Post-Variable Density Treatment Monitoring in Dry-Site Mixed Conifer Stands with Unmanned Aircraft Systems

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ABSTRACT.—Variable density thinning (VDT) post-treatment monitoring is challenging and potentially costly because resulting stand structure is not well characterized by small area plots used in forestry. Unmanned aircraft systems (UAS) offer a potential solution for efficient VDT monitoring via rapid survey and subsequent generation of a stem map. In this study we used a UAS to survey and estimate spatial dispersion and stand structure (e.g., basal area, trees per acre, and quadratic mean diameter) in untreated and VDT-treated stands. Results showed evidence of increased clustering in the treated stand at intertree distances between 17 and 25 feet while the untreated stand exhibited a pattern of random dispersion. UAS-derived stand structure estimates differed in comparison to stand exam estimates with UAS underestimating basal area and trees per acre and overestimating quadratic mean diameter. However, comparison between UAS estimates in the treated and untreated stands revealed expected trends of decreased density and increased diameter. UAS survey and data processing time was less than one-fifth of the time required for common stand exams. Given the increased time efficiency, the biased UAS estimates are likely an acceptable tradeoff for VDT monitoring. Although this study demonstrates the utility of UAS for post-treatment monitoring, additional testing through research and management collaboration is required to refine the method and quantify error.

INTRODUCTION

Federal forest managers in the west are increasingly embracing novel silvicultural treatment methods in an effort to restore fire resiliency and ecosystem function to a landscape that has been altered by over 100 years of fire suppression (Churchill et al. 2013, Stephens et al. 2016). Variable density thinning (VDT) is a promising tool for such restoration in specific forest types that increases spatial heterogeneity by creating variable density stem clusters Churchill et al. 2013, Clyatt et al. 2016, Larson and Churchill 2012). Although monitoring VDT treatments is essential to providing feedback for the adaptive management process and responding to the reporting requirements established by the Collaborative Forest Landscape Restoration Program, it has the potential to be costly because the resulting stand structure is not well characterized by conventional small area plots.

Unmanned aircraft systems (UAS) technology has been shown to produce quantitative and interpretive data that is meaningful to forest managers in numerous applications and offers a potential solution for increasing efficiency of post-treatment monitoring activities (Bedell et al. 2017, Pádua et al. 2017, Wing et al. 2014). Although the USDA Forest Service has been conservative in the implementation of UAS technology, the 2018 modernization agenda

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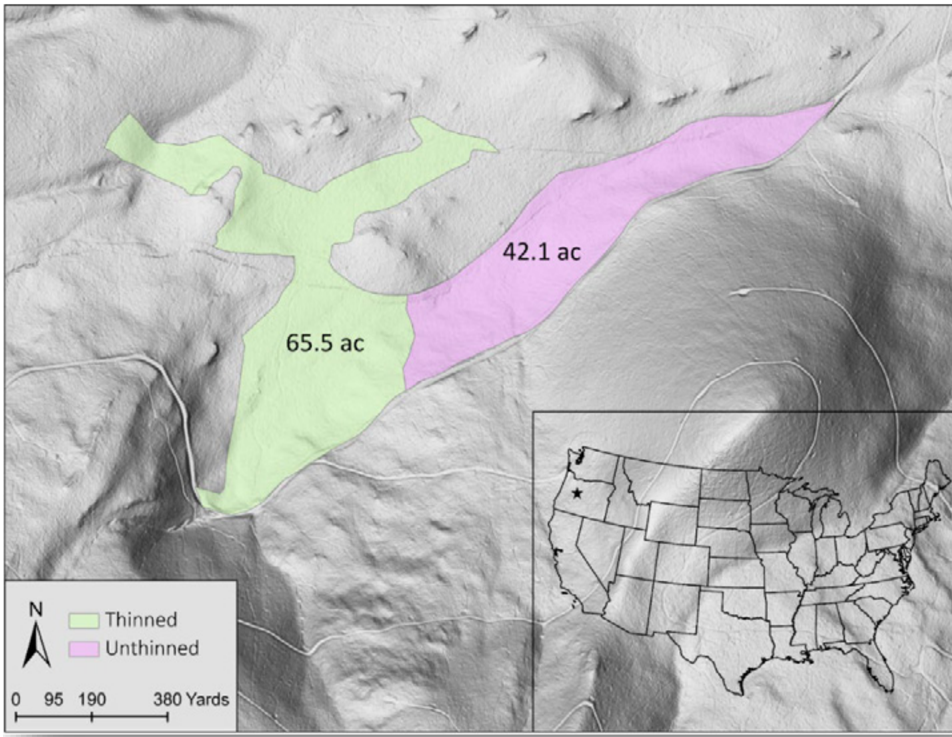

