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# Low-cost drones help measure tree characteristics in the Sahelian savanna

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## Highlights

- Lowcost UAV can be used in Sahelian savanna to evaluate tree morphology variables.
- Tree height can be easily estimated from the 3D model.
- Tree species were determined from UAV output variables

## Abstract

Savanna is one of the main African ecosystems. The tree community in the savanna is a key element and provides many ecosystem services. Unmanned aerial vehicles (UAVs) combined with photogrammetric analysis are useful tools to produce accurate 3D maps, which, in turn, help describe the structure of the tree populations. The purpose of this study was to evaluate the use of commercial economical UAVs to assess tree characteristics in the

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savanna. A Dji Spark UAV was used to map 24 one-hectare plots in northern Senegal. The images were processed using Pix4D software to produce a high-resolution canopy height model (CHM). A total of 239 trees were selected and their heights and crown areas were manually measured in the field. A strong correlation was found between UAV and field measurements with $R^2$=0.84 for height and $R^2$=0.93 for crown area. Based on tree canopy colours and tree morphologies measured by UAV, it was possible to predict tree species with an error rate of 20%, using a random forest classification. This study thus confirms the possibility of using low-cost UAVs to assess tree structures in the savanna not only for research on tree communities in savanna, but also by forestry agencies to inform stakeholders.

## Introduction

Savanna is defined is a mixed woodland-grassland ecosystem, where trees are often sparse with low ground cover. Two plant communities thus coexist: a herbaceous cover with either annual or perennial species and a woody layer with trees and shrubs (Hiernaux and Le Houérou, 2006). Savanna ecosystems account for 50% of the African continental area (Olson et al., 2001). The Sahelian Acacia savanna type covers around 3,042,417 km², i.e., 10% of the African continent(Olson et al., 2001). The Sahel is a semi-arid region between the Sahara desert and the Guinean coastal rainforest extending from Senegal in the west to Djibouti in the east. The Sahelian bioclimatic region is generally defined by annual rainfall of between 200 mm and 700 mm. Rain falls during the wet season (from June to October), with high temporal variability (Nicholson, 2013).

Woody vegetation in the Sahelian savanna ecosystem, especially trees, provides numerous ecosystem services. As some species bear leaves during the dry season (from November to May), they provide fodder for animals when the grass layer is depleted (Assouma et al., 2018) . Trees and shrubs have a longer vegetative period than herbaceous plants, making them an important contributor to the carbon, nutrient and water cycles. Their deep rooting system enhances water and nutrient uptake and largely contributes to evapotranspiration

(Sinare and Gordon, 2015). In addition, the nutrients uptaken benefit all plants through litter deposits (Sinare and Gordon, 2015). Moreover, by providing shade, the trees create microclimates that enhance the productivity of the grass layer in Sahel (Grouzis and Akpo, 2006). They are also used by the local population for food, housing construction, energy and medicines.

In the 1970s and 1980s, woody vegetation was severely affected by droughts. Many authors reported a decrease in density and in species richness(Gonzalez et al., 2012; Herrmann and Tappan, 2013), whereas some remote sensing studies reported large-scale greening of the Sahel (Dardel et al., 2014; Olsson et al., 2005). An increase in woody cover seems to have been one of the reasons for the greening (Anchang et al., 2019; Brandt et al., 2015).

Field measurements, such as tree height, crown diameter, trunk circumference and species identification are thus required to document these changes and analyse their consequences for ecosystem services. However, field inventories are time consuming and require a substantial workforce. Furthermore, a sampling protocol needs to be established to study woody vegetation, especially the minimum sampling area required.

UAV is a new technology that could provide indirect and low-cost measurement protocols for woody communities. UAVs can produce very high definition maps of the vegetation in an area of several hectares in a few minutes. 3D vegetation models can be built by combining numerous images with multiple view angles using RGB photogrammetry (Grenzdörffer et al., 2008). Photogrammetry is a technique that uses several pictures of the same object to produce 3-dimensional representations of it. The processes use different viewpoints of the images to create a 3D model of the object. This process is called 'structure from motion' (SfM). During a UAV flight, many overlapping pictures can be taken. A photogrammetric software can then be used to build a digital surface model (DSM) and a digital terrain model (DEM). Using these 3D models makes it possible to compute a canopy height model (CHM) as the difference between the DSM and the DTM. With this technique, UAVs can be used to measure the structural metrics of woody plants, such as height, crown area, volume (Mayr et al., 2018; Sarron et al., 2018b; Surový et al., 2018) or for spatial patterns and species distributions(Wu et al., 2021). One interesting aspect of 3D models based on photogrammetry is that they can be computed using a simple RGB camera and do not require specific sensors such as NIR or LIDAR. For this reason, as commercial UAVs have recently become widely available and inexpensive, they can be very useful. These low-cost UAVs could easily be used in developing countries in the Sahel region.

