Received: 6 November 2018 | Revised: 4 March 2019 | Accepted: 23 May 2019
DOI: 10.1002/eco.2115

RESEARCH ARTICLE

Drone-based photogrammetry-derived crown metrics for predicting tree and oil palm water use

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Funding information
Deutsche Forschungsgemeinschaft (DFG), Grant/Award Numbers: DFG, CRC990, A02 and B11

Abstract

Transpiration at the stand level is often estimated from water use measurements on a limited number of plants and then scaled up by predicting the remaining plants of a stand by plant size-related variables. Today, drone-based methods offer new opportunities for plant size assessments. We tested crown variables derived from drone-based photogrammetry for predicting and scaling plant water use. In an oil palm agroforest and an oil palm monoculture plantation in lowland Sumatra, Indonesia, tree and oil palm water use rates were measured by sap flux techniques. Simultaneously, aerial images were taken from an octocopter equipped with an Red Green Blue (RGB) camera. We used the structure from motion approach to compute several crown variables such as crown length, width, and volume. Crown volumes for both palms (69%) and trees (81%) explained much of the observed spatial variability in water use; however, the specific crown volume model differed between palms and trees and there was no single linear model fitting for both. Among the trees, crown volume explained more of the observed variability than stem diameter, and in consequence, uncertainties in stand level estimates resulting from scaling were largely reduced. For oil palms, an appropriate whole-plant size-related predictor variable was thus far not available. Stand level transpiration estimates in the studied oil palm agroforest were lower than those in the oil palm monoculture, which is probably due to the small-statured trees. In conclusion, we consider drone-derived crown metrics very useful for the scaling from single plant water use to stand-level transpiration.

KEYWORDS

agroforest, bootstrapping, sap flux, scaling, structure from motion, transpiration, uncertainty

1 | INTRODUCTION

Transpiration is a central flux in the ecosystem water cycle. In forests or similar vegetation types, it is often estimated from individual plant water use assessments, for example, with sap flux techniques (Granier, 1985; Wullschleger, Meinzer, & Vertessy, 1998). In most studies, the number of plants directly analysed for water use is lower than the number of plants in the stand. The individual plant water use rates are then scaled to stand-level transpiration by biometric variables. Scaling is thus a critical issue that needs to be optimized in order to improve transpiration estimates and to reduce associated uncertainties (Hatton & Wu, 1995; Jarvis, 1995; Moore, Orozco, Aparecido, & Miller, 2017).

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Candidate variables for scaling include tree diameter, crown metrics, and leaf area. Among these, tree diameter and the number of trees (stand density) are often used, as they are easy to assess and often available from forest inventories. The relationships between tree water use and tree diameter often have R^2 values around 0.66 (Schiller, Cohen, Ungar, Moshe, & Herr, 2007; Yue et al., 2008), but closer (Wang, Xing, Ma, & Sun, 2006), and less close correlations (Kume et al., 2009) have also been observed. Stem diameter has some limitations that include a potentially slow response to concurrent dynamics in the stand such as crown damages or crown expansions into gaps. In addition, recently increasingly monocot species such as bamboos and palms came into the focus of transpiration studies (Mei et al., 2016; Röll et al., 2015), in which intraspecific diameter variation may be low but nonetheless variation in water use occurs. Leaf area index can be a very powerful variable for scaling (Hatton & Wu, 1995; Medhurst, Battaglia, & Beadle, 2002; Vertessy, Benyon, O'Sullivan, & Gribben, 1995), but it is often only available at the stand level and not at the tree level. In contrast, crown dimensions are easier to measure and thus more commonly available and yielded good results in mature oak (*Quercus robur*) forest (Čermák, 1989). Similarly, in *Taxodium distichum* forest and olive orchard, crown structure correlated closely with tree water use (López-Bernal, Alcántara, Testi, & Villalobos, 2010; Oren, Phillips, Ewers, Pataki, & Megonigal, 1999). Crown exposure also indirectly affected transpiration by influencing leaf wetness and dryness in a premontane forest of Costa Rica (Aparecido, Miller, Cahill, & Moore, 2016).

Despite the long-recognized potential of crown variables for scaling up from tree water use to stand transpiration, diameter-based approaches remain popular, as crown variables are more difficult and time consuming to assess in ground-based stand inventories. With the recent development of drone technologies and their application in ecological studies, this might change. Drones equipped with optical detectors such as cameras capturing specific light wave lengths or laser-based approaches offer new opportunities for crown and canopy assessments (Barnes et al., 2017; Díaz-Varela, de la Rosa, León, & Zarco-Tejada, 2015; Thiel & Schmullius, 2016). Crown variables such as crown length (Kallimani, 2016), crown diameter (Lim et al., 2015; Panagiotidis, Abdollahnejad, Surový, & Chiteculo, 2016), or crown volume (Torres-Sánchez, López-Granados, Serrano, Arquero, & Peña, 2015) were calculated using photogrammetric techniques. Even though drone technologies have previously been applied in ecohydrological studies (Vivoni et al., 2014), the applicability of drone-based photogrammetry for scaling up tree water use to stand-level transpiration has to our knowledge not yet been explored.

Uncertainties associated with sap flux measurements and stand level estimates of transpiration are manifold and include the assessment of sap flux variation in a given tree, the number of trees sampled, and the scaling (Peters et al., 2018). For a better understanding of ecohydrological consequences with land-use and land-cover change, it will be important to produce stand-level transpiration estimates with a high accuracy and, thus, a low associated uncertainty. The basis for this is the further optimization of current sampling and scaling schemes, potentially also by employing innovative drone-based methods.

In our study, we assessed relationships between crown metrics and the water use of oil palms and trees in lowland Sumatra, Indonesia. In this region, natural forests have largely been converted and monoculture oil palm plantations are widespread (Drescher et al., 2016). The land cover change and the expansion of oil palm plantations are associated with losses of biodiversity and impaired ecosystem functions (Barnes et al., 2014; Clough et al., 2016; Dislich et al., 2017). Transpiration rates from commercial oil palm plantations can be high and may exceed those of remaining forests (Meijide et al., 2018; Röll et al., 2015). To test possibilities of alleviating the ecological impacts of oil palm cultivation, a biodiversity enrichment experiment, EFForTS-BEE, was set up in a commercial oil palm plantation by planting native tree species and establishing oil palm agroforests (Teuscher et al., 2016). Within EFForTS-BEE, we conducted our study on plant water use and scaling by crown variables. The objectives were (a) to test drone-derived crown variables for the prediction of tree and palm water use, (b) to analyse uncertainties resulting from scaling plant water use to stand-level transpiration, and (c) to compare transpiration rates of an oil palm monoculture with an oil palm agroforest.