Figure 1.—Study area on the Deschutes National Forest near Sisters, OR.

(USDA Forest Service 2018) and a 2018 Executive Order[2] all but ensure eventual integration, making the current era an optimal time to think about how to best leverage this technology.

In this management-driven research and development (R&D) collaboration, we examine the efficacy of using a UAS-based methodology to survey post-treatment stand structure and spatial dispersion of a VDT treatment in a dry mixed-conifer stand.

STUDY AREA

The study site consisted of two adjacent dry mixed-conifer stands on the Deschutes National Forest near Sisters, OR (44.160° N, 121.618° W) (Fig. 1). Stand compositions and spatial dispersions were nearly identical before treatment and were dominant to *Pinus ponderosa* (ponderosa pine) with an *Abies concolor* (white fir) understory component. The larger stand of 65.5 acres was prescribed a VDT treatment to increase the presence of stem clustering while the smaller stand (42.1 acres) was unthinned to provide a reference condition for comparison.

[2] Executive order 13855 of December 21, 2018, 84 FR 45. Executive Order for promoting active management of America's forests, rangelands, and other federal lands to improve conditions and reduce wildfire risk.

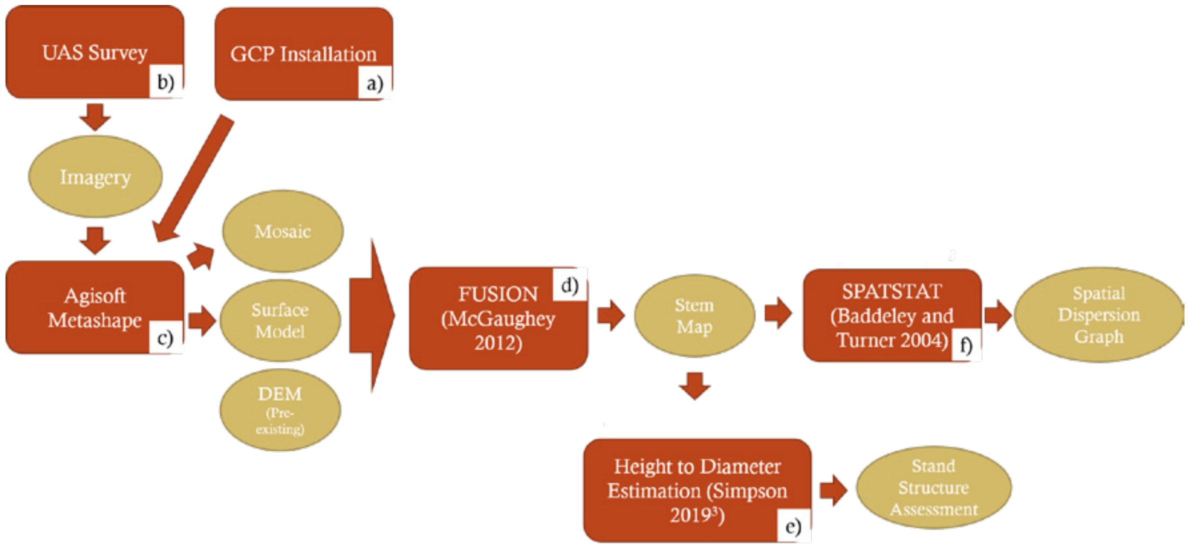

Figure 2.—UAS image processing and analysis workflow.