In this context, the purpose of this study was to assess the characteristics of tree communities in the Sahelian savanna ecosystem by comparing field measurements and measurements made using low-cost UAV-based products.

## Material and methods

The overall approach of the study is schematised in Figure 1.

### ***Study sites***

All the measurements were carried out at the ISRA (Senegalese Agricultural Research Institute) Dahra Djoloff zootechnical centre (coordinates:15.3665, -15.398935 UTM 28N), which receives an average 400 mm of rain during the three months of the wet season between August and September. This research station covers 6.800 hectares, with 4.800 hectares of natural savanna and 2.000 hectares of *Senegalia senegal(L.) Britton* plantations for the production of gum arabic (Ndiaye et al., 2014; Ndiaye et al., 2015). The plantations were established in the savanna area belonging to the station. The main savanna tree species in the study area are *Balanites aegyptiaca* (L.) Del*., Vachellia tortilis* (Forssk.) Galasso & Banfi*, Senegalia senegal*(L.) Britton*, Vachellia nilotica* (L.) P.J.H.Hurter & Mabb., *Vachellia seyal*

(Delile) P.J.H.Hurter and *Boscia senegalensis* (Pers.) Lam. ex Poir. The soils at the study sites are sandy and sandy-clay with a succession of dunes and low-lying hilly areas.

Twenty-four one-hectare plots on the station were selected. The plots were a subset of plots that were sampled in the studies by Raynal (1964) and Ndiaye et al. (2015). The initial selection was made to represent the spatial variability of the vegetation at the station.

***UAV and flight plans***

A DJI® spark UAV (DJI, DJI Inc., Shenzhen, China) equipped with the native RGB (Red-Green-Blue) camera of the DJI spark was used in the study (1/2.3" CMOS® sensor with an effective resolution of 12 Mpx). The lens of the camera has a field of view of 81.9° 25 mm (35 mm format equivalent) and a shooting range of 2 m to ∞ (f/2.6). Litchi applications (i.e., flyover mission) were used for the flight plans (https://flylitchi.com). For each plot, one flight with six 100-m transects each separated by 20 m was programmed at an altitude of 80 m and a speed of 5 m.s-1. Pictures were taken at two-second intervals throughout the flight in autofocus mode. The camera was set at an angle of 80°.

The frontal overlap was around 90% and the side overlap around 80%. All flights took place at the end of the rainy season (between the 1$^{st}$ and the 15$^{th}$ of October 2018), at the peak of grass growth.

***Image processing***

The images taken during each flight were processed using a PiX4D mapper (Pix4D SA, Lausanne, Switzerland). 3D mapping is the basic parameter proposed in the software. For each plot, an orthophotograph, a digital surface model, and a digital elevation model were computed and exported in GeoTIFF format. These different raster images were then further processed using ArcGIS 10.3 (ESRI, Redlands, CA, USA). The difference between the digital surface model and the digital elevation model provided the canopy height model (CHM). From the orthophotograph, and in each plot, 10 trees were selected and their crowns were manually delineated to calculate the area covered. The 10 trees were selected based on their crown areas to cover the range of crown areas present in the plots. The geotag and the position on the image were recorded. When a tree was not found on the ground, we selected another tree on the ground in its place.

The crown limits obtained (i.e., crown masks in shapefiles) were then used to extract the tree height from the CHM. For each tree, the computed UAV variables were the crown area, average height, minimum and maximum heights, and the red, green and blue reflectance across the crown limit. The colour contrasts between the different images were not corrected.

***Field measurements***

Field measurements on trees were carried out in December 2018. First, the trees previously selected were identified using the GPS coordinates extracted from the orthophotograph of the plots. Measurements of the trees were then taken in the field. The measured variables were the maximum height of the tree (using a clinometer), the diameter of the tree crown in the north-south direction (NSD) and in the west-east direction (WED). All woody species were identified at the species and genus levels and their tree crown area was calculated using the following formula assuming that the crown was a circle:

$$Crown\ Area = ((\mathrm{NSD} + WED/4)^2 \times \pi$$

***Data analysis***

Tree height and crown area

For tree height and crown area, a linear regression model was built between field and UAV variables. The model residuals were analysed according to the species, the genus, the plot, the crown area, the maximum height, and the crown area to maximum height ratio using ANOVA.

The aim of the ANOVA was to identify ways of improving predictions. The linear model was built using 66% of the dataset, randomly selected. Model performance was then assessed using the remaining 33% of samples. A bootstrap technique was used to assess the predictive performance of the model. The root mean square error (RMSE) was computed from predicted and measured variables. RMSE was computed for the 100 replicates and the average value was used as the accuracy metric of the prediction model.

Species identification.

