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# Dry Biomass Estimation of Hedge Banks: Allometric Equation vs. Structure from Motion via Unmanned Aerial Vehicle

*Stefan LINGNER*[1]*, *Eiko THIESSEN*[1], *Kerrin MÜLLER*[2], *Eberhard HARTUNG*[1]

[1]*Institute of Agricultural Engineering, University of Kiel, Kiel, Germany*

[2]*Institute for Natural Resource Conservation, University of Kiel, Kiel, Germany*

**Corresponding author: sdittmann@ilv.uni-kiel.de*

**Abstract**

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The wood yield of hedge banks is very heterogeneous and hard to estimate in advance. The aim of the present study was to estimate the dry biomass of hedge banks shortly before harvesting using two different non-destructive approaches: (*i*) allometric equation based on DBH, (*ii*) volume calculations based on Structure from Motion; and to compare these estimations to the results of the (invasive) reference method: weighing after harvesting. Study objects were three different 100 m hedge banks in Schleswig-Holstein, Germany that were divided into 10 m segments ($n$ = 30). These segments were harvested and weighed separately to calculate dry biomass. The allometric equation yielded a relative root mean square error (rRMSE) of 32.4%. The Structure from Motion (SfM) volume models yielded an rRMSE of 30.0%. These results indicate that SfM approaches are comparably precise to allometric equations for dry mass estimations of hedge banks. SfM approaches are less time consuming but have higher technical requirements.

**Keywords**: drone; dry mass; point cloud; trees outside forests

According to the European Renewable Energy Directive (2009/28/EG) renewable energy is supposed to cover at least 20% of the gross energy consumption in 2020 within the European Union. In Germany, the amount of woody biomass used as a source for energy has already increased during the last decades (Mantau 2012). The future demand for woody biomass could in part be supplied by existing hedge banks (Isensee et al. 2000; Seidel et al. 2015). The total length of hedge banks in Schleswig-Holstein is assumed to be around 46,000 km (Eigner 1982).

Hedge banks as field margins are an important factor for biodiversity in agricultural landscapes (Marshall and Moonen 2002; Marshall 2004). They serve as habitat, shelter and migration path for numerous species. To preserve this ecological value the hedge banks need to be artificially maintained (Roßkamp 2001; Ministerium für Energiewende, Landwirtschaft, Umwelt und ländliche Räume des Landes Schleswig-Holstein 2017). This maintenance mainly consists of full cutting back in intervals of 10 to 15 years with only a few trees left standing (Roßkamp 2001). This cutting back allows shrubs to prevail, which in turn serve as shelter and breeding ground for numerous animals.

To date no reliable and time efficient (non-destructive) method exists to estimate the potential woody biomass of single hedge banks. Biomass estimations based on allometric equations usually are more accurate compared to remote sensing techniques, however they are very time consum-

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ing (Dittmann et al. 2017). Remote sensing techniques like Lidar or Structure from Motion (SfM) for point cloud generation could be considered on the spatial scale of single hedge banks. The present study focuses on the utilisation of SfM, due to its lower technical effort. SfM is a remote sensing technique that constructs 3D point clouds from numerous overlapping photos. The underlying algorithms use methods of computer vision and photogrammetry. These algorithms are looking for key points in individual photos and are matching these points with associated key points in other photos. Thus, the camera position and its calibration plus the location of the key points are estimated. Afterwards these key points are converted into a 3D point cloud (Snavely et al. 2007; Turner et al. 2012).

For tree parameter estimation SfM top-down approaches of leafy trees (Dandois, Ellis 2010; Tao et al. 2011; Fritz et al. 2013; Zarco-Tejada et al. 2014; Díaz-Varela et al. 2015) and SfM side-on approaches of bald trees (Miller et al. 2015) have been applied. SfM at bald trees allows the reconstruction of pure wood and thus supposingly achieves high accuracies. However by now pure wood reconstruction has only been applied successfully to single trees (Miller et al. 2015). SfM at leafy trees for height estimations or coarse volume models is less accurate but can be applied to grouped trees as well (Dandois, Ellis 2010; Fritz et al. 2013; Zarco-Tejada et al. 2014).

In the present study dry biomasses of 30 segments in three different hedge banks were determined separately by weighing after harvesting. These reference values were compared to both biomass values estimated shortly before harvesting by an allometric equation based on DBH and to volume calculations based on SfM.

## MATERIAL AND METHODS

**Study objects**. Data for the present study were sampled in 2016 at three different hedge banks in the Schleswig-Holstein Uplands, northern Germany (54°14'N, 10°24'E). Average yearly temperature is around 10°C and annual precipitation is around 750 mm. The aim was to select three hedge banks that vary in orientation, width, species composition and dry mass yield. Fig. 1 presents an aerial image of hedge bank 3 as an example of a typical hedge bank in the study region. A representative length of 100 m was selected for each hedge bank. Each of these 100 m objects was further divided into 10 m segments. In each of these 30 segments shrubs and

Fig. 1. Hedge bank 3 photographed by the HT-8 C180 unmanned aerial vehicle (Height-Tech, Germany) as an example of a typical hedge bank in the study region

trees were inventoried. SfM volume models were generated per segment.