METHODS

While stem maps are the preferred method for quantifying post-VDT spatial heterogeneity (Larson and Churchill 2012), they can be costly due to the need to visit every tree. In effort to reduce this cost burden, we used UAS to collect the data necessary for assessing stand structure and creating remotely sensed stem maps for the ultimate purpose of quantifying spatial heterogeneity. A conceptual processing workflow (Fig. 2) shows how stem maps were produced from UAS imagery. The UAS survey took place on 11 October 2018 near solar noon in full unobstructed sunlight. Eight ground control points (GCPs) were installed and surveyed with a high accuracy global positioning system (GPS) for the purpose of improving georeferencing accuracy during image processing (Fig. 2a). The UAS survey (Fig. 2b) was conducted with a DJI Phantom 4 Pro which can produce imagery at 1.3-inch resolution when flown at an altitude of 400 feet above ground level. UAS navigation was automatic and used a preplanned 75 percent overlap/sidelap flight plan created in DJI's GS Pro application (Dà-Jiāng Innovations, Shenzhen, Guangdong, China).

Image processing (Fig. 2c) occurred in Metashape ver. 1.5.0 (Agisoft 2019), which ingested the image set and GCP data to produce a georeferenced mosaic and a digital surface model (DSM). The DSM and a pre-existing LIDAR-derived digital elevation model (DEM) were input into FUSION's CanopyMaxima function (McGaughey 2017) (Fig. 2d) to produce a stem map. The output stem map was a georeferenced dataset complete with estimates of relative tree height and crown diameter.

Comparison of thinned and unthinned stand structure was conducted by feeding the stem map data into a height-to-diameter allometric equation[3] to estimate diameter, which was ultimately used to estimate stand level tree density (trees per acre or TPA), quadratic mean diameter (QMD) and basal area (BA; square feet per acre) (Fig. 2e). As a form of validation, these data were compared to the results of post-treatment common stand exams (CSE) with 23 and 26 plots in the unthinned and thinned stand, respectively. CSE plots consisted of variable radius plots randomly allocated within each study unit with selection of trees <5

[3] USDA Forest Service internal unpublished report by Mike Simpson, forest ecologist. For more information, email at michael.simpson@usda.gov.

inches diameter at breast height (4.5 feet above ground; d.b.h.) for subsequent height and d.b.h. measurement occurring with a 20 basal area factor prism. Trees <5 inches d.b.h. were selected for measurement based on a 1/10th acre circular plot and 1/100th acre circular plot for the thinned and unthinned stands, respectively.

Spatial dispersion (Ripley 1976) (Fig. 2f) was quantified by feeding the stem map into the pairwise correlation function (PCF) algorithm in the SPATSTAT package (Baddeley and Turner 2004) in R ver. 3.5.3 (R Core Team 2017) for the thinned and unthinned stand. PCF produces a density-independent estimate of dispersion that can range from 0 to infinity where 0 is perfectly uniform, 1 is random and anything greater than 1 is clustered.

Work-hours were tallied and compared to man-hours invested in the UAS survey and analysis to assess time differences between the two CSE and UAS methods.

RESULTS AND DISCUSSION

Absolute differences of BA, QMD, and TPA between the UAS and CSE estimates suggest that UAS method underestimated TPA in the thinned stand and underestimated both TPA and BA in unthinned stand. (Fig. 3). Since QMD is a function of TPA and BA, the differences between estimation methods for stand structure are in line with expectation given that the stem map likely under represents suppressed crowns, and because the unthinned stand has more suppressed trees the magnitude of underestimation is higher than in the thinned stand. The fact that the error is explainable suggests that it might be possible to improve accuracy by the integration of field data in a model-assisted approach to account for bias (Kangas et al. 2018, McRoberts et al. 2018). It is important to note that these estimates should