2 | METHODS

2.1 | Study area and sites

The study was conducted in Jambi province, Sumatra, Indonesia. The region is tropical humid, with mean annual precipitation of 2,235 mm year^{-1} and average annual temperature of 26.7° C (Drescher et al., 2016). The study sites were located just south of the equator (01.95°S and 103.25°E), within the commercial oil palm plantation PT Humusindo, near Bungku Village. Mean elevation is 47 m asl. The biodiversity enrichment experiment (EFForts-BEE) was established in monoculture oil palm plantations. Oil palms were planted in a 9 × 9 m^2 triangular grid resulting in approximately 143 oil palms per hectare; the age of the oil palms at the time of study was approximately 9–15 years (Teuscher et al., 2016). The broad age range refers to the entire experiment with 56 plots that covers an area of about 150 ha. After thinning of oil palms, six native tree species were planted in a 2 x 2 m^2 grid. The tree species were mixed in a way to maximize the number of hetero-specific neighbours (i.e., no conspecific rows or groups; Teuscher et al., 2016). There are 52 experimental plots varying in plot size and in tree species diversity level. In addition, there are also four control plots with oil palm management as usual and no enrichment planting. Our main study site was at a 40 x 40 m^2 plot with six tree species planted (Figure 1) and a nearby monoculture control plot of the same size. The agroforest plot was selected based on the criteria plot size (as big as possible, ie, 40 x 40 m^2) and highest tree diversity level (six tree species). The monoculture control plot was located approximately 60 m away from the agroforest plot. At the selected agroforest and monoculture study plot, oil palms were of similar age. In the agroforest, the studied oil palms had an average meristem height of 6.8 ± 0.2 m (mean ± *SD*), whereas the sample trees had an average height

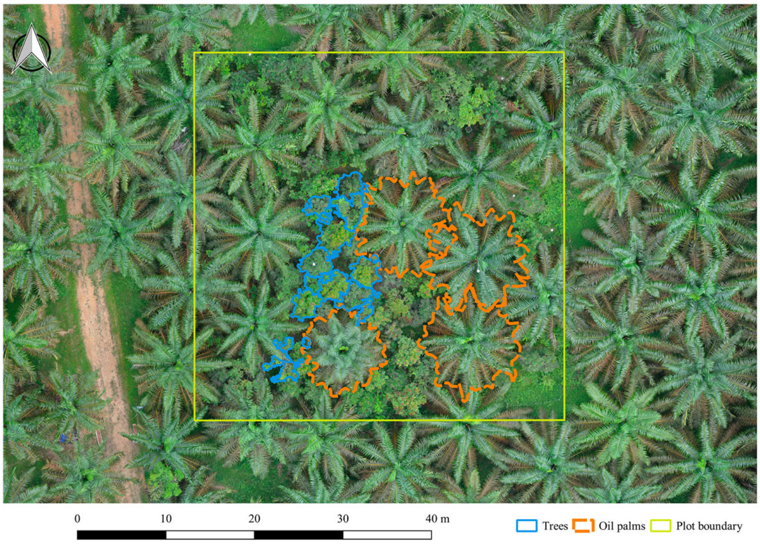

FIGURE 1 Aerial view of a studied oil palm agroforestry plot. Three years prior to the study, the stand was thinned with reduction in oil palm stems by 40% and six tree species were planted

of 4.7 ± 0.6 m (Appendix A). The reported measurements were conducted between September and November 2016, which was the beginning of the rainy season.

2.2 | Sap flux measurements

Eight palms and 16 trees were equipped with sap flux sensors. Selected tree species were *Archidendron pauciflorum*, *Parkia speciosa*, *Peronema canescens*, and *Shorea leprosula*. As *S. leprosula* did not perform well on the multispecies plot, it was measured on a nearby single tree species enrichment plot, under otherwise very similar conditions. One further tree species, *Dyera polyphylla*, was not included in the measurements because almost all individuals had died on the multispecies plot and no plot with well performing *D. polyphylla* trees were available nearby. *A. pauciflorum*, *P. speciosa*, and *P. canescens* are early successional and light demanding species (Aumeeruddy, 1994; Lawrence, 2001; Lee, Wickneswari, Clyde, & Zakri, 2002; Orwa, Mutua, Kindt, Jamnadass, & Simons, 2009); *S. leprosula* is considered a gap opportunist (Ådjers, Hadengganan, Kuusipalo, Nuryanto, & Vesa, 1995; Bebber, Brown, Speight, Moura-Costa, & Wai, 2002). Sap flux sensors were installed in four trees for each tree species and on four oil palms in an oil palm agroforest and additionally on four oil palms in the oil palm monoculture.

For trees, we used heat ratio method sensors (Burgess et al., 2001; ICT International, Australia). One heat ratio method sensor per tree was installed radially into the xylem at breast height. To process raw data we used the software Sap Flow Tool, version 1.4.1 (ICT International, Australia). The mean sap velocity output data was converted into "sap flow" ($cm^3\ hr^{-1}$) by multiplying it with the cross-sectional water conductive area A_c (cm^2). As the studied trees were rather small (diameter at breast height, DBH < 11 cm), we considered A_c to be equal to the cross-sectional area at breast height. Estimation errors associated with assuming fully conductive cross-sectional areas of the relatively small trees for the up-scaling to tree water use are likely to be small; for similar sized trees, Delzon, Sartore, Granier, and Loustau (2004) found a difference of approximately 4% with this assumption.

For oil palms, we used thermal dissipation probes (Granier, 1985) as this method had previously been tested on oil palm and a sampling scheme had been developed (Niu et al., 2015), which we followed closely. Like Niu et al. (2015), we installed the thermal dissipation probes sensors in leaf petioles rather than the stem of oil palms due to presumably higher vessel density and homogeneity in vascular bundle distribution (Madurapperuma, Bleby, & Burgess, 2009; Renninger, Phillips, & Hodel, 2009). Niu et al. (2015) also tested the influence of leaf characteristics such as leaf orientation, inclination, and horizontal shading on leaf water use for 56 oil palm leaves, but no statistically significant effects were observed. The authors argued that the examined factors partly counteract (Niu et al., 2015). We followed their suggested scheme in our study and selected four leaves per palm in the cardinal directions. Sap flux density J_s ($g\ cm^{-2}\ hr^{-1}$) was calculated using the equation derived by Granier (1985), but with oil palm specific, calibrated equation parameters (Niu et al., 2015). Zero-flux conditions were examined following Oishi, Oren, and Stoy (2008); it was found that zero-flux conditions were met during the early morning hours during our entire sap flux measurement period. Individual leaf water use rates ($kg\ day^{-1}$) were calculated by multiplying J_s day sums by A_c of the according leaf petioles. Those were derived from a previously presented linear relationship between petiole baseline length (which was measured with a calliper) and A_c at the location of the sensor (Niu et al., 2015). Individual daily leaf water use rates were averaged for each palm and multiplied by the number of leaves per palm to derive palm water use rates ($kg\ day^{-1}$). Water use rates were based on averages of three sunny days on which soil moisture was nonlimiting in order to minimize the effects of varying environmental conditions; this approach is in accordance with previous research on oil palm water use (e.g., Hardanto et al., 2017; Niu et al., 2015; Röll et al., 2015). In the nomenclature across the applied sap flux methods, we follow Edwards, Becker, and Cermák (1997) in expressing individual tree and oil palm water use as mass per time ($kg\ day^{-1}$) and stand-scale transpiration in "$mm\ day^{-1}$."

2.3 | Drone image acquisition and processing

At the time of the sap flux measurements, drone flights were conducted using an octocopter (MikroKopter OktoXL, HiSystems GmbH, Germany) equipped with a digital RGB camera (Nikon D5100, Japan). Flight routes were planned with MikroKopter-Tool V2.14b. Flight altitude was 39 m above ground, flight speed was 7.2 km hr^{-1}, and one picture was taken per second (Appendix B).

The flight missions were performed in circular and grid pathways to get different perspectives and an overlap of 70% for the construction of 3D maps. After eliminating blurry pictures, 3D point clouds were created from an average of 600 geo-referenced images per study site with Agisoft Photoscan Professional 1.2.6 software (Agisoft LLC, Russia). The achieved point cloud density was 3 points cm^{-2}. In the analysis, we used the pictures from one single flight to construct the 3D models.

The workflow included image alignment, georeferencing, building dense point clouds, the generation of digital elevation models (DEM), and orthomosaic generation. Ground-control points printed as 8-bit barcodes and laid out during the flight campaigns were used to determine the overall positional accuracy of orthomosaic images. The 3D point clouds were generated using the Structure from Motion technique (Lowe, 2004; Westoby, Brasington, Glasser, Hambrey, & Reynolds, 2012). Orthomosaic and DEM were created for each plot for further visualization and interpretation.