The main objective of this analysis was to check the potential of UAV outputs to identify the species and genus of the trees in the study area. The UAV variables used were crown area, tree height (mean crown height and maximum height) and the area to height ratio obtained from the 3D model. The colour (i.e., RGB) values of the trees were also extracted from the orthophotograph. The extracted values were then used to calculate three normalized difference indices considering colours two by two, and using the following equation (C1 is the value for colour 1 and C2 the value for colour 2).

$$NC1C2DI = \frac{ABS(C1 - C2)}{C1 + C2}$$

The calculated indices were (i) between green and red (NGRDI), (ii) between blue and green (NBGRI), and (iii) between blue and red (NBRDI). We performed a random forest analysis (Breiman, 2001; Breiman et al., 1984) to predict the species and the genus of each tree. The V The input variables in the random forest were the different colour indices and the variables obtained from the 3D model. We used the Random Forest package in Rcore software. We obtained a confusion matrix from the random forest. We also extracted the importance of each input variable of the random forest. All analyses were carried out using R 3.23. (R Core, 2013)

## Results

The field inventory showed that six woody species were present in the study site: *Vachellia tortilis, Senegalia senegal, Vachellia nilotica*, *Vachellia seyal, Balanites aegyptiaca* and *Boscia senegalensis.* The full list of available metrics for the 239 trees can be found in appendix 1.

*Tree height*

The height of the assessed woody plants ranged from 0.37 m to 13.20 m (average 5.57 m). Figure 2 shows the correlation between the maximum tree height measured with the UAV and in the field. This relationship was significant at $P < 0.01$ and with an $R^2$ of 0.83. A residual analysis of the model showed that all the tested parameters (species genus, area, area/height ratio (AH) and plot) had a significant effect on the residuals. However, the effect was quite low for all the parameters ($R^2$ ranging from 0.023 to 0.041) with the exception of the plot parameter. The plot parameter explained 40% of the variability of the model residuals ($R^2 = 0.40$). When the plot was included in the model between field height and UAV height measurements as a nested factor, $R^2$ rose to 0.92. The root mean square error (RMSE) was 0.95 m.

*Tree crown area*

The woody crown area measured in the field ranged from 1.1 $m^2$ to 213.7 $m^2$ (average 29.03 $m^2$). The relationship between field and UAV measurements was significant ($P < 0.01$) and showed a high $R^2$ (0.93) (Figure 3). Table 1 lists the results of the residuals analysis. The plot had the most effect on the residuals; the $R^2$ was 0.14 for the model explaining the residual variability from the different plots. The area/height ratio also had on effect on the residuals. The root mean square error mean obtained from the bootstrap was 7.46 $m^2$.

Species identification

Of the 239 trees whose contours were available, 132 were *B. aegyptiaca*, 54 *V. tortilis*, 29 *S senegal*, 10 *B. senegalensis, 9* V*. nilotica* and *5 V. seyal*. Table 2 presents the confusion matrix obtained from the random forest computed at species level. The overall error of the random forest for species identification was 20.08%. During the classification, 124 individuals of *B. aegyptiaca* were correctly identified by the random forest model, while two were identified as *V. tortilis* and four as *S. senegal* (6% of errors in the classification). Forty-three *V. tortilis* individuals were correctly classified, while the other 11 were classified as *B. aegyptica* (20% of errors). Nine out of 10 *B. senegalensis* were classified correctly. The tenth was classified as *S. senegal* (10% of errors). Thirteen out of 29 *S. senegal* were classified correctly. The other nine were classified as *V. tortilis, B. aegyptica* and *Boscia senegalensis* (55% of errors). Only two V*. nilotica* trees were classified in the right category. The other seven were classified as *S. senegal*, *V. tortilis, B. aegyptica* and *Boscia senegalensis* (78% of errors). Due to the small number of individual *V. seyal*, the random forest did not create a class for them, consequently all the individuals were wrongly classified. Figure 4 shows the importance of the variables in the classification. The normalized green-red difference index (NGRDI) was the most important variable for species classification, followed by the area to height ratio. Table 3 lists the confusion matrix obtained from the random forest at genus level. All the *Acacia (Vachellia and Senegalia)* species were clustered together and the overall error was 13.81%. Among the 97 Acacia trees, 75 "*Acacia"* were correctly classified and 22 wrongly classified (23% of errors), 124 *B. aegyptica* were in the right class (with eight in the wrong classes) and seven out of 10 *B. senegalensis* were correctly classified.

## Discussion

### ***Low-cost UAVs can be used to assess the dendrometric parameters of woody species in the savanna***

Our results show that low-cost UAVs can successfully assess certain characteristics of the woody vegetation in the Sahelian savanna. Indeed, strong relationships were found between tree characteristics measured in the field and those obtained from the UAV. For tree height, we found a very good correlation with no more than 1m difference between the field measurement and the UAV measurements. The difference between field and UAV measurements was not necessarily due to inaccuracies produced by the UAV. The clinometer is not the most accurate of field methods for estimating height (Williams et al., 1994). Similar results for estimated tree height were found in the literature for different types of tree communities: tropical forests, orchards, plantations (Sarron et al., 2018b). We assume that UAV is sufficiently accurate compared with the other methods. The tree crown area estimated in the field was largely explained by the area measured on the orthophotograph (Figure 3). The area in the field was obtained by considering that the tree crown is circular. Conversely, in the UAV measurement, the border of the tree crown was manually drawn on the orthophotograph. It can be assumed that the area obtained with a UAV would be more accurate for a tree with an unbalanced crown.

