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Estimates of Willow (*Salix* Spp.) Canopy Volume using Unmanned Aerial Systems[☆]



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ABSTRACT

Management of livestock grazing in riparian areas is an important aspect of rangeland management. Willows (*Salix* spp.) are a common riparian plant serving as an ecosystem stabilizer, as well as providing important habitat, but browsing or trampling by cattle can decrease willow canopy volume. Canopy volume can be measured on the ground with hours of meticulous data collection. However, canopy volume estimates from drone-collected images could be a more efficient and objective method for measuring willow canopy volume and understanding the impact of livestock use on riparian woody vegetation. Our objective was to determine how well drone-based measurements of willow canopy volume corresponded to field measurements in a southern Idaho riparian area before and after a grazing trial. We used sets of overlapping aerial images from a DJI Phantom 4 Professional drone to construct 3-dimensional point clouds of willows. From these point clouds we estimated willow canopy volume using 2 techniques and compared those with canopy volume estimates from field measurements of 58 willows ranging in height from 0.76 m to 4.57 m. Point cloud canopy volume estimates using both techniques showed high correspondence with field-estimated volume ($R^2 > 0.8$) for both pregrazing and postgrazing. However, point cloud techniques generally underestimated canopy volume compared with the field technique. Drone-based estimates took ≈ 4 h per sampling event (i.e., pregrazing, postgrazing) including acquiring and processing the imagery, whereas field-based measurements took ≈ 10 h per sampling event. These results demonstrate drone-collected images may be an effective tool for measuring and monitoring riparian woody vegetation.

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Introduction

Management of livestock grazing in riparian areas is an important aspect of rangeland management. Livestock tend to congregate in riparian areas, especially during seasons with high temperatures, because they provide easy access to water, shade typically provided by willows, and an abundance of palatable and nutritious vegetation like grasses, forbs, sedges, and willows.

Willows (*Salix* spp.) function as an ecosystem stabilizer, as well as providing important wildlife habitat (Kovalchick and Elmore 1991), but excessive browsing and/or trampling by cattle can decrease willow canopy cover and establishment (Schulz and Leininger 1990). Utilization of willows by cattle can be driven by

numerous factors, including stocking rates, timing and duration of use, forage availability in the riparian area and surrounding uplands, and growth stage of the willows. Consequently, utilization of a willow community by livestock is a dynamic process that can be affected by changing management over the short and long term. However, it is debatable as to the most effective method to evaluate and quantify temporal changes occurring in a willow community during grazing events.

Numerous methods are used by land managers to evaluate willow utilization including the twig length measurements and the extensive browse estimation method (US Forest Service 1994; Bureau of Land Management 1999). Holland et al. (2005) concluded canopy volume is as an effective indicator of changes in willow communities subjected to either livestock utilization or exclusion of livestock altogether. To further evaluate characteristics of shrub communities subjected to wildlife and livestock utilization, researchers have used estimates of canopy volume based on canopy height and width measurements. Creamer (1991) and

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Mannoukian (1994) used the volume (V) of an ellipsoid to calculate willow volume:

$$V = \pi h \left(\frac{AB}{2} \right), \quad (1)$$

where h is the shrub height and A and B represent perpendicular diameter measurements, or the major and minor axis. Mannoukian (1994) specifically used this canopy volume formula to describe changes in willow communities subjected to seasonal wildlife and livestock usage.

Thorne et al. (2002) further modified volume of the ellipsoid by using this formula:

$$V = \frac{2}{3} \pi h \left(\frac{AB}{2} \right), \quad (2)$$

where A and B represent perpendicular diameter measurements taken at 50% of the plant height. Thorne et al. (2002) indicated the advantages of this formula: It measures canopy volume in multiple dimensions, adjusts to the varying sizes and shapes of plants, and is sensitive to the changes in plant dimensions over time. They further concluded that their technique was precise, was efficient, provided repeatable measurements, and it also required minimal training. Using this measurement method could prove advantageous to land managers evaluating both short- and long-term grazing management decisions; however, all described methods for evaluating willow canopy cover are time consuming and can be sensitive to human error.

The availability of low-cost consumer unmanned aerial systems (i.e., drones) with high-quality imaging sensors has made it possible to collect very-high-resolution (i.e., image pixels with a ground sampling distance, or resolution, of < 1 cm) imagery easily and inexpensively. The advent of new photogrammetric techniques that can create high-quality 3-dimensional models and orthomosaics from drone imagery (Westoby et al. 2012) has opened up new possibilities for using drones as a supplement or replacement for field measurement methods. Thus, canopy volume estimates from drone-collected images could be a more efficient and objective method for measuring willow canopy volume and understanding the impact of livestock use on riparian woody vegetation.