In order to create canopy height models (CHM), digital terrain models (DTM) were generated from the point cloud data. For this, the three main parameters (maximum angle, maximum distance, and cell size) were defined with Agisoft's ground point classifier tool and used to differentiate ground and nonground points. The classified ground points were converted to raster format as DTM. Further, we overlaid the DEM and DTM and applied smooth filters to derive the canopy height model. Subsequently, crown polygons were delineated for target trees and oil palms through visual interpretation and tree location information. One major challenge of using aerial imagery for delineating individual tree canopies is the overlapping of crowns. It was not major issues in our study as the studied trees are young and located in gaps created by the previous thinning of oil palms. The 3D crown models of the studied palms and trees (extracted from the Structure from Motion point clouds) were derived from multiple shots at different angles and positions, thus allowing to delineate even overlapping canopies. Additionally, the very high point cloud density of 3 points cm^{-2} allowed modelling the crown structures in great detail. However, for some sample trees, we experienced difficulties with automatic 3D segmentation, for example, when branches from different trees connect (Tao et al., 2015). In such a case, we performed additional manual segmentation and processing and added clusters for the automatic approach (Trochta, Kruček, Vrška, & Kraâl, 2017). The individual canopy height of trees and meristem height of oil palms were obtained by overlaying individual crown polygons with the CHM. For trees, the highest point in CHM within the individual crown polygon was considered as the canopy height of trees (Birdal, Avdan, & Türk, 2017), whereas the lowest point was taken as the meristem height of oil palms. As a ground-based reference, canopy height of each individual was measured using a pole, and canopy width and projection area were established with the vertical sighting method (Preuhsler, 1979, also see Pretzsch et al., 2015) in the eight cardinal directions. The heights obtained by the drone-based and the ground-based methods were well correlated along a 1:1 line (R^2 = 0.69, p < 0.001; Appendix C). Also, the canopy diameter obtained by terrestrial measurements and drone based analyses were highly correlated along a 1:1 line (R^2 = 0.95, p < 0.001), suggesting the applicability of the drone-based approach. The PolyClip function in Fusion software v3.6 (USDA, USA) was used to extract individual point clouds for each tree and oil palm crown. Crown variables of each individual were obtained using measurement marker functions in the same software. For crown volume and planar area, the point clouds were interpolated in R software v3.4.3 (R Development Core team, 2016) using the Alphashape3D (Lafarge & Pateiro-Lopez, 2014) and rLiDAR (chullLiDAR2D, Silva et al., 2017) packages, respectively.

There are several different ways to compute crown volumes including convex hull and alpha shape algorithms (Colaço, Trevisan, Molin, Rosell-Polo, & Escolà, 2017). In convex hull, it constructs an envelope by considering the number of input points belongs to the convex hull to represent the outward curving shape of tree crowns. In the alpha-shape approach, a predefined and reduced alpha value serves as size criterion to construct more details, thus shrinking the corresponding convex hull closer down to the 3D point cloud (Colaço et al., 2017; Pateiro-López & Rodrıguez-Casal, 2010). In our study, we calculated the crown volumes for both trees and oil palms with a convex hull algorithm and alpha-shape algorithms, the latter using the alpha values 0.75, 0.50, and 0.25 (Appendix D). Two contrasting models (convex hull and alpha shape 0.25) are illustrated in Figure 2 for a studied oil palm and a studied tree.

2.4 | Statistical analyses

To test for differences in tree water use among species, and for differences in oil palm water use between oil palm agroforest and oil palm monoculture, we used ANOVAs, followed by post hoc Tukey's HSD; differences were assumed as significant at p < 0.05.

Plant size related variables such as crown volumes as predictor of plant water use were tested by linear regressions. We tested the variance of residuals for normal distribution by the Shapiro–Wilk test and homoscedasticity with residual plot analysis. The null hypothesis of normality was rejected at p < 0.05.

The linear regressions served as the basis for subsequent scaling of tree- and palm-level water use to stand-level transpiration. To compare the uncertainties associated with different scaling variables, we performed parametric bootstrapping with the linear relationships between water use and the predictor variables with 50,000 iterations using the R package "boot" (Canty & Ripley, 2017; Davison & Hinkley, 1997). This yielded estimates of means and corresponding standard deviations as measures of uncertainty.

All statistical analyses and plotting were performed with R version 3.4.3 (R Development Core Team, 2016).

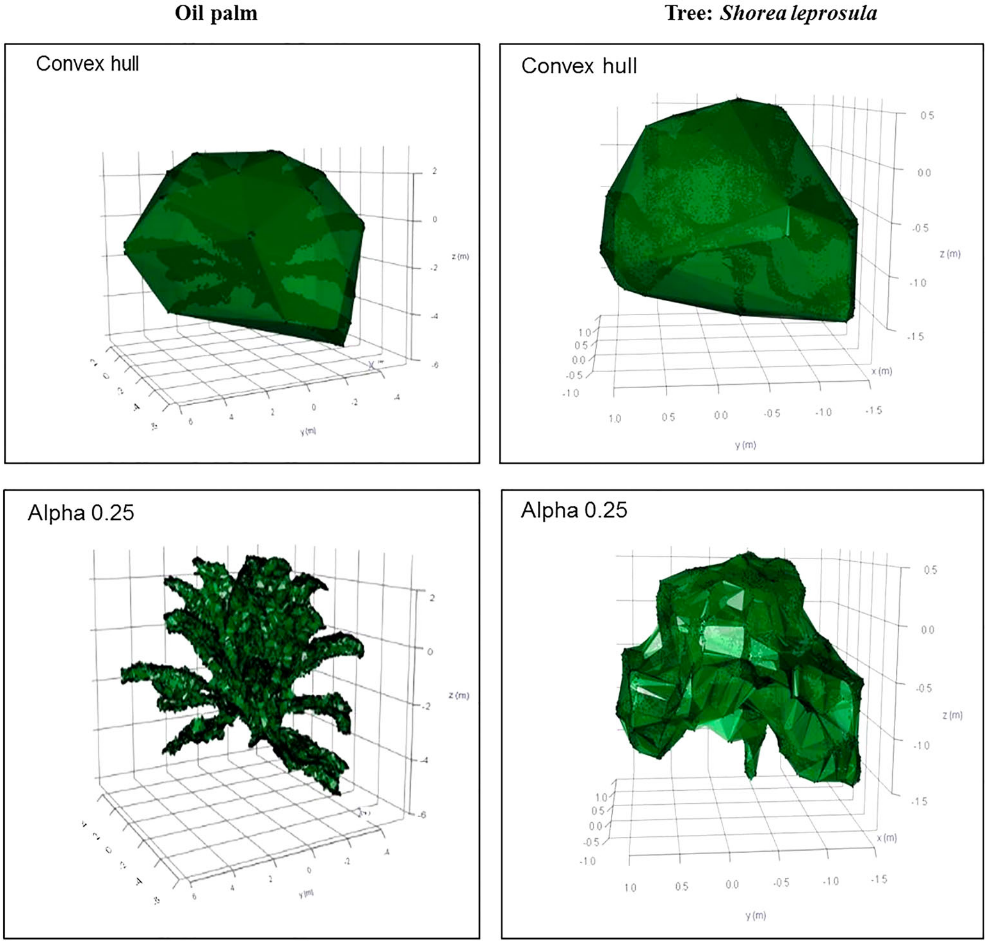

FIGURE 2 Canopy of an oil palm and a tree (*Shorea leprosula*) using point clouds from the drone missions and convex hull and alpha shape algorithms. Other tree species are shown in Appendix D

3 | RESULTS

3.1 | Plant water use

On sunny days, the daily water use per palm ranged between 158 and 249 kg day^{-1} and on average was by 32% higher in the agroforest than in the monoculture (ANOVA, $p < 0.01$). Daily water use of the interplanted trees was much lower and per tree ranged from 1.1 to 19.8 kg day^{-1}. There were species-specific differences among the trees ($p < 0.001$; Appendix A).