Our results also showed that UAV metrics can discriminate between the four species present in the study area. Woody vegetation diversity was quite low at the study site where the woody species displayed very distinct features in terms of shape (only four species were represented by more than 10 individuals in our sample). It would thus be interesting to test UAVs on more diverse species. Two criteria were mainly used for woody species discrimination, NGRDI and the area/height ratio. These two variables are indicators of the morphology of a tree. "*Acacia*" species generally have a larger crown area height ratio than other species. Indeed, "Acacia" species have a more elongated structure than other species. The NGRDI index was also higher for *Acacia* than for the other species. One objective of future research will be to distinguish the species in the "*Acacia*" genus. "*Acacia*" species are legumes and generally have greener leaves than other species. Our acquisition flights were only performed during the wet season, when almost all species had green leaves. As many species lose their leaves during the dry season, further flight tests should be made to ensure that species recognition works correctly whatever the time of year.

Limits of commercial UAVs

We analysed the residuals of the model to estimate the height and crown area. Our goal was to identify potential sources of error to see how the model could be improved. The ANOVA of the residuals showed that they differed between plots in both models. When the plot was added as a nested factor for height and crown area, we found a significant increase in $R^2$. These differences between plots may have originated in the 3D mapping in the Pix4D software. In fact, the exact position of the images (geotagging) is required for photogrammetric analysis and the software used the geotag of the image produced by the UAV. These coordinates come with a number of inaccuracies. Consequently, one of the first steps in the process is to recalibrate the position of the images using the key point on the ground. One characteristic of Dji Spark is that the GPS coordinates are only recorded up to 4 decimal points, unlike higher UAV standards used by the same company (Mavic, Phantom or Matrice 600 for instance). This low accuracy increased the repositioning process, and it can be assumed that some differences in recalibration for each plot added some differences to the size referential. To correct these differences, a similar object between plots, such as a car, could be used to recalibrate the 3D model. This problem could also be reduced by using a UAV with higher positioning accuracy, such as the Dji mavic pro (8 decimals), which was used, for example, in the study by Sarron et al. (2018a). Low geotag resolution is also problematic for the accuracy of positioning objects in the field. This is one of the reasons why some trees could not be found in the field. Furthermore, with the problem of positioning accuracy, some flight planning applications could not be used with the Dji spark (Pix4D capture) and, in this study, we only identified the Litchi application as a solution. Another drawback is that flight planning cannot be carried out directly in the field. Dji spark has only one 12Mpx captor, so the orthophotograph produced with an 80 m flight had a resolution of around 4 cm. Some commercial UAVs now have higher resolution cameras and could be used instead to produce higher-resolution maps. Of course, higher resolution includes longer calculation times and heavier images. In each case, it needs to be decided whether a more precise map is more important than ease of use. However, this work showed that a commercial UAV equipped with RGB camera can be used to estimate tree communities. Of course, higher spectral resolution captors could be worthwhile, perhaps using different variables from the ones we used. Indeed, some indices calculated from NIR and thermal variables provide information about the physiological stage of the tree (evaluation of photosynthesis, hydrological status of the tree).

***Future outlook for the use of UAV in the Sahelian savanna***

UAV is currently a hot topic in forestry research. Many studies have been published on the use of UAV to estimate the morphological features of trees using structure from motion processes in plantations(dos Santos et al., 2020), drylands (Cunliffe et al., 2016) or in natural savanna (Mayr et al., 2018). UAV is also used to identity tree species mainly using a multispectral camera. (Kolarik et al., 2020; Oldeland et al., 2017) In these studies, the trees are mostly isolated like in our study. Our study confirmed that UAV can also be used for Sahelian tree communities where the woody cover is around 5%.

We suppose this approach could be limited in denser savanna such as the Guinean savanna with more 40% of woody cover, but other approaches based on UAV can be used in dense savanna or forest (Bourgoin et al., 2020).

In the present study, we used the cheapest UAV with GPS navigation available at the time, the DJI Spark system (around 500€). Few studies on UAV in forest science have used the Spark (Anifantis et al., 2019). We also used a user-friendly structure from motion software PiX4D mapper with the basic 3D map parameter, showing that UAV can be used on the woody community at very low cost without specialised knowledge of image analysis. UAV could thus be a tool for forester research and agencies in the Sahel region.

UAVs have other drawbacks. The maximum flight time of a low-cost drone is between 15 min (For the Dji Spark) and 30 min (for the Dji Mavic or Parrot Anafi), so the area covered by the UAV is limited to a few tens of hectares, so cheap UAVs cannot be used to monitor large areas. Another drawback is the calculation time needed to produce 3D maps (around 6 or 7 hours for each map on a basic computer). Further, regulations on the use of UAV may be restrictive.