Several studies have demonstrated the utility of digital photogrammetric analysis of drone-acquired imagery for sampling vegetation attributes. Puttock et al. (2015) used imagery from small drones to identify vegetation structure changes and the extent of beaver dams and ponds. Hortobágyi et al. (2015) found high correspondence between canopy-height models of riparian vegetation from drone images and field measurements on wooded bars of the Allier River, France. Michez et al. (2016) used multitemporal hyperspectral imagery from a drone to classify and monitor health of riparian vegetation. While studies have shown the value of drone imagery for estimating biomass in arid systems (e.g., Cunliffe et al. 2016) and effects of grazing on rangeland vegetation (e.g., Breckenridge and Dakins 2011), few studies have examined the utility of drone imagery to detect livestock utilization (either through browse or destruction) of woody riparian species.

Photogrammetrically derived 3-dimensional models of vegetation height and structure, however, are limited by what is visible to the imaging sensor. Elevations can only be estimated for objects seen in the images; thus, it can become challenging to estimate ground surface elevations (and by extension, vegetation height) in areas of dense vegetation cover. Accordingly, the utility of drone-acquired imagery for estimating canopy volume of riparian shrubs must first be evaluated against in situ measurements. Our objective in this study was to determine how well drone-based measurements of willow canopy volume corresponded to field measurements in a southern Idaho riparian area before and after a grazing trial.

Study area

This study was conducted at the University of Idaho's Rinker Rock Creek Ranch in southern Idaho (43.4139°N, 114.3946°W, Fig. 1). The 4210-ha Rock Creek Ranch is a collaborative research effort among the University, Wood River Land Trust, and Idaho Chapter of The Nature Conservancy. The main Rock Creek drainage bisects the ranch from north to south and consists of an incised stream with broad floodplains dominated by meadow foxtail (*Alopecurus pratensis* L.), smooth brome (*Bromus inermis*), sedges (*Carex* spp.), and willows. The study area consisted of a single rectangular pasture (1.6 ha) with an electric fence perimeter. The pasture was flood irrigated with water from an irrigation ditch bisecting the eastern one-third of the pasture. The pasture was grazed for 4 d by 30 cow/calf pairs and 20 pregnant cows to target 50–60% grazing utilization rate of available grasses. Willows were interspersed primarily across the center section of the fenced area with available grazing area located on both the eastern and western sides of the greatest willow density (see Fig. 1).

Methods

Field data collection and willow canopy estimation

The canopy volume of the willows was determined by the allometric method described by Thorne et al. (2002) using Eq. 2. The height measurement was the distance from the plant base to the tallest active photosynthetic material of the plant, whereas A and B were perpendicular diameter measurements taken at 50% of the height. Willows ($n = 58$) were selected at random across the area of the pasture and were selected to represent the different size categories of willows present ranging in height from 0.76 m to 4.57 m. Pregrazing willow measurements were taken on 27 and 28 July 2018, and postgrazing measurements on the same shrubs were taken on 9 and 10 August 2018. Pregrazing and postgrazing forage (i.e., grass) biomass of the pasture were determined at five random locations across the pasture within each grazing event. The calculated pregrazing and postgrazing values were 6379 and 3630 kg/ha dry matter basis, respectively, and the grazing utilization of the pasture was estimated at 46%.

Drone image collection

Imagery was collected with a Phantom 4 Professional drone (see Fig. 2a, <https://www.dji.com/>, accessed 23 January 2019) with autonomous flight and camera triggering controlled by Pix4DCapture (<https://www.pix4d.com/product/pix4dcapture>, accessed 23 January 2019). The area to be imaged was defined in the field, and a double-overlap grid pattern consisting of parallel flight lines in north-south and east-west directions was created. The drone flew at an altitude of 20 m above ground level (AGL). With the Phantom 4 Professional's 20-megapixel RGB camera, each image had a ground-sampling distance (GSD, or spatial resolution) of ≈ 6.9 mm and scene extent of ≈ 13 m \times 7 m. The drone's camera was oriented at 20° off-nadir. James and Robson (2014) demonstrated off-nadir images improved the accuracy of structure-from-motion photogrammetric models.

Drone flights and image acquisitions were conducted on 27 June 2018 (before the grazing treatment) and 7 September 2018 (following the grazing treatment). A slightly larger area was imaged during the postgrazing flight to ensure the pregrazing area was adequately represented. The pregrazing and postgrazing flights resulted in 206 and 276 images, respectively. We relied on the internal GPS of the Phantom 4 Professional drone for assigning initial coordinate locations to each image. No ground control points were employed in this study.