3.2 | Drone-derived crown metrics and their relation with plant water use

Crown volumes (convex hull) for the eight oil palms with sap flux measurements ranged between 332 and 831 m^3 and on average were by 79% higher in the agroforest than in the monoculture. Crown volumes (convex hull) of the trees were much lower and ranged between 0.95 and 81.0 m^3. There were species-specific differences among the trees (Appendix A).

Crown metrics were highly correlated with tree and palm water use (Table 1). For oil palm, crown volume convex hull explained 69% of the observed palm-to-palm variability in daily water use (0.01). For trees, crown volume models with an alpha level 0.25 (see Appendix D) explained 81% of tree-to-tree variability ($p < 0.001$; Figure 3) across the studied species. Due to violated quality criteria (Shapiro–Wilk test, 0.000042), there was however no single linear crown volume model that fit both oil palms and trees. Nonetheless, the single linear relationship crown volume alpha 0.75 to tree/palm water use is depicted in Appendix E.

For trees, stem diameter as measured in ground-based inventories explained 65% of the variability observed in daily tree water use ($p < 0.01$), whereas for oil palms, no significant ground-based explanatory variables were available for comparison.

3.3 | Transpiration estimates and uncertainties

On the basis of scaling with crown volumes, the stand-level transpiration estimate in the oil palm agroforest is 1.9 mm day^{-1} and 3.0 mm day^{-1} in the oil palm monoculture (Table 2). Scaling with ground-based DBH measurements in trees resulted in only minor

TABLE 1 Linear regressions between daily water use (kg day^{-1}) and different aerial and ground based variables of oil palms (n = 8) and trees (n = 15). Only those linear regressions that satisfy normality and homoscedasticity conditions are presented

			b_0—water use **b_1—variables**	***P* value**	**R^2**
Drone based					
Crown volume (m^3)	Oil palms	convex hull	$b_0 = 0.14\ b_1 + 122$	.010	.69
		alpha 0.75	$b_0 = 0.74\ b_1 + 49.1$	.038	.53
	Trees	alpha 0.75	$b_0 = 0.39\ b_1 + 2.12$	<.001	.73
		alpha 0.5	$b_0 = 0.51\ b_1 + 1.84$	<.001	.77
		alpha 0.25	$b_0 = 0.82\ b_1 + 1.70$	<.001	.81
Ground based					
Diameter at breast height (cm)	Oil palms		—	—	—
	Trees		$b_0 = 2.46\ b_1 - 8.42$	<.01	.65

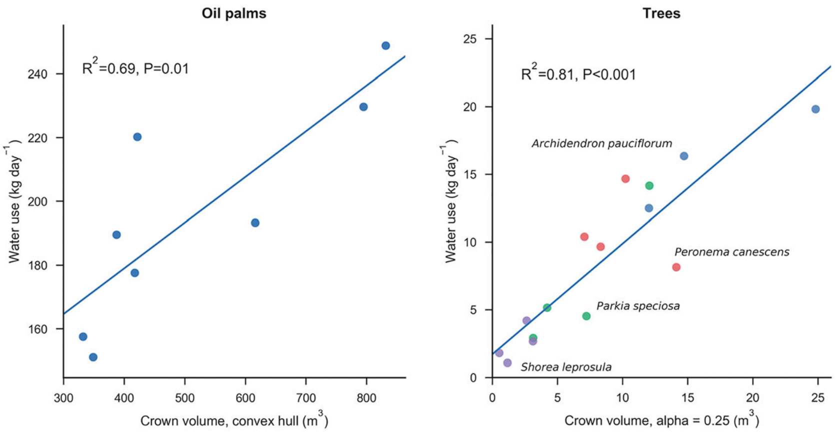

FIGURE 3 Daily water use of (a) oil palms and (b) trees versus crown volumes. Note the different crown volume models and scales

TABLE 2 Transpiration of the oil palm agroforest and monoculture plot with uncertainties for the scaling from individual plants to the plot level by bootstrapping linear relationships. For uncertainty estimates from ground-based scaling in oil palm we used an approach by Niu et al. (2015), which is based on the number of leaves that measurements were performed on and the resulting cumulative coefficient of variation (marked with an *)

		Transpiration (mm day^{-1}) Estimate ± uncertainty
Drone-based		
Agroforest	Trees	0.28 ± 0.08
	Oil palms	1.61 ± 0.61
	Total	1.89 ± 0.69
Monoculture	Oil palms	3.04 ± 1.05
Ground-based		
Agroforest	Trees	0.38 ± 0.38
	Oil palms	1.67 ± 0.88*
	Total	2.05 ± 1.26
Monoculture	Oil palms	2.96 ± 0.78*

differences in stand transpiration estimates. For trees, bootstrapping suggests that the estimate based on crown volume is associated with an uncertainty due to scaling of 28%. In contrast, using diameter for scaling results in an uncertainty of 100%. For the oil palms in the agroforest and the monoculture, the uncertainty estimates associated with crown volume scaling were 37% and 35%, respectively.

4 | DISCUSSION

In our study, we found that drone-based assessments of oil palm and tree crowns predicted individual plant water use quite well and better than, for example, diameter in trees, and thus led to reduced uncertainties in spatial scaling and stand-level estimates of transpiration.

A popular variable for the prediction of plant water use is stem diameter. In our study, DBH yielded an R^2 of 0.65, which is quite similar to several recent studies (Granier, Biron, & Lemoine, 2000; Schiller et al., 2007; Yue et al., 2008). In our study as in many others, the relationship between DBH and tree water use was found to hold across species. In contrast, in a premontane forest in Costa Rica the correlation of water use to DBH showed differences among species (Moore et al., 2017). Likewise, species-specific trajectories were suggested from reforestations in the Philippines (Dierick & Hölscher, 2009). There are further general concerns in using diameter for scaling. As such, diameter integrates over large time spans and a tree may have achieved its diameter under conditions that no longer prevail at the time of study. Cases in point are damages by storm or lightning, or in the other direction crown expansion into a gap that was formed by the dieback of a neighbour.

Our study also included oil palm, a monocot plant that lacks secondary diameter growth. Consequently, significant correlations between stem diameter and water use can hardly be expected. Thus far, to our knowledge, no scaling scheme from an individual oil palm to the stand level had been established. On the basis of leaf level measurements in 56 oil palm leaves, Niu et al. (2015) tested for relationships between leaf characteristics (e.g., orientation, inclination, and horizontal shading) and leaf water use but did not find significant relationships. In contrast, the approach of our study with crown volume and whole plant water use resulted in an R^2 of 0.69 (0.01). On the basis of their results, Niu et al. (2015) suggested a nonstratified sampling scheme. Our results would suggest that a sampling scheme in oil palm would benefit from representing different crown dimensions.

For trees and palms the best fitting (as based on high R^2 and low p) crown volume model differed with alpha 0.25 for trees and convex hull for palms. There was however one single intermediate crown volume model, alpha 0.75, that appears suitable for both trees and palms (Table 1). However, applying this model for the pooled dataset of all trees and palms resulted in nonnormality and too high heteroscedascity to be accepted (Shapiro–Wilk test, 0.000042), even though R^2 was very high and the p value was low (Appendix E). Our dataset certainly lacks values in the mid-range of crown volume and water use for a further examination of this “universal” crown model. Also, it can be seen that crown alpha 0.75 is not the best predictor for oil palm water use. However, the universal model may indicate that trees and oil palms do not differ significantly in water use per crown volume, even though more and more equally distributed data will be needed to further test this contention. On the other hand, it may also well be that a universal crown volume to plant water use relationship does not exist. As such, across (tree) species, eg, when comparing early successional and late successional species, substantial differences regarding crown shape, the occurrence of sun and shade leaves and leaf stomatal conductance exist (Bazzaz, 1979; Poorter, Bongers, & Bongers, 2006).