Nevertheless, simple UAVs, like the one we used in the present study could be a useful tool for forestry researchers and agents in all Sahelian countries and would be very useful for future research on woody communities in the following cases:

- to study the spatial distribution of trees (distance between trees, pattern of distribution).
- to assess woody biomass (tree and leaf biomass) and density on a scale of 1 to 20 ha. They could also be an intermediate stage between field measurements and satellite measurements and could be used to produce maps of tree variables on a large scale.
- to monitor tree communities in the savanna.

## CONCLUSION

The goal of this study was to estimate tree parameters using a low-cost UAV in a Sahelian savanna. Our results show that tree height and crown area in the savanna can be easily assessed from UAV images using structure from motion techniques. These results confirm the results of previous studies on the use of the UAV to study isolated trees in other types of ecosystem.

In this work, we used the cheapest UAV available with GPS and use structure from motion software without changing the mapping parameter, thus confirming that UAV may be a cheap and user friendly tool for forest studies in drylands.


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## CRediT author statement

**M. Bossoukpe**: Methodology, Investigation, Data Curation, Visualization, Writing - Original Draft **E. Faye**: Conceptualization, Methodology, Data curation, Writing - Review & Editing, **O. Ndiaye:** Methodology, Investigation, Supervision, Writing - Review & Editing **S. Diatta**, Supervision and Writing - Review & Editing **O. Diatta**: Methodology, Investigation, **A.A. Diouf:** Writing - Review & Editing, **M Dendoncker**: Writing - Review & Editing ,**M.H. Assouma,** Methodology, Writing - Review & Editing, **S. Taugourdeau:** Conceptualization, Methodology, Data curation, Writing, Supervision Writing - Original Draft, Project administration

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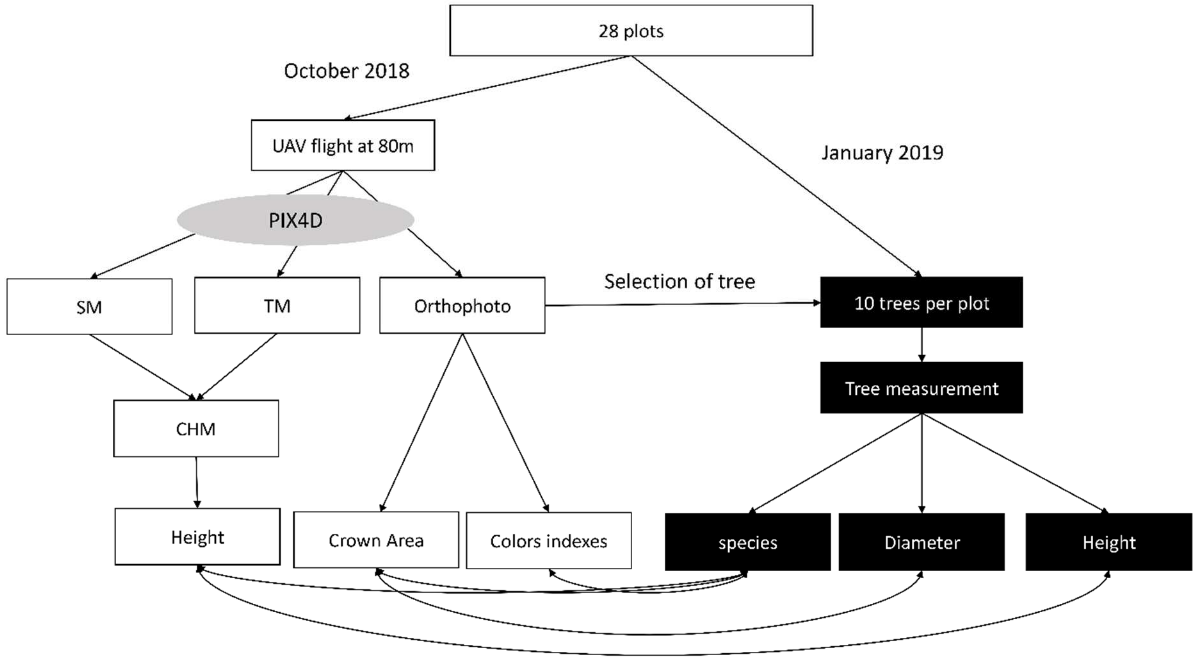


*Figure 1: Methodological approach used in this work. The study was conducted on 24 plots. The white boxes show the workflow of the UAV images. The black boxes represent the tree measurements made on the ground. Details of the methodology can be found in the material and methods section.*