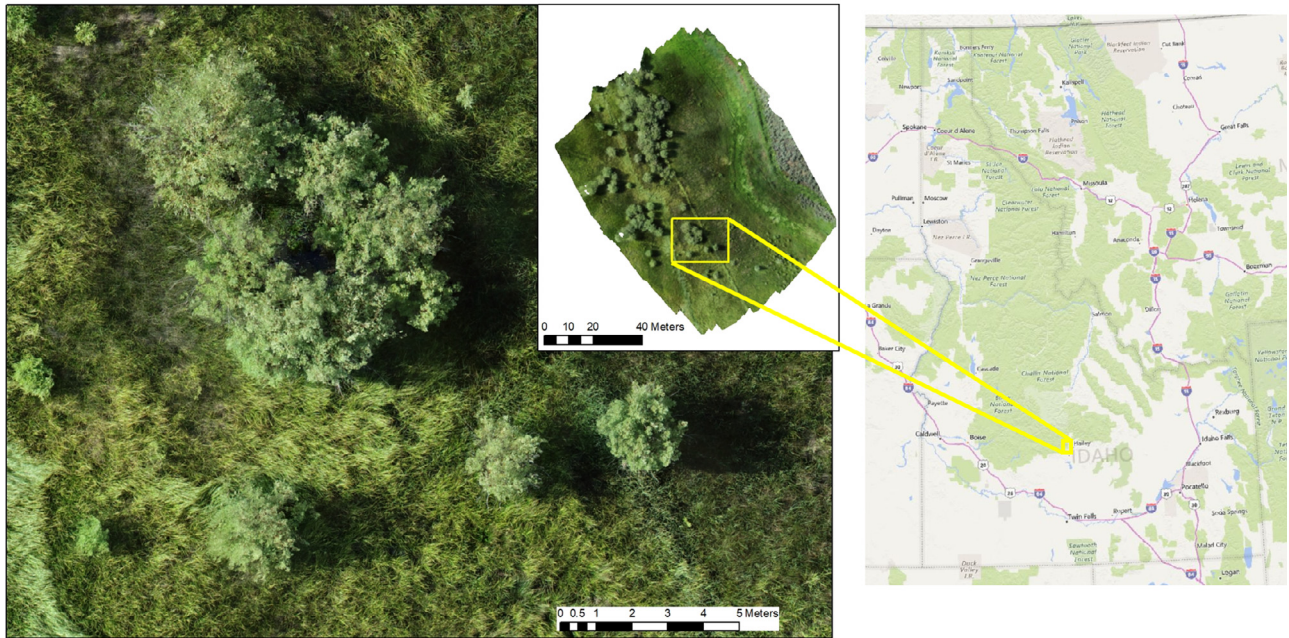


Fig. 1. Location of the study area within the Rinker Rock Creek Ranch in southern Idaho and close-up aerial view of willow (*Salix* spp.) shrubs in the Rock Creek riparian area.