Sap flux measurements and subsequent scaling up to the stand level are associated with a multitude of uncertainties, including the positioning and number of a sensor in a given plant, methods of zero-flow conditions and sensor calibration (Peters et al., 2018), and the number of plants studied. Our study addresses the spatial scaling from the individual plant to the stand. The uncertainty estimates as the result of the applied bootstrapping are directly related to the explained variance in the linear relationships with water use. They suggest that for trees, the uncertainty of the stand-level estimate is 28% with drone-based imagery, whereas it is 100% with ground-based diameter measurements. The drone-based approach thus has at least one clear advantage. For oil palms, our reported uncertainty of 37% is the first estimate that to our knowledge addresses whole-plant to stand scaling. However, Niu et al. (2015) estimated that counting leaves per oil palm and oil palms per stand, and scaling based on sap flux measurements in 12 leaves, would result in uncertainty of stand-level transpiration of 14%. For oil palms, it thus seems that the previously proposed ground-based method has an advantage. Nonetheless, the crown dimension approach is still valuable, as it may also allow to estimate water use across different conditions. For example, in our case, an oil palm stand was thinned and trees were interplanted in gaps 3 years prior to the study (agroforest), whereas the control stand remained untreated (monoculture). We found significant differences in crown volume and water use of the studied oil palms, but the two variables were significantly related to each other across treatments. The ground-based leaf-count approach, on the other hand, was previously only tested in one single stand with homogenous conditions. Their applicability will have to be tested further in follow-up studies focusing on how to best assess (and reduce) such estimation uncertainties.

The crown volumes in our study were derived from RGB images and a photogrammetric approach. Other drone-derived structural variables such as height and projected crown area show a high correlation with ground-based reference measurements along a 1:1 line, suggesting the applicability of the aerial method. The point cloud density in our study was 3 points cm^{-2}, which can be regarded as quite high and compares with or is even higher than those that result from laser scanning (Vauhkonen, Næsset, & Gobakken, 2014). Drone-based imagery performs particularly well for the upper part of the canopy, which is also where a large part of the transpiration takes place. So far, we only tested this method in a relatively simply structured monoculture and an oil palm agroforest with relatively young trees. As we regard the results as promising, it will be interesting to test it in more heterogeneous stands in next step.

Oil palm water use in the studied monoculture and the agroforest ranged between 158 and 249 kg day^{-1}. The studied monoculture is relatively intensively managed, with fertilizer application including 230 kg N ha^{-1} $year^{-1}$ (Teuscher et al., 2016). The observed water use rates exceed those of small-holder plantations of similar age (108 ± 8 kg day^{-1}, mean ± SE among eight sites) and compare with values from another intensively managed, commercial oil palm monoculture plantation in the region (178 ± 5 kg day^{-1}; Meijide et al., 2018; Röll et al., 2015). Thus, our data indicates that intensive oil palm management leads to high water use rates.

The water use per oil palm in the agroforest was 31% higher than in the monoculture. This is likely due to the reduction of oil palm stand density by previous thinning in the agroforest, which leads to increases in light, soil water, and nutrient availability for the remaining oil palms in the stand. This is also in line with a previous study showing 36% higher per-palm fruit yield in thinned agroforests than in untreated monocultures (Gérard et al., 2017). The mean individual tree water use in agroforest, on the other hand, was very low (1.1–19.8 kg day^{-1}) compared with the water use of the surrounding oil palms. The large difference in tree water use is likely due to the substantial differences in tree size (4.2 vs. 11 cm) and canopy volume (1.1 vs. 24 m^3). However, tree size also coincides with species identity in our case, so “ultimate reasons” cannot be disentangled. However, these low absolute rates of the interplanted trees of relatively small diameter (DBH range 4.2–11.0 cm) compare well with values provided for rubber trees of similarly small diameter in a previous study in the lowlands of Sumatra (Niu, Röll, Meijide, Hendrayanto, & Hölscher, 2017). The general observation of high water use per palm also corresponds with data from Amazonian fruit plantations, where it was found that palms consumed 3.5 times more water than trees (Kunert, Aparecido, Barros, & Higuchi, 2015).

Scaled to the stand-level based on our aerial approach, stand transpiration of the oil palm agroforest (1.9 mm day^{-1}) was 37% lower than in the oil palm monoculture (3.0 mm day^{-1}). The higher per-palm water use in the oil palm agroforest thus did not compensate for the reduction in oil palm stand density when scaled to the stand level. The 3-year-old, comparably small interplanted trees in the agroforestry plot contributed rather little to overall stand transpiration (15%). The oil palm agroforestry experiment EFForTS-BEE was designed and established to test possibilities of reducing the impact of oil palm cultivation on biodiversity and ecosystem functioning. Oil palm monocultures are associated with ecohydrological problems arising from high transpiration rates and low soil water infiltration capacities (Merten et al., 2016). At the time of study, transpiration rates from the agroforest were substantially reduced in comparison with the commercial monoculture, which may help to alleviate some of the ecohydrological problems. However, restoring the integrity of the local hydrological cycle by means of oil palm agroforestry will also largely depend on whether soil infiltration capacities will increase due to the presence of the interplanted trees.

5 | CONCLUSIONS

Crown volumes derived from drone-based imagery predicted tree and palm water use quite well. For oil palms, such a scaling variable at the whole-plant level was previously not available. For predicting individual water use, tree crown volumes performed better than the more conventionally used variable stem diameter. In consequence, stand-level transpiration estimates based on crown volumes were associated with reduced uncertainties. We therefore see great potential for future applications of our aerial method in studies scaling plant water use from individual plants to the stand level.

ACKNOWLEDGEMENTS

This study was financially supported by the Deutsche Forschungsgemeinschaft (DFG) in the framework of a collaborative German–Indonesian research project (CRC 990 “EFForTS” project: sub-projects A02 and B11). Watit Khokthong was supported by a PhD-fellowship grant given by the Development and Promotion of Science and Technology Talents Project (DPST) from the Royal Government of Thailand. We would like to thank the Ministry of Research, Technology and Higher Education, Indonesia, for providing the research permit for field work (No. 285/SIP/FRP/E5/Dit.KI/VIII/2016). We would further like to thank our field assistant Erwin Pranata for great support during the field campaigns. Thanks to all EFForTS colleagues and friends in Indonesia, Germany, and around the world.

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How to cite this article: Ahongshangbam J, Khokthong W, Ellsäßer F, Hendrayanto H, Hölscher D, Röll A. Drone-based photogrammetry-derived crown metrics for predicting tree and oil palm water use. *Ecohydrology*. 2019;e2115. https://doi.org/10.1002/eco.2115

APPENDIX A

Drone-derived crown metrics for oil palm and four studied tree species. Tree height as derived from the canopy height model and diameters as measured at breast height are further provided. Means ± standard deviations of the palms and trees where sap flux measurements were done, sample size $n = 4$ for all groups. Crown volume was derived using convex hull and alpha shape algorithm for oil palms and trees, respectively

	Diameter at breast height (cm)	Height (m)	Crown length (m)	Crown diameter (m)	Crown volume (m^3)	Crown projection area (m^2)	Crown surface area (m^2)	Daily water use (kg day^{-1})
Oil palms (agroforest)	90.1 ± 8.6	6.8 ± 0.2	4.7 ± 0.2	11.3 ± 1.1	665.7 ± 162.8	92.3 ± 14.4	392.2 ± 65.0	223.0 ± 20.0
Oil palms (monoculture)	85.2 ± 7.3	5.9 ± 0.6	3.8 ± 0.3	10.2 ± 0.8	371.1 ± 33.2	77.5 ± 12.0	274.0 ± 18.4	168.9 ± 15.4
Trees								
Archidendron pauciflorum	8.8 ± 1.2	7.9 ± 1.0	5.5 ± 1.2	4.2 ± 0.6	15.5 ± 5.5	12.0 ± 3.2	65.2 ± 21.5	16.2 ± 2.9
Parkia speciosa	7.2 ± 1.6	7.5 ± 1.0	4.0 ± 0.8	4.0 ± 0.9	6.6 ± 3.4	8.8 ± 3.5	52.6 ± 28.3	6.6 ± 4.3
Peronema canescens	9.2 ± 1.1	7.1 ± 0.9	4.9 ± 0.6	3.8 ± 0.3	9.9 ± 2.6	9.6 ± 1.3	56.5 ± 8.1	15.0 ± 6.3
Shorea leprosula	5.1 ± 0.6	1.9 ± 0.3	1.7 ± 0.3	1.8 ± 1.0	2.2 ± 1.0	21.6 ± 5.9	2.4 ± 1.1	4.2 ± 0.6