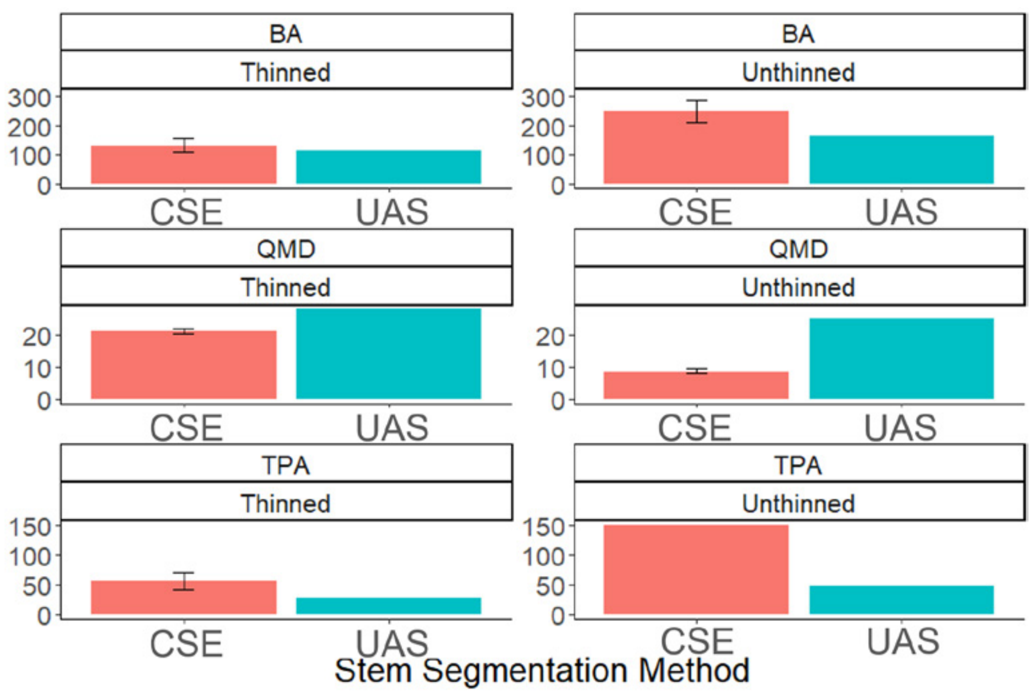

Figure 3.—Common stand exam (CSE) and unmanned aircraft system (UAS) estimates of stand structure in the thinned and untinned stands as characterized by basal area in units of ft^2 per acre (BA), quadratic mean diameter in inches (QMD), and tree density (trees per acre or TPA). CSE estimates are plot means with 95 percent confidence intervals shown with error bars. UAS estimates do not have confidence intervals since observations were not derived from samples and characterization of UAS estimate uncertainty was beyond the scope of this pilot project.