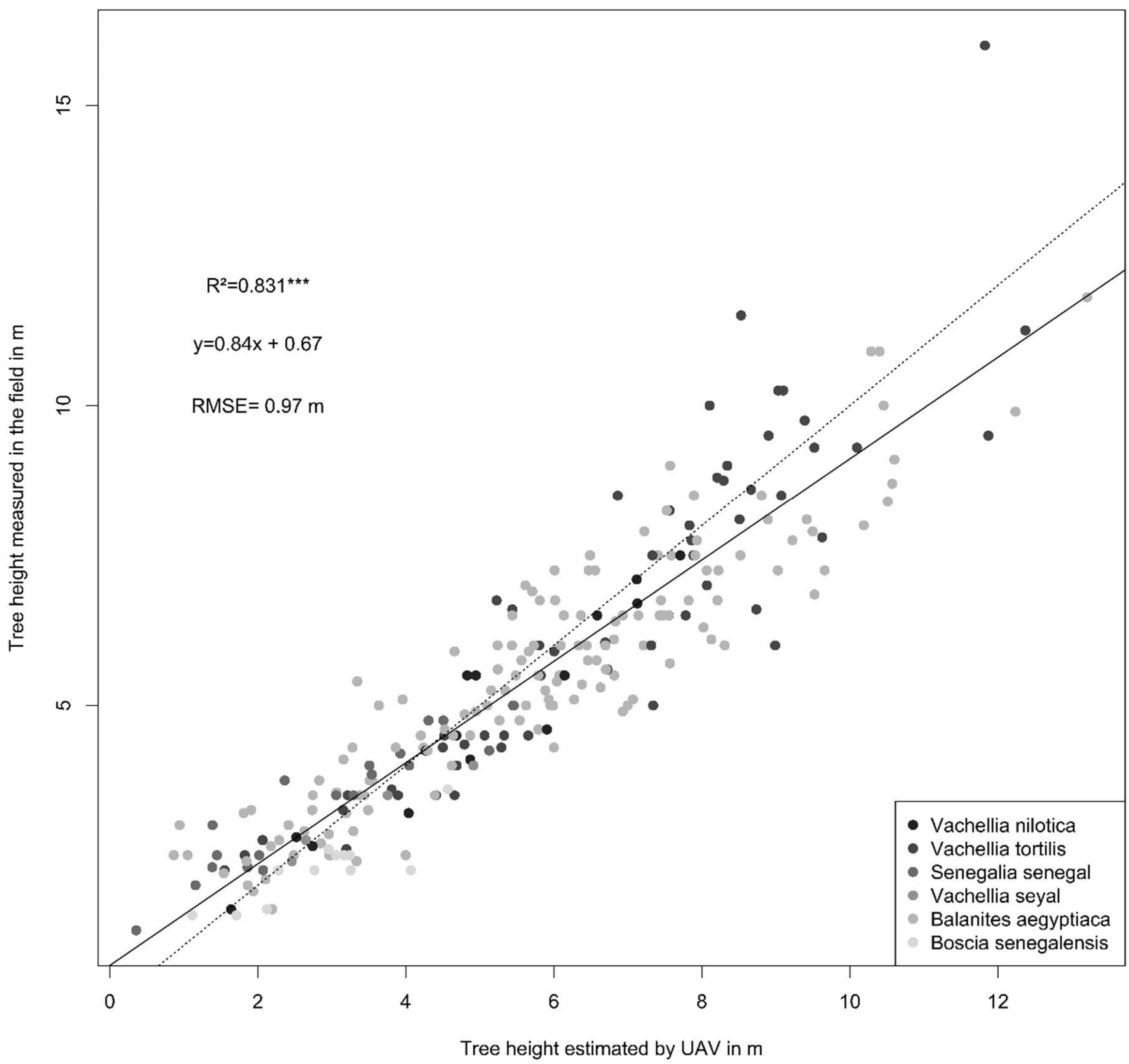


*Figure 2: Correlation between tree height measured from the UAV and tree height measured in the field. The grey level of the dots represents the species. The black line represents the model between the two variables. and the dotted line represents the 1:1 line*