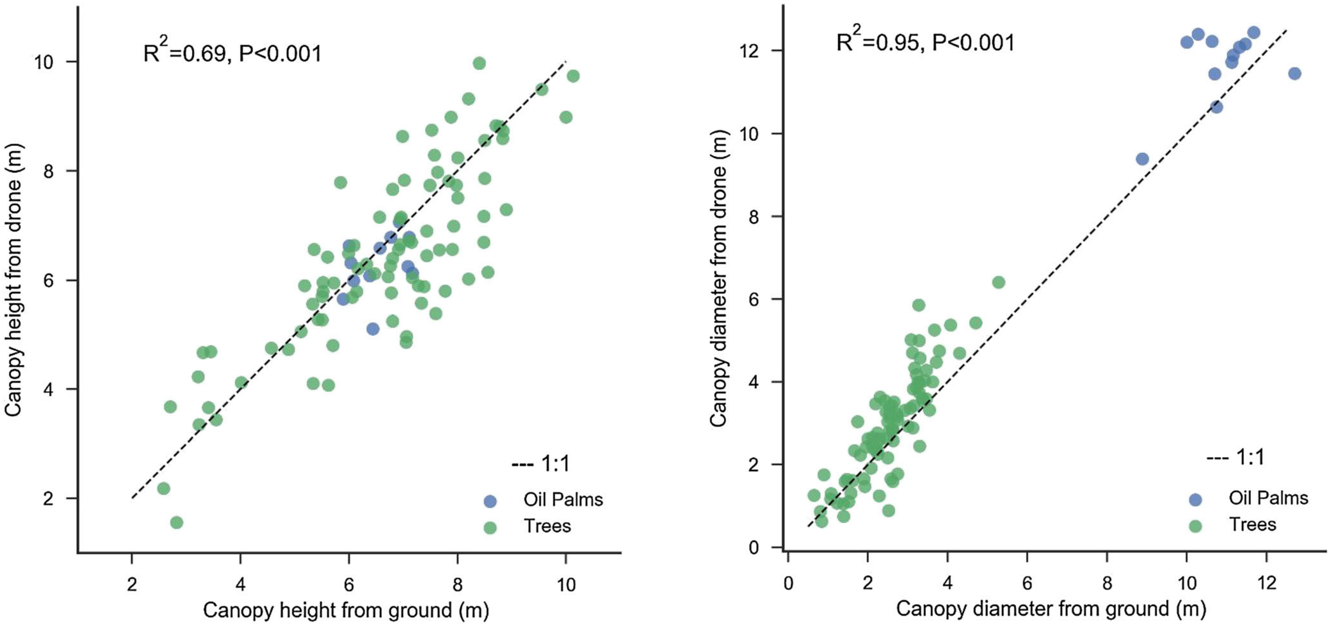
APPENDIX B

Equipment and flight details

Camera	Nikon D5100
Drone	MikroKopter OktoXL
Flight altitude	39 m
Image overlap	70%
Number of images	995 ha^{-1}
Focal length	35 mm
Ground resolution	5 mm/pixel
Point density	3 points cm^{-2}

APPENDIX C

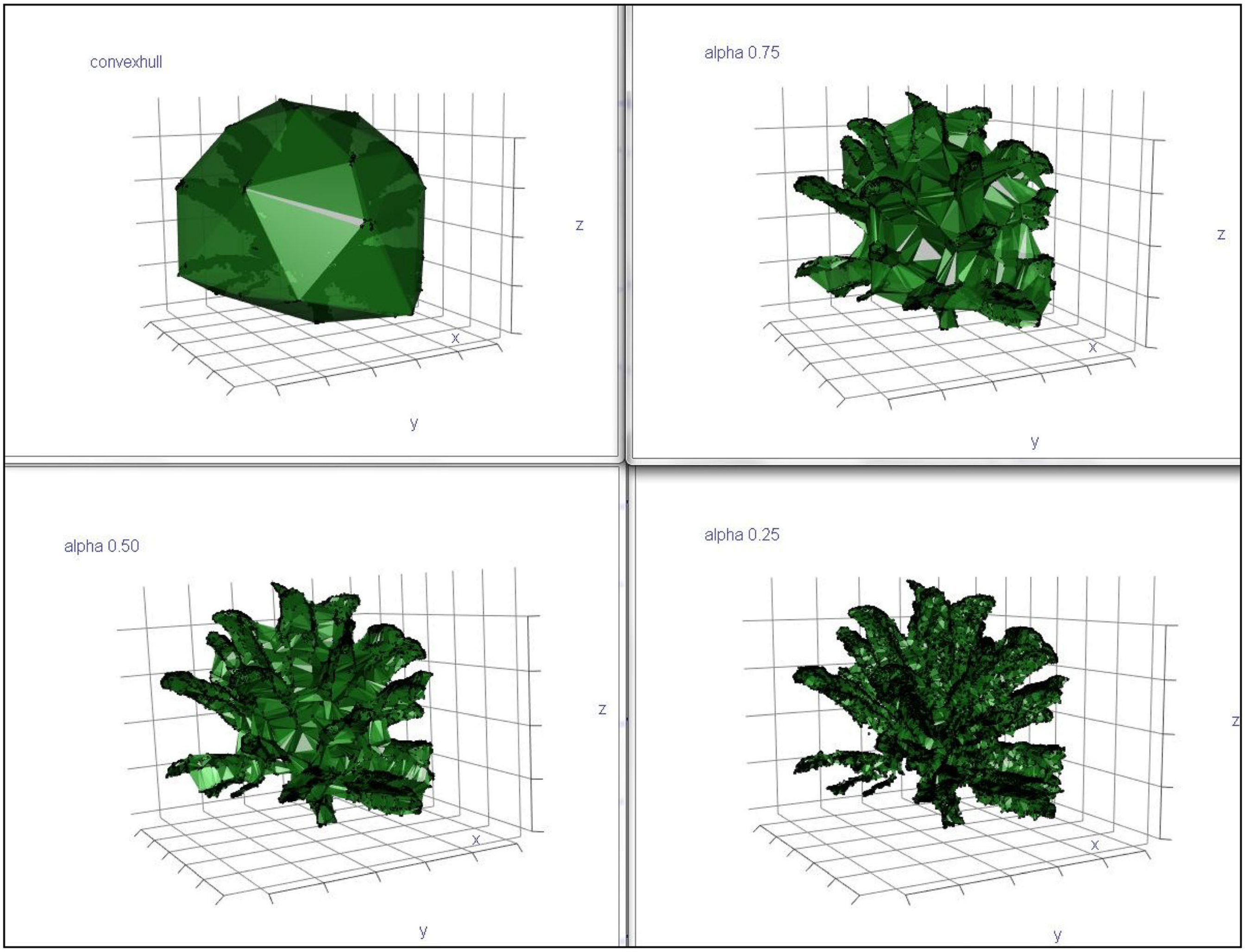
Validation of drone-derived canopy heights and widths with ground reference measurements (*n* = 99 trees and palms)