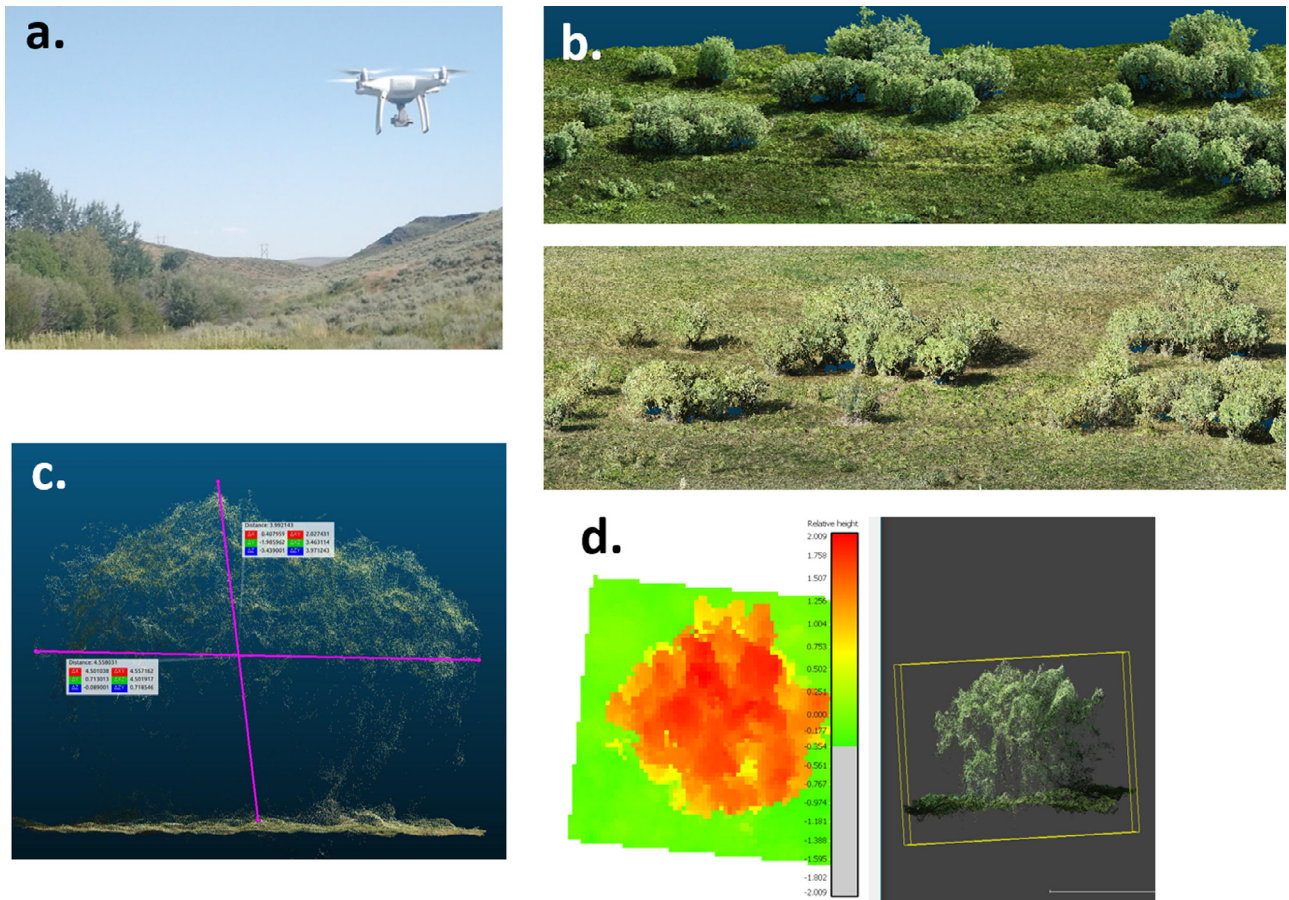


Fig. 2. The study site was imaged before and following the grazing trial using the stock RGB 20-MP camera from a DJI Phantom 4 Professional (a). Images were processed using structure from motion photogrammetry to produce three-dimensional point clouds (b). Willows (*Salix* spp.) measured in the field were extracted individually from the point clouds, and canopy volume was measured using (c) the method of Thorne et al. (2002) and the “surface drape” technique (d).

Image processing and willow canopy estimation

Images from each drone flight were processed into photogrammetric point clouds using Agisoft Photoscan Professional version 1.4.4 (<https://www.agisoft.com/>, accessed 23 January 2019). Photoscan uses a structure-from-motion (SfM) approach to digital photogrammetry. Unlike traditional photogrammetric techniques that use individual stereo-pair images with known location and orientation for estimation of elevations and creation of orthomosaics, SfM uses multiple overlapping images of the same area to solve for the camera's location and orientation during each image and simultaneously estimate the scene's elevation and geometry (Westoby et al. 2012). SfM techniques are particularly well suited for processing drone-collected images when the exact position or orientation of the camera cannot be tightly controlled (James et al. 2017).

Processing of the images in Photoscan followed James et al. (2017) and Gillan (2018). Within Photoscan, after the images from a flight were imported, initial alignment of the images was performed with the high accuracy setting, a key point limit (number of unique points identified per image for potential matches with overlapping images) of 60,000, and unlimited tie points (points found in common among two or more overlapping images). This process orients the images and finds tie points. Once the location and orientation of the camera are estimated for each image, the spatial location of each tie point in three dimensions can be estimated. The result of this first step is a sparse point cloud. Optimization of the sparse point cloud must be performed to remove low-quality points. This was done using the “gradual selection” tool in Photoscan to identify and remove points with high projection error, reconstruction uncertainty, and reprojection error (see James et al. 2017, for specific criteria). A bundle adjustment optimization was performed after each batch removal of low-quality points.

The optimized sparse point cloud defines the photogrammetric solution for the full extent covered by the images. This becomes the model for generating dense point clouds and orthomosaics. We created a dense point cloud for each drone flight using Photoscan's “high” density setting and “mild” point filtering. The default “aggressive” filtering removes points that are significantly higher than surrounding points. In areas with heterogeneous vegetation, however, this can lead to removal of points that define branches and leaves that extend beyond the core canopy of a plant. Through anecdotal testing, we determined the “mild” filtering option removed points of likely spurious elevations but retained the most detail for the shrub canopies. Dense point clouds for the pregrazing and postgrazing flights contained 47,555,796 points (~3500 points/m²) and 74,866,713 points (~4800 points/m²), respectively (Figs. 2a and b).

Orthomosaics and digital surface models were created from the pregrazing and postgrazing images for reference purposes but were not directly analyzed for this study.

Accuracy specifications for the Phantom 4 Professional's on-board GPS were not available from the manufacturer but were presumed to be commensurate with other consumer-grade GPS (~2–3 m). However, instantaneous GPS error during flight is less important than the overall positioning error of the photogrammetric products. Using the location of two permanent posts installed after the pregrazing flight and located using an Emlid Reach RS+ real-time kinematic GPS (<https://emlid.com/reachrs/>, accessed 23 January 2020), the horizontal error of the postgrazing orthomosaics was 0.55 m and 0.56 m, respectively.

