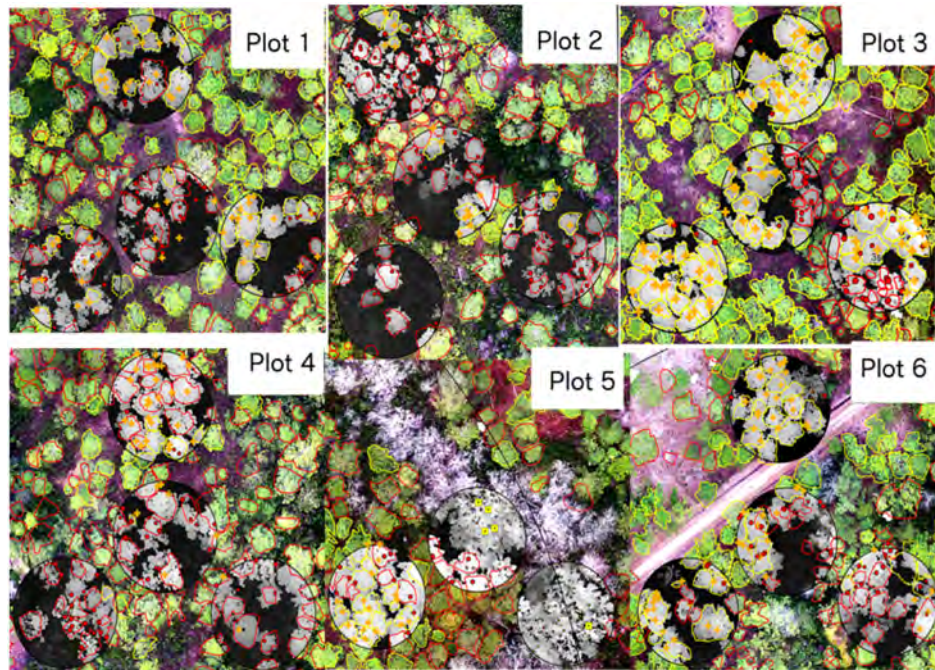


Figure 4: Comparison as in Figure 3 but on ground-controlled February mosaic, with crown polygons moved to match the ground-controlled mosaic.

X, Y coordinates of flights varied by 2-3m. Therefore, all orthophotos had to be rectified to a single base before crown matching was possible. If a site does not have well established ground control points, then flights will need to be rectified to each other.,

Identification of individual trees was not successful on mosaics created without ground control. Only 24% of identified crown polygons representing a single stem and less than 18% when species was considered. Nearly 30 of the measured stems fell outside of a DSM cloud or crown polygon. In general, we could not do single tree comparisons between ground measured values and interpreted crowns without ground control

Table 2. Regression equations of measured values (x) and UAV estimated values (y) of number of trees, basal area vs crown area, height. Basal Area (BA) and Crown Intercepted Area (CA) are m^2 and height is m.

Addition of ground control greatly improved our ability to match crown polygons to stem locations. The number of correctly identified crowns increased by nearly 100% after the crown polygons were moved to fit the ground-controlled mosaic. Also the number of errors fell from 71 to 17. After the positional errors were improved the limitation from visual interpretation of tree crowns became apparent. In addition to the correctly identified trees, the number of *hit* with an incorrect species and the number of *split* with an incorrect species both increased. That indicated it was not possible to detect

multiple stems and the appearance of longleaf needle clusters was difficult to see in younger mixed groups. The visual identification of crowns also led to several crowns being missed by the interpreter.

Comparisons of the number of trees per plot (Table 2) also show the improvement associated with accurate position. Based on the regression slopes the percentage of trees correctly identified rose from 58 to 63% in longleaf and 55 to 61% in loblolly + pond. The regression r^2 did not change much indicating the much of the error was not due to inaccurate ground position, but from uneven ages and sizes of the three species.

Diameter or basal area and height are the parameters used to calculate both biomass and merchantable volumes. While height can be measured directly from the DSM, neither diameter nor basal area are observable from above. However, if there is a close relationship between basal area and the 2d crown area, then crown area could be a surrogate in volume calculation. Comparisons in this stand reveal that correct positional data is vital to developing a relationship. Table 2 shows without ground control there is little relation in loblolly + pond pine with and r^2 of only 0.26. With ground control the regression slopes approach the same ratio of crown area to basal area and r^2 improves, greatly in the case of loblolly + pond. An r^2 of 0.78 indicates a strong relationship if species is not considered. This suggests the relationship is quite strong but mistakes in species