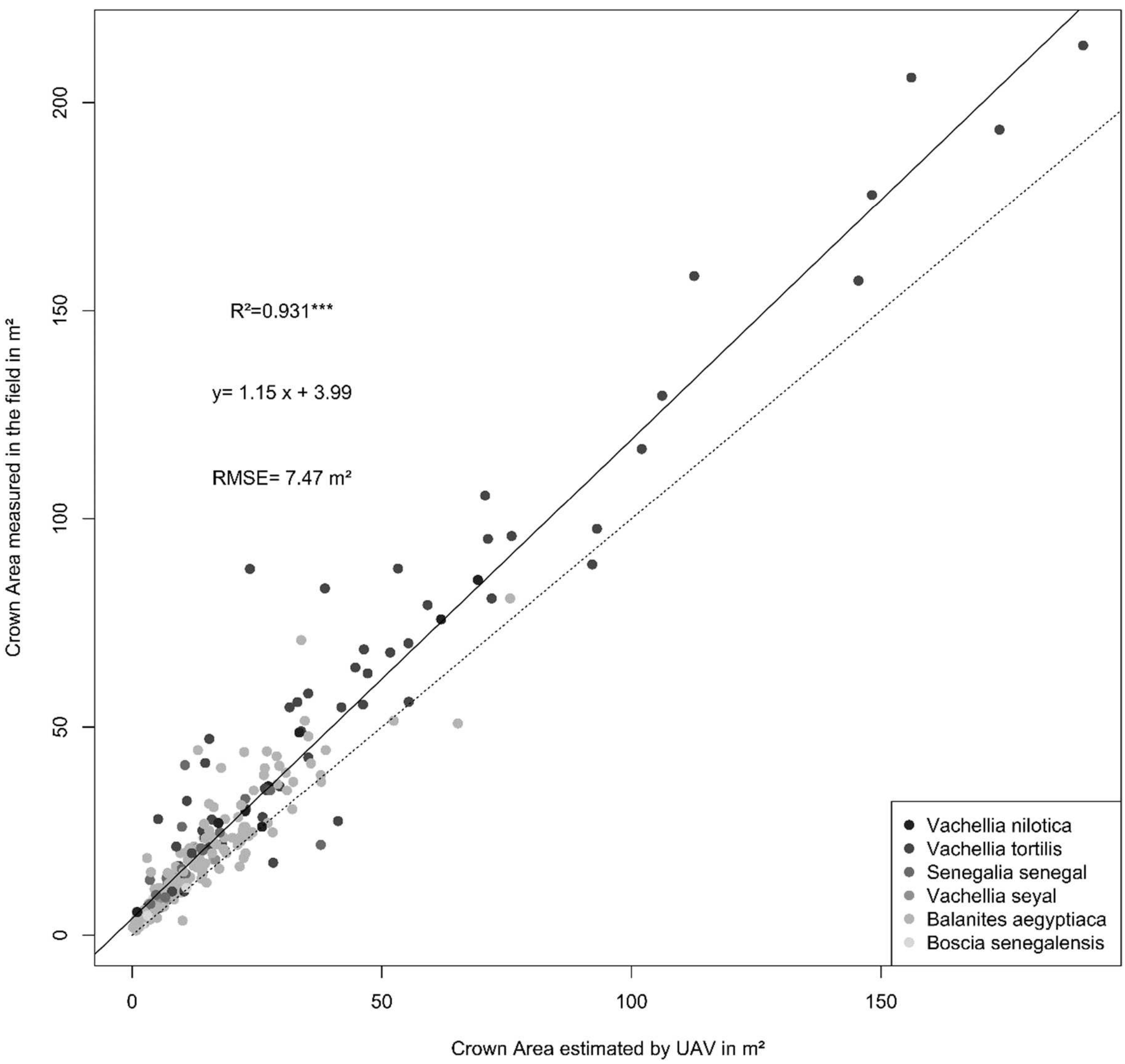


*Figure 3: Relationships between the area measured on the orthophotograph and the area measured in the field. Grey levels represent the species. The black line represents the model and the dotted line represents the 1:1 line*

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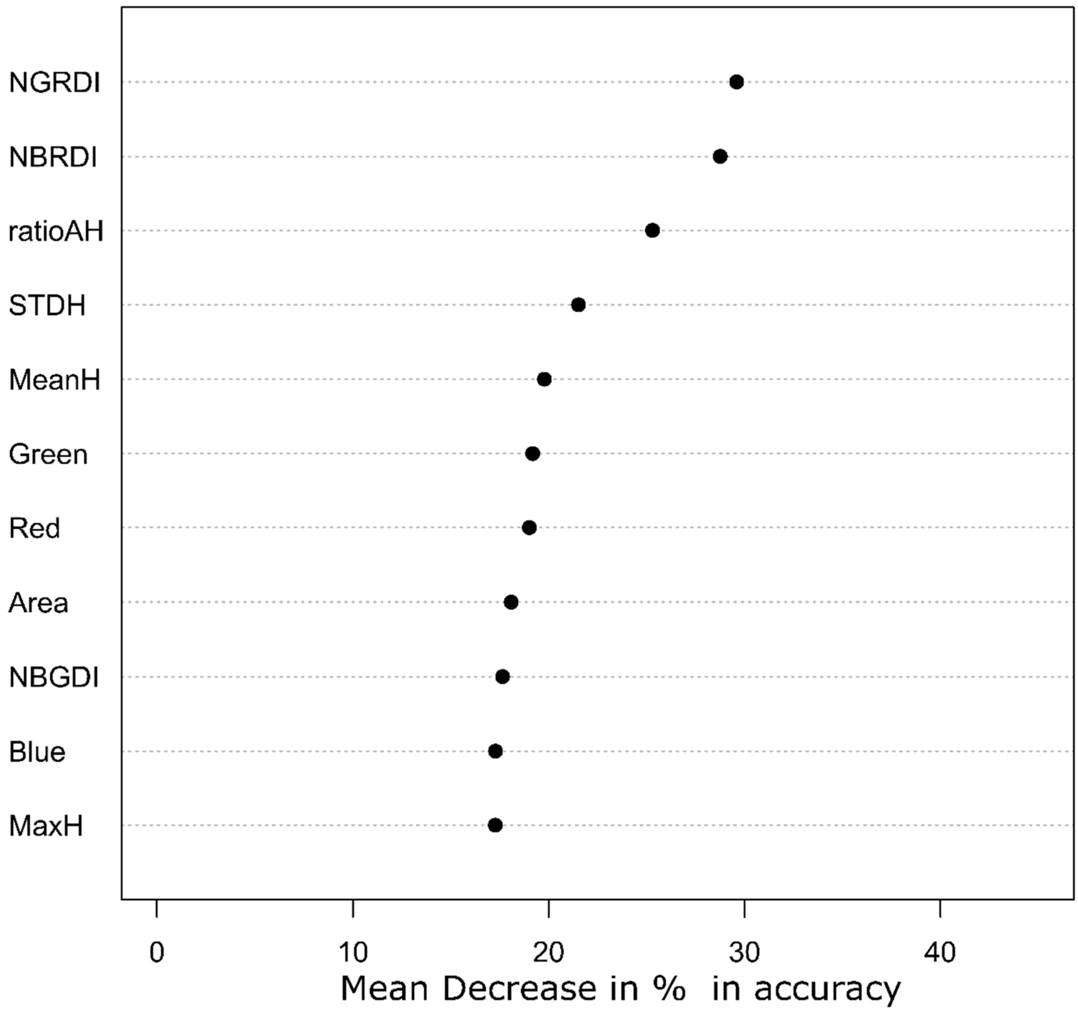