Willow canopy volume was estimated from the point clouds using only knowledge of what willows were measured (i.e., without knowing actual ground measurements). Willow canopy volume was estimated using two techniques in CloudCompare v2.10 (<http://www.cloudcompare.org/>, accessed 23 January 2019). Each

willow measured in the field was identified in the dense point clouds and extracted to its own point cloud file with an extent slightly larger than the shrub. The first canopy volume method replicated the field measurement technique as closely as possible. For this method, orthogonal measurements of shrub width were made at 50% of the shrub's height from the base of the point cloud (which was the closest approximation to the ground surface) to replicate the field method by Thorne et al. (2002). Measurements were always made from the south and east directions looking directly perpendicular to the vertical axis of the shrub (see Fig. 2c). Height of the shrub was measured from the lowest point to the tallest extension of the shrub as represented by the point cloud. Volume for each shrub was then calculated using the equation presented by Thorne et al. (2002).

The second method used CloudCompare's Calculate 2.5D Volume tool, which generalizes the point cloud to a surface elevation model and then calculates volume on the basis of the difference between the surface model and a fixed ground elevation (see Fig. 2d). This technique is conceptually analogous to draping fabric over the shrub and measuring the volume under the fabric. For this technique, raster resolution was set to 15 cm, and ground elevation was determined for each shrub using the lowest point in the point cloud.

Statistical analysis

Statistical analysis was performed in R version 3.5.2 (R Core Team 2018) using base functions and consisted primarily of linear regression between field estimates of willow canopy volume and drone estimates. Additionally, willow height and width measurements were compared via linear regression to better understand the source of discrepancies between the field- and drone-based estimates. Pregrazing and postgrazing estimates were analyzed separately for the same shrubs ($n = 58$). Bland and Altman (1995) point out that the correlation between two measures is not always a good measure of agreement because estimates from two methods measuring the same indicator (i.e., on the same scale) are expected to be highly correlated even if there is a systematic bias between the two methods. In our case, however, the expectation was not that the measures of canopy volume would be the same, only strongly correlated, and thus permit a double-sampling approach to estimating willow canopy volumes (sensu Ahmed et al. 1983; Andersen and Breidenbach 2007; Karl et al. 2014). Lack of ground control and dense vegetation obscuring the ground surface both may contribute to underestimation of willow canopy heights. However, if a consistent relationship between field and drone estimates of canopy height is found, regression estimators (Lohr 2009) can be used to estimate canopy volume from point cloud measurements with limited field data.

Results

Canopy volume estimates

Canopy volume estimates from the point cloud showed strong relationships with field-estimated canopy volume for both the allometric (Figs. 3a and b) and volumetric (see Figs. 3c and d) methods. Results were similar for pregrazing and postgrazing measurements. For the allometric method (see Figs. 3a and b) and the postgrazing volumetric method (see Fig. 3d), point cloud estimates of canopy volume were on average 25% lower than the field estimates. For the pregrazing volumetric method (see Fig. 3c), point cloud volume estimates were ~40% lower than field estimates.