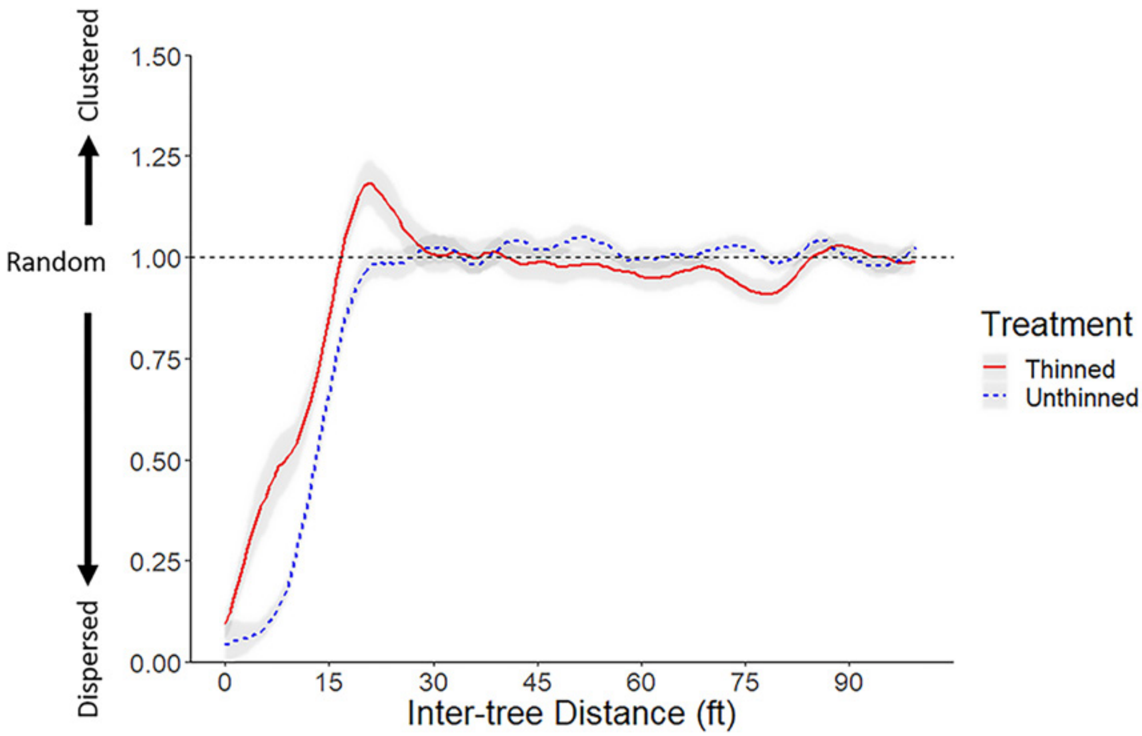

Figure 4.—Spatial dispersion of the thinned and unthinned stands as a function of inter-tree distance relative to a random Poisson distribution reference (dashed line). The transparent (grey) band around each line is the 95 percent confidence interval.

be considered carefully and in the context of management-driven error tolerances before drawing conclusions about meeting silvicultural objectives. Despite the inaccuracy of the absolute TPA and BA estimates from UAS, the method captured the same directional trends between unthinned and thinned stands as the CSE estimates with TPA and BA reducing after thinning and QMD increasing. When the costs of field estimates are considered, knowing that the method is capturing the representative qualitative indications may be acceptable for addressing the monitoring requirements of collaborators.

The results of the PCF analyses indicate evidence of clustering in the thinned stand at inter-tree distances between 17 and 25 feet whereas the unthinned stand exhibits evidence of random dispersion (Fig. 4). The strongly dispersed signal apparent in both the thinned and unthinned stands at distances less than 17 feet is likely associated with the minimum inter-bole distance of neighboring trees. Omission and commission errors are inherent in stem maps derived from UAS (and LIDAR) data with suppressed trees (under dominant and codominant trees) being omitted and mature trees with complex crowns being detected as multiple trees (i.e., commission; Popescu and Wynne 2004). Although the influence of these errors are not quantified, we are confident that the assessed spatial clustering pattern in the thinned stand is representative of true conditions because (1) clustering is evident in the post-treatment imagery, (2) both stands exhibited the same spatial dispersion pattern prethinning, and (3) clustering is likely underestimated because suppressed trees in the clusters were likely not detected by the stem mapping algorithm thus reducing the strength of the clustering signal.

Overall, the entire UAS workflow took approximately 12 work-hours while the CSEs took 64 work-hours resulting in an 81 percent time savings using the UAS method instead of CSE. It is worth noting that UAS surveys become more time efficient as survey areas increase because flight time is a very small portion of the overall workflow, so larger areas may show larger divergences in time costs depending on how variability influences CSE intensity. Further time savings could be gleaned by the utilization of real-time kinematic (RTK)-capable UAS, such as the Phantom 4 RTK, which would potentially negate the need for GCPs.

This pilot study was of limited scope in order to assess feasibility. Future study in quantifying efficiency gains, characterizing the uncertainty in UAS stand structure estimates, and evaluating the influence of stem mapping errors on estimates of spatial dispersion should be undertaken with replication in multiple forest types and multiple stand structures before a definitive conclusion on the UAS methodology can be made.

UAS survey methodology shows promising potential for rapid assessment of spatial dispersion in dry-site conifer dominant stands post VDT treatment given the method's ability to quantify changes in spatial dispersion, detect trends in stand structure, and reduce survey work-hours. While additional research is needed to fully understand the utility of the method, the positive indications of this study suggest that UAS utilization for post-harvest monitoring is a matter of when and not if.

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