*Figure 4: Importance of the different variables in the random forest prediction of species (the importance is expressed by the mean decrease in accuracy as a percentage). In the random forest process, the predictor variables were not used in each of the 500 regression trees. The mean decrease in accuracy was calculated by comparing the quality of the regression trees using a variable and without the variable. The variable with the highest mean decrease in accuracy in % is the variable that was the most important.*

*Table 1 Analysis of the residuals of the model for height and crown area. The impact of the species, the genus, the plot, the crown area, the height of the tree and the area to height ratio were tested. The two first columns represent the analysis in the model of tree height and the two last the crown area for each, the p value and the $R^2$ of the model between the residuals and the tested factors are presented*

| | Height (m) | | Area ($m^2$) | |
|---|---|---|---|---|
| | pvalue | $R^2$ | pvalue | $R^2$ |
| Species | 8E-03 | 0.04 | 0.4 | 0 |
| Genus | 2E-03 | 0.04 | 0.2 | 0.01 |
| Plot | 2.E-16 | 0.40 | 5E-05 | 0.14 |
| Area | 8.E-03 | 0.02 | / | / |
| Maximum height | / | / | 0.2 | 0 |
| AH ratio | 4E-03 | 0.03 | 5E-05 | 0.07 |

*Table 2: Confusion matrix of the random forest for the prediction of the species from UAV variables. The rows show the species of the individual trees that were identified on the ground and the columns show the species predicted by the random forest based on UAV input. The last column gives the percentage of individuals that were classified in the correct category.*

| | *Vachellia nilotica* | *Acacia senegal* | *Vachellia seyal* | *Vachellia tortilis* | *Balanites aegyptiaca* | *Boscia senegalensis* | Class error in %r |
|---|---|---|---|---|---|---|---|
| *Vachellia nilotica (9)* | 2 | 2 | 0 | 2 | 1 | 2 | 78 |
| *Senegalia senegal (29)* | 0 | 13 | 0 | 7 | 8 | 1 | 55 |
| *Vachellia seyal (5)* | 0 | 0 | 0 | 0 | 5 | 0 | 100 |
| *Vachellia tortilis (54)* | 0 | 0 | 0 | 43 | 11 | 0 | 20 |
| *Balanites aegyptiaca (132)* | 1 | 4 | 0 | 2 | 124 | 1 | 6 |
| *Boscia senegalensis (10)* | 0 | 1 | 0 | 0 | 0 | 9 | 10 |

*Table 3: Confusion matrix of the random forest for the prediction of the genus from UAV variables. The rows show the genus of the individual trees that were identified on the ground and the columns show the genus predicted by the random forest based on UAV input. The last column gives the percentage of individuals that were classified in the correct category. The genus Senegalia and Vachellia (Old Acacia genus) were put together.*

| | *Senegalia and Vachellia (97)* | *Balanites(132)* | *Boscia(10)* | Class error in % |
|---|---|---|---|---|
| *Senegalia and Vachellia (*97) | 75 | 20 | 2 | 23 |
| *Balanites(*132) | 8 | 124 | 0 | 6 |
| *Boscia(*10) | 2 | 1 | 7 | 30 |

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