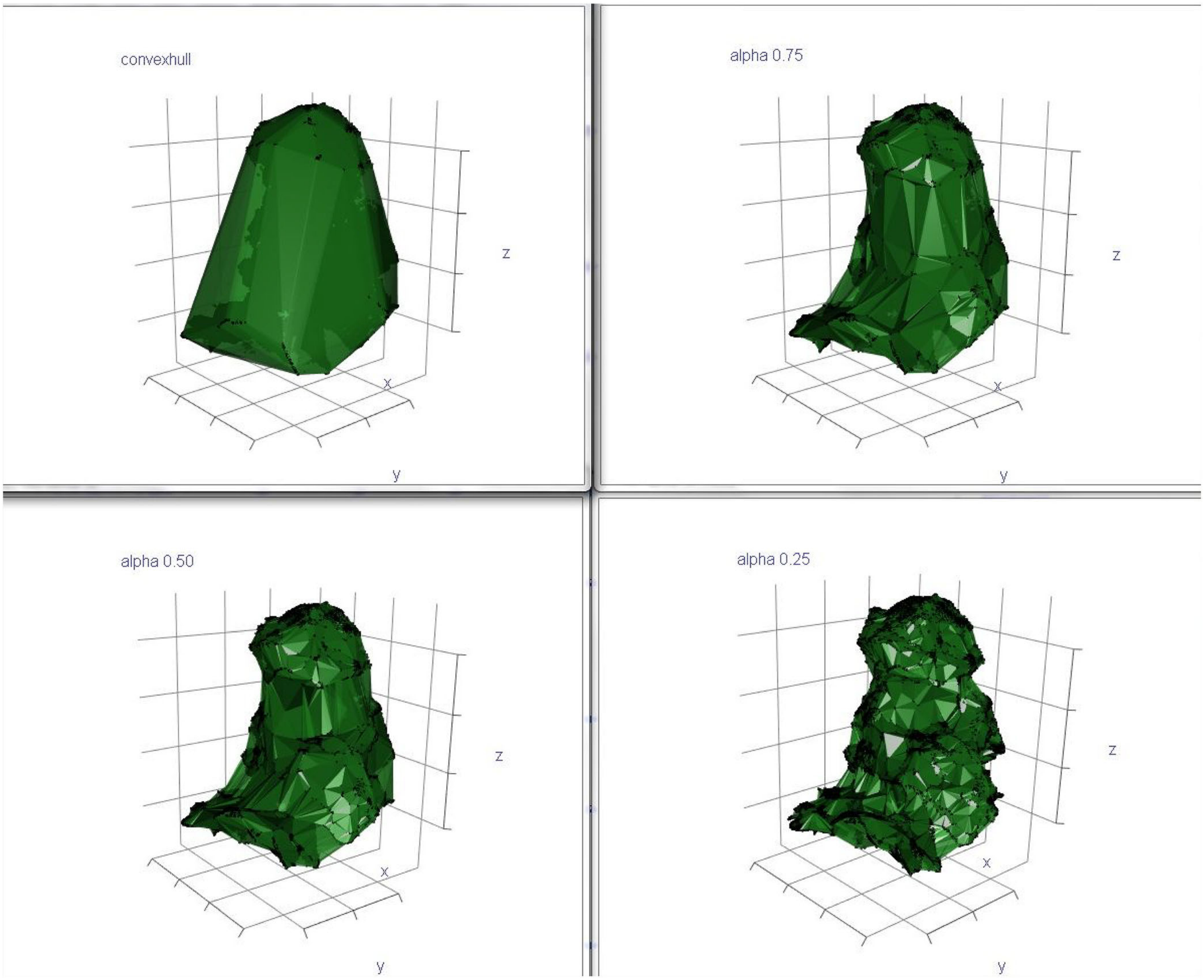
APPENDIX D

3D visualization of oil palm and tree (four tree species) crowns derived from different crown volume models (convex hull and different alpha levels)

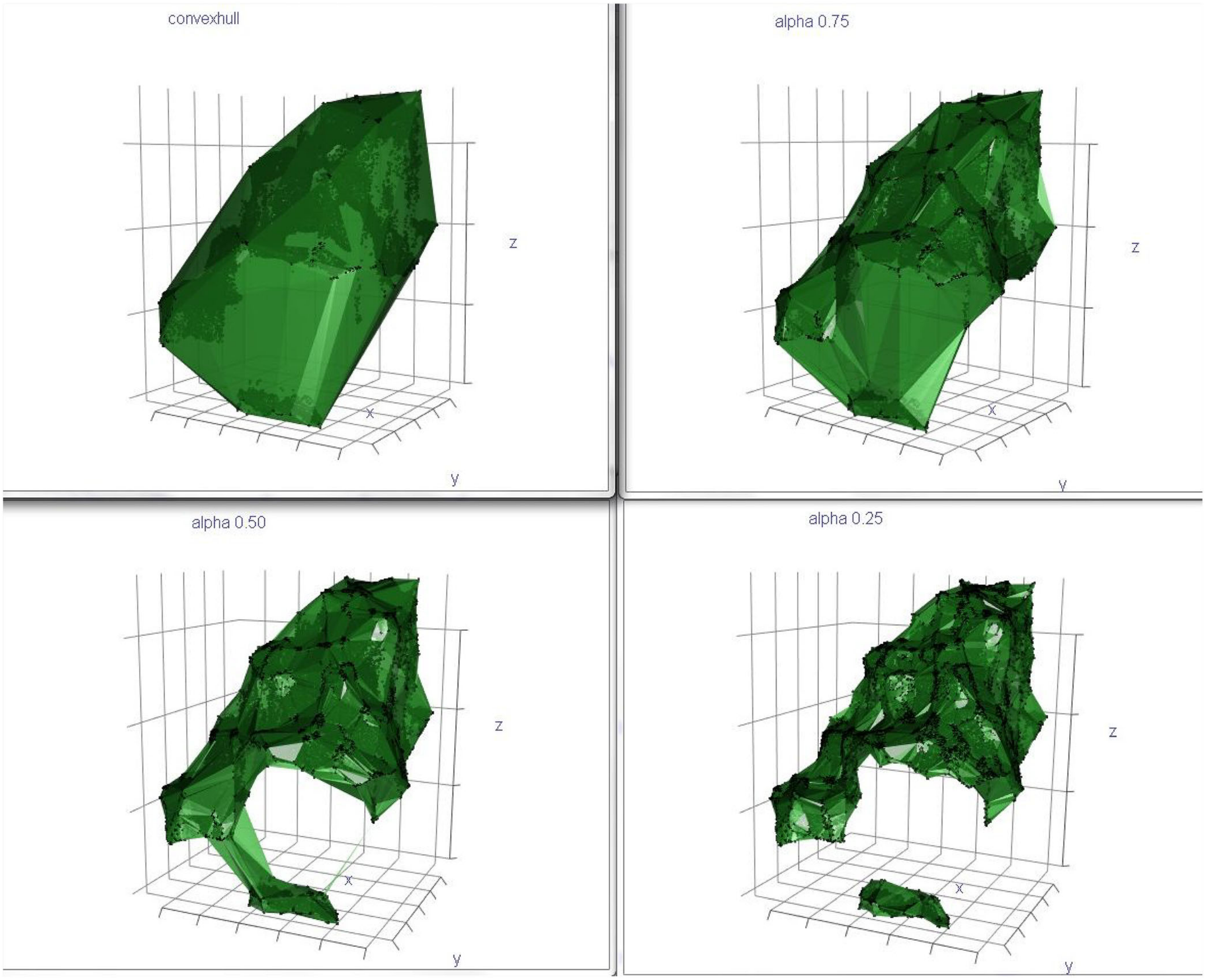
Oil palm (*Elaeis guineensis* Jacq.)