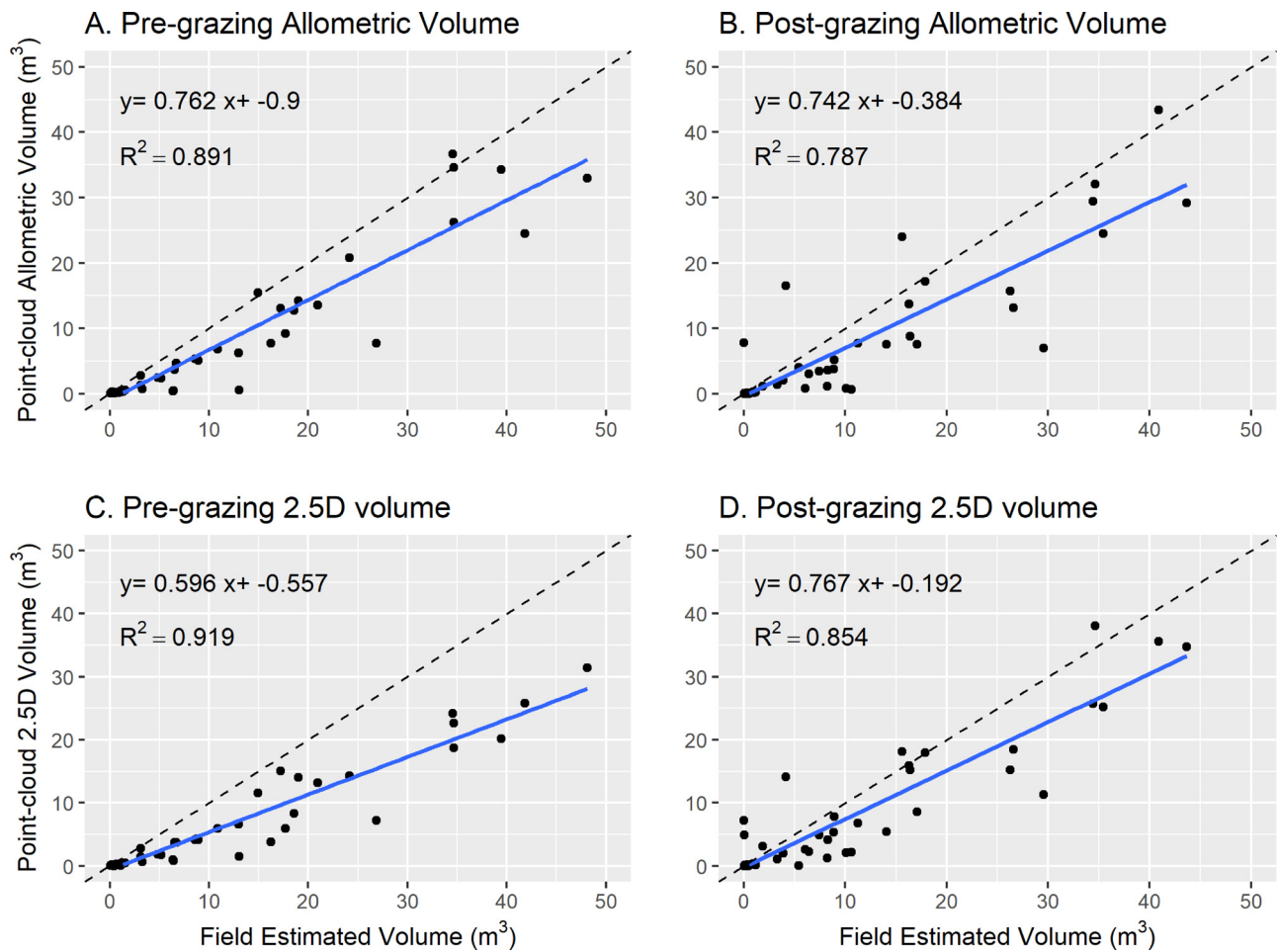


Fig. 3. A–D, Comparison of point cloud and field-based estimates of willow canopy volume before and after the grazing trial. The same set of shrubs ($n=58$) were measured at each time period. Point cloud measurements were made with an allometric method that mirrored the field measurements and with a volumetric (2.5D) technique. Blue lines represent linear regression equations. Dashed line is 1:1.

Canopy height and width measurements

When considering the constituent measurements of the canopy volume estimates, heights estimated from the point clouds corresponded well to field-measured height ($R^2 = 0.944$ for pregrazing, $R^2 = 0.927$ for postgrazing, Figs. 4a and b). Slope of regression lines > 1.0 indicates the point cloud measurements underrepresented heights for smaller willows more than for larger ones. Point cloud height estimates were, on average, 1.022 m (45.8%) lower than field measurements of canopy height for pregrazing measurements and 0.689 m (30.6%) lower for postgrazing measurements.

Correspondence of point cloud and field measures of canopy width (where the perpendicular width measures for each shrub were averaged), however, were slightly lower than for height ($R^2 = 0.89$ for pregrazing, $R^2 = 0.776$ for postgrazing, see Figs. 4c and d). Canopy widths from the point cloud were underestimated relative to field measurements by 11cm to 13cm. This may be because canopy widths were always taken from standard orientations, whereas the orientation of measurements for the field methods varied.

Time cost of estimating canopy volume

Field measurements of the willow heights and widths took ≈ 10 person-h per sampling event (i.e., pregrazing and postgrazing). Total time for estimating willow canopy volumes from the drone

Table 1

Time to complete tasks for estimating willow canopy volume from field- and drone-based measurements. Travel time to and from the field site was considered the same between methods and was not counted here.

Task	Approximate time to complete task (person-h)
Field measurements of willow shrubs	10
Drone image acquisition (includes setup, flight, and take down)	0.75
Drone image processing to produce point clouds ¹	1
Willow shrub extraction and measurement from point clouds	2.75
Drone-based measurement total time	4.5

¹ This estimate considers only the time a person needed to be interacting with the computer processing the imagery. Actual computer time to generate point clouds was considerably longer.

point clouds was ≈ 4.5 person-h per sampling event (Table 1). Of that time, the actual flight took the least amount of time. The majority of the time for estimating willow canopy volume from the drone point clouds came from isolating and measuring the individual shrubs. Field measurements also required a minimum of two people to accurately handle measurement devices, whereas the drone point cloud workflow could be implemented by a single person.