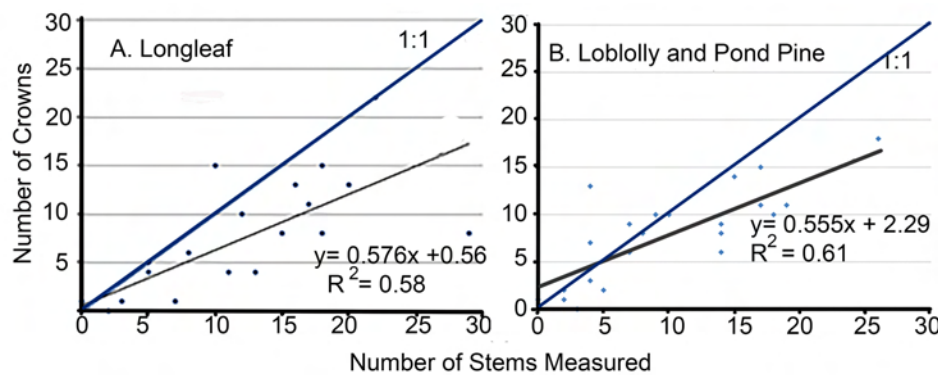


Figure 5: Regression of number of (A) longleaf pine and (B) loblolly+pine trees measured on the ground vs. crowns estimated from the orthophoto by species group.

interpretation was the primary cause of poorer performance of the ratio. Tree height is the other parameter needed for merchantable volume and biomass estimates. Tree height was the most problematic estimation. Without ground controls there were no individual trees that could be evaluated. One method we tried, evaluating height of the tallest tree of each species in each plot produced dismal results with r^2 as low as 0.17 and a strong bias that caused over estimation of height. Comparing the tallest tree to the highest DSM point in a plot resulted in an r^2 of 0.54 revealing a relationship that was being hidden by our inability to locate trees correctly. With ground control we could compare heights of 102 trees with a resulting r^2 of 0.67.

In this study we found that ground control points were vital for measuring individual tree location, and tree height estimates but were only slightly more accurate in determining the number of trees and ratio of crown area to basal area. With ground control points height measurement achieved an r^2 of 0.67 that is nearly identical to Wallace et al. (2016) of 0.68. in an open forest. Wang et al. (2008) were able to achieve hit percentages up to 84% in mature stands using an automated procedure on high density LiDAR point clouds although UAV LiDAR has been found to be superior to SfM (Wallace et al. 2016, Pulti et al. 2019). Pulti et al. (2019) also examined UAV, SfM without a precision DTM with similar poor results. In this study we also tried the high point in a plot and the tallest measured tree in that plot to make height measures without ground control produced an r^2 of 0.54. All methods of height measurement on the DSM overestimated the ground measures by 20–30%. We found the UAV estimates of ellipsoid height varied from -10m to -65m on various flights. Defining a correct ground surface elevation proved difficult in this stand due to very thick ground cover.

6 CONCLUSIONS AND RECOMMENDATIONS

The goal of this paper was to examine the feasibility of low-cost UAV for forest inventory of small private forest owners. Our approach assumed a landowner would fly his woodlot and produce an inventory from his home computer. We applied that approach on a 12-ha mature natural stand of mixed southern pines. With careful autonomous flying we could obtain high quality vertical photos that could produce point clouds, DSM, and orthomosaics with a low-cost UAV intended for hobby flying. The horizontal precision of these orthomosaics did not allow mapping of individual trees and degraded other plot based estimates of tree number and basal area vs crown area. Height measures required ground control to assure the stem measured in the field corresponded to the high point measured on the DSM. In this stand we could not obtain a high quality DTM, which has been a problem seen in other research using SfM on stands with thick vegetation.

Creating height and diameter needed for biometric calculations are not easily obtained from the UAV products, and without ground control resulted in large errors in those measures. Surveying accurate ground control points may well exceed the cost of a traditional inventory done by a forestry consultant. At present accurate tree inventory requires UAV LiDAR (Pulti et al. 2019) which means a larger drone with an expensive RTK receiver and expensive laser scanner.

Yet, state of the art is continually improving, and new ideas and technology may change these conclusions. A low-cost instrument capable of establishing sub-meter accurate ground control points in the forest would be one solution. Another may be; Machimura et al. (2021) proposed a novel solution based on Shinozaki, et al. (1964) pipe model that would base biomass and tree volume

entirely from an estimate of crown volume from SfM. Such an idea would allow direct measure of the entire stand from a point cloud rather than from sample plots. Progress in technology or analysis may alter our conclusions.

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