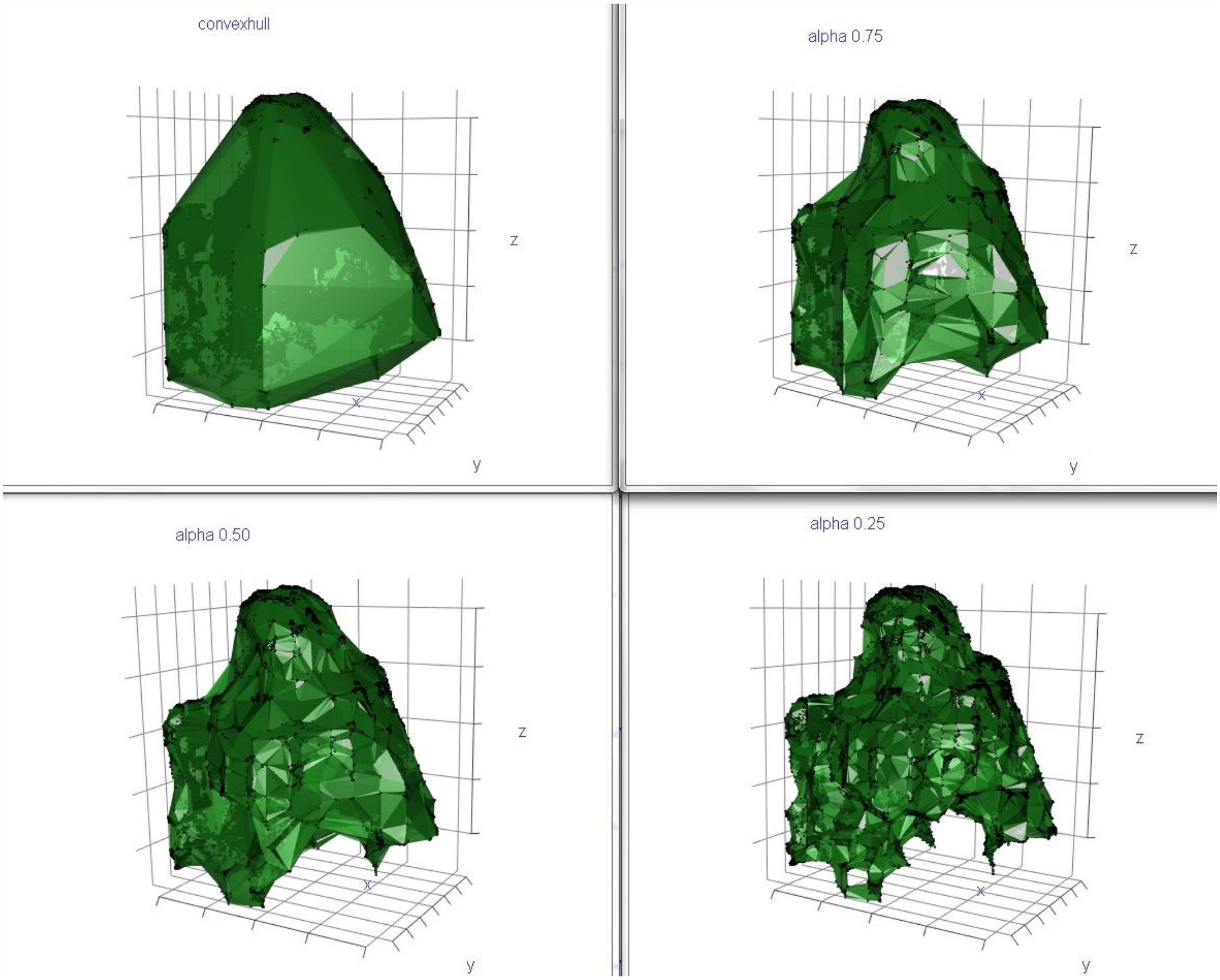
Archidendron pauciflorum



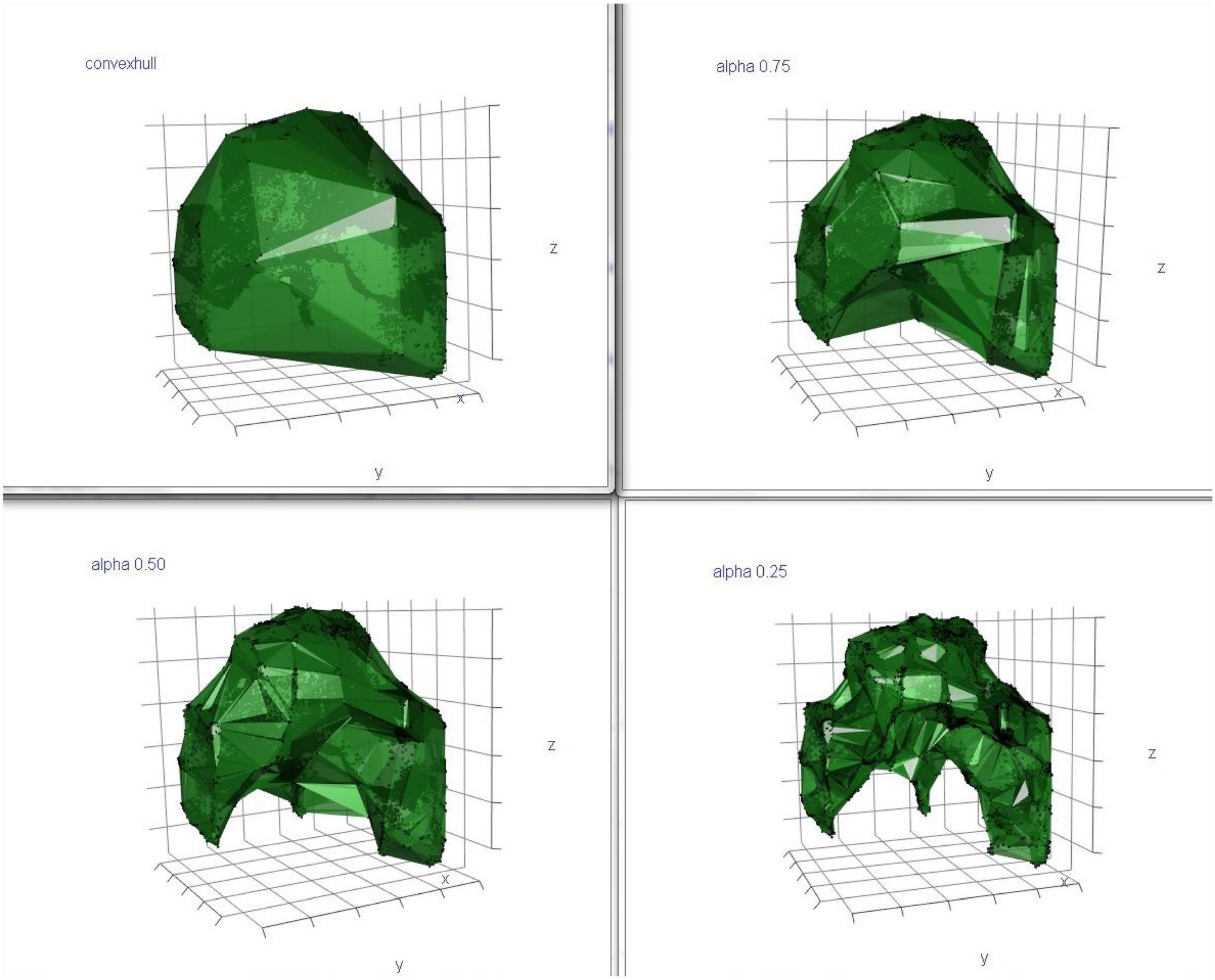
Parkia speciosa



Peronema canescens



Shorea leprosula



APPENDIX E

Daily water use across trees and oil palms versus crown volumes alpha shape 0.75. The quality criterion of normality and homeoscedascity was however violated (Shapiro Wilk test, 0.000042)