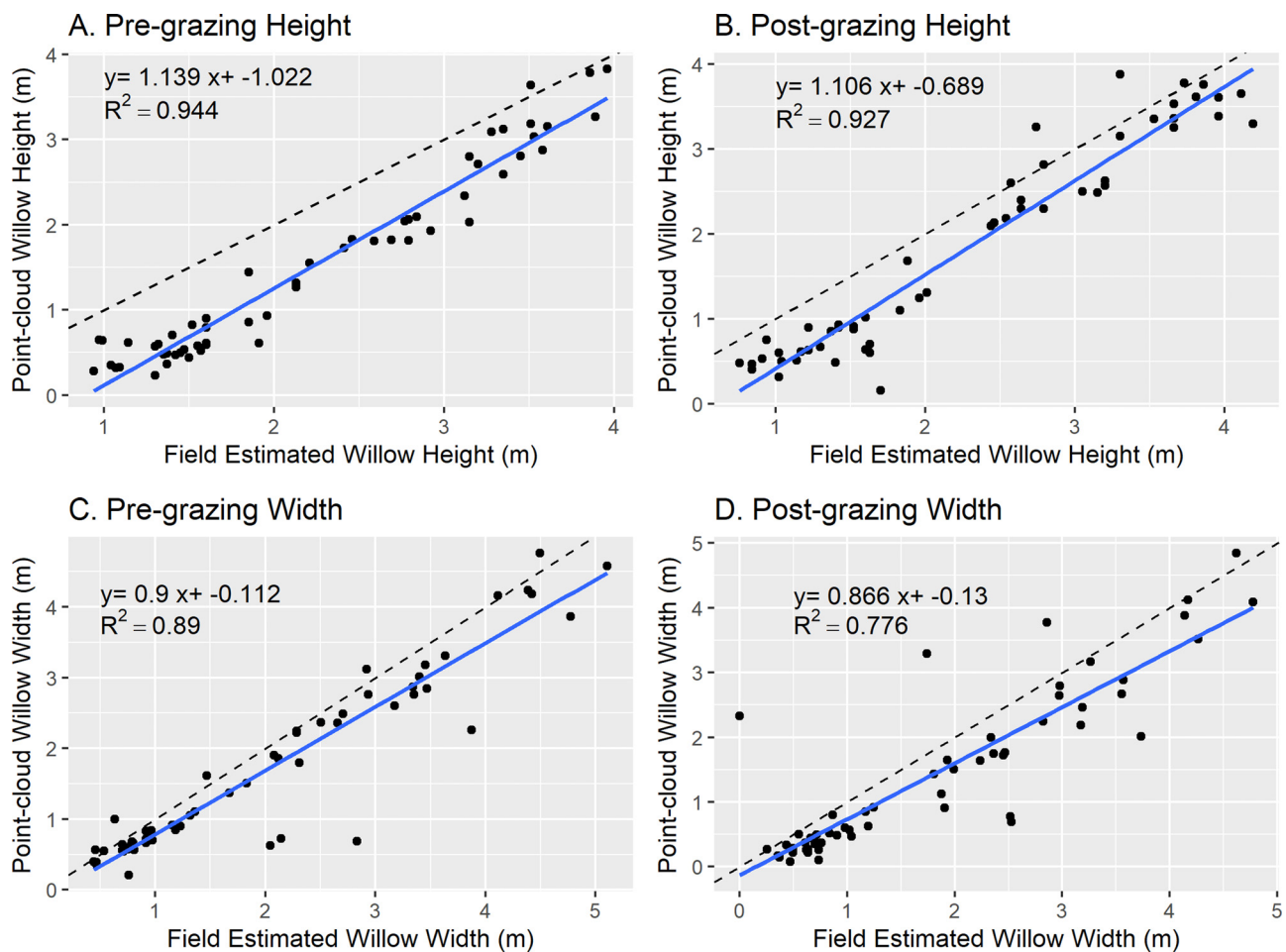


Fig. 4. A–D, Comparison of point cloud and field measurements of canopy height and width of willow shrubs. Blue lines represent linear regression equations. Dashed line is 1:1.

Discussion

Our results demonstrate measurements of willow canopy volume from drone point clouds are a viable approach when compared with field-based estimates. Though the point-cloud estimates were consistently lower than the field estimates of volume, bias was relatively consistent between methods and across the range of shrub sizes.

Underestimation of willow canopy volume from the point clouds was largely from underestimation of willow heights due to the ground surface being occluded by meadow grasses. Photogrammetric methods, because they rely on aerial photographs, can only estimate elevations for visible locations in two or more of the original images. Ground surface elevation is typically estimated from point clouds by the lowest points within localized regions (e.g., grid cells of a defined size). Thus, in dense vegetation that obscures the ground surface, the lowest points in the point cloud do not represent the ground. This results in overestimation of the ground surface elevation and, consequently, underestimation of vegetation height. This was evident with the dense meadow grasses in our study. Shrub heights were underestimated in both sampling periods, but pregrazing showed a larger percentage difference between field- and point cloud-measured heights compared with postgrazing (i.e., after 46% of the grass biomass had been removed through grazing).

An alternative technique that could help alleviate underestimation of canopy height would be terrestrial or aerial light detection and ranging (LiDAR), which measures distance to surfaces from

the reflection of laser light pulses. Because LiDAR is an active remote sensing technology, it has the potential to penetrate deeper into plant canopies and provide information on vegetation structure and ground surface elevation below the canopy top. However, in dense vegetation, even LiDAR may not be able to achieve full canopy penetration.

This study was conducted without the aid of precisely located ground-control points, instead relying on the coordinates recorded to each image from the drone's internal GPS. Ground control is not used in the initial alignment of the drone images or the generation of tie points (SfM photogrammetry can work well without any coordinate information for the images at all), but for correctly locating, orienting, and scaling the resulting point clouds and image products in space (James et al. 2017). In the absence of ground control, dimensions (especially elevations) in photogrammetric products are relative. In the case of estimating willow dimensions, the point cloud measurements of willow width and height may deviate from the field measurements (e.g., show bias) because the point clouds are not accurately scaled. In our case, however, this would affect only the bias estimate and not the strength of the relationship (correlation or coefficient of determination) between the drone and image measurements, provided the mis-scaling was consistent across the entire study area. Similarly, without ground control, regression coefficients between field and drone measurements would not be expected to be constant over time or between areas. This would necessitate measurement of a subset of willows for each unique drone flight. With high-quality ground control (ideally using the same, permanent ground control

between successive flights of the same area), regression equations between field and drone measurements should be more consistent, reducing the need for extensive field measurements of willows at every site.

Underestimation of willow heights is a product of photogrammetric limitations of estimating elevations for only visible parts of the scene (i.e., if an area cannot be seen in an image, elevations cannot be estimated for it). This hampers the ability to accurately determine where the ground surface is relative to the vegetation. Active remote sensing such as with light detection and ranging (i.e., LiDAR) sensors can provide more information on ground surface elevations by detecting returns from laser pulses penetrating the plant canopy (Lefsky et al. 2002). Accordingly, LiDAR sensors have been shown to give more accurate estimates of ground surface elevation and vegetation canopy height than photogrammetric techniques (Wallace et al. 2016). However, LiDAR sensors remain expensive and, given their weight, must be carried by larger, more expensive drones. Even though our estimates of willow canopy height and volume were negatively biased relative to the field measurements, given the high correlations with the field data, photogrammetric methods may be a more cost-effective solution for monitoring than a LiDAR-based approach.

Photogrammetric estimation of willow canopy volume from the drone imagery took less time than collecting measurements in the field. Additional efficiencies gained through repeated monitoring efforts may further reduce the time to acquire drone measurements. This could facilitate more frequent data collection for estimating trends in plant communities within seasons and over the long term. However, drone-based measurements carry an additional burden of managing and processing the drone images before measurements can be made. In contrast, field methods provide all the data to calculate canopy volume as soon as the measurements are taken. The advantage of drones as a data collection platform, however, would likely increase with the size or number of study areas. Additionally, the drone-collected images, point clouds, and orthomosaics provide an additional record and dataset of the site that may be useful for data verification or other purposes.

Ultimately, though, field methods for shrub canopy volume are estimates based on assumptions of canopy shape and not direct measurements of volume. The technique by Thorne et al. (2002), which based canopy volume estimates on orthogonal width measurements at 50% of the shrub height, may underestimate canopy volume of that height does not represent the widest part of the canopy (e.g., if the shrub were hedged at 70% of its height). Often field methods are not assessed for the validity of assumptions or effects of measurement error on their estimates. Thus, processes or events that change the shape of the shrub canopy (e.g., browsing or physical damage from grazing animals) may not be detected by field methods based on allometric methods. Drone-based measurements that estimate volume directly from photogrammetric products may be less sensitive to this problem.

Management implications

The results presented here demonstrate drone-based imaging is a suitable method for measuring willow shrub dimensions and estimating canopy volume. This study supports a growing body of literature documenting the usefulness of drone-collected data for achieving high-quality measurements of ecosystem indicators. In particular, our work shows low-cost consumer drones and commercial photogrammetry software can deliver repeatable, precise measures of shrub canopy properties and can potentially realize significant time and labor savings for monitoring shrub

systems. For implementing drone-based measurements of shrub canopies in monitoring programs, the use of ground control reference information is important for achieving consistency in the relationship between field and image-based measurements. While drone-based measures underestimated shrub height, the bias was consistent and predictable, suggesting limited field measurements should be collected during each sampling period to calibrate drone measurements.

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