**Reference data**. Shrubs and trees of the three hedge banks were felled, chopped to woodchips and weighed segment-wise with a telescopic handler. Leaves did not contribute to this total aboveground biomass due to the harvesting time in late winter. The telescopic handler had a measurement resolution of 50 kg. From each 10 m segment three samples of woodchips (approximately 5 l each) were taken. These samples were dried at 103°C to constant weight for dry mass content estimation. Thus the dry mass of each segment could be estimated.

Usually not all trees are felled in hedge banks. Some trees are left standing for ecological reasons. However these trees were already recorded by the camera and were part of the volume models. Consequently the dry masses of the trees left standing were estimated based on species-specific allometric equations provided by Zianis et al. (2005). These dry masses were added to the harvested dry masses to gain reference dry masses.

**Biomass estimation based on allometric equation**. In each 10 m segment all shoots of shrubs and trees higher than 1 m were assessed. The assessments per shoot included: (*i*) the determination of the species, (*ii*) the record of the DBH if the DBH was larger than 10 cm.

Usually shoots with a DBH larger than 10 cm are considered for allometric equations (Sader et al. 1989; Mitchard et al. 2009; Ploton et al. 2012; Véga et al. 2015). Consequently, in the present study all DBH larger than 10 cm were recorded in $DBH_i$, $i = 1, \dots n_L$. DBH smaller than 10 cm were not recorded but counted in $n_S$. Eq. 1 was fitted to obtain estimates for the coefficients *a*, *b* and *c* with a Nonlinear Least Squares Model (R function nls). The fitting was performed with the 30 reference dry masses – DM (kg) and the shoot information of the corresponding segments. Eq. 1 allows increasing weights with increasing DBH (cm) but assumes that all shrubs and trees with a DBH smaller than 10 cm have the same weight:

$$DM = \left(\sum_{i=1}^{n_L} a \times \left(DBH_i\right)^b\right) + c \times n_S \qquad (1)$$

**Biomass estimation based on SfM volume**. For image acquisition an HT-8 C180 Unmanned Aerial Vehicle (Height-Tech, Germany) equipped with a Sony Alpha 7 camera (Sony Corporation, Japan), 24 mega pixel, 30 mm lens (Zeiss, Germany) was used. This camera and lens combination resulted in a pixel size of 6 mm × 6 mm at a distance of 30 m. The octocopter was programmed and flew automatically along each hedge bank at both sides in multiple different heights (Table 1).

Table 1. Examples of flight heights and flight distances to hedge bank. Exact heights and distances depended on hedge bank size and ground relief

| Height (m) | Distance to hedge bank (m) |
|---|---|
| 10 | 30 |
| 17 | 25 |
| 24 | 18 |
| 30 | 10 |

Flights were performed in October and November 2016 with most of the trees still leafy. Approximately every second meter a photo was taken. This resulted in an overlap of more than 90% between collected images. The SfM algorithm was performed in Agisoft Photoscan (Version 1.2.6, 2016). Overlapping images of the individual hedge banks were processed to point clouds (alignment: highest; dense cloud: lowest). Then these point clouds were further processed in Matlab (Version R2017a). The switch to Matlab was done, since the volume calculation in Agisoft Photoscan has limited options and cannot be run segment-wise automatically. Point cloud processing in Matlab included filtering based on *k*-nearest neighbours, segmenting and volume calculation (Fig. 2). For volume calculation all points were used for polyhedron construction up to a maximum edge length of 2.5 m.

**Data handling, statistics and graphics**. Data handling, statistics and graphics were performed in R software (Version 3.2.1, 2015) using the packages xlsx (Version 0.5.7, 2014), plyr (Version 1.8.4, 2011) (Wickham 2011), reshape2 (Version 1.4.1, 2007) (Wickham 2007), vegan (Version 2.4-0, 2015), ggplot2 (Version 2.1.0, 2009) (Wickham 2009) and fmsb (Version 0.6.1, 2017).

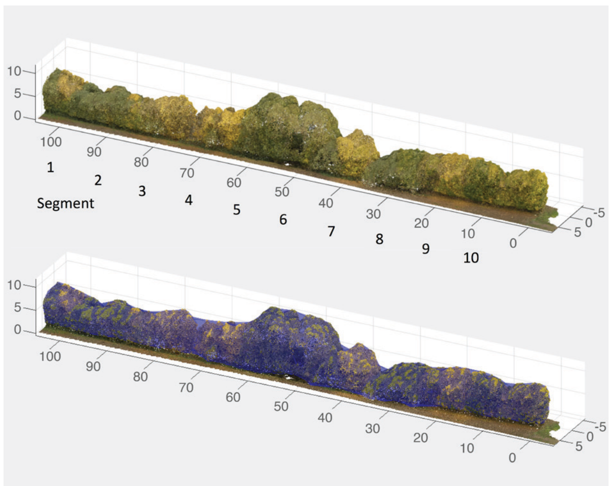


Fig. 2. Point cloud and volume model of hedge bank 3 and its 10 segments (distances in meters)

Statistical non-intercept models were built for both approaches. The first model tested the effect of allometric estimated dry mass on reference dry mass. The second model tested the effect of volume on reference dry mass. In both models different coefficients per hedge bank were allowed. $R^2$ was calculated to compare the goodness of fit in these models. For this $R^2$ calculation the default equation for non-intercept models in *R* was used (Eq. 2):

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{n} y_i^2} \quad (2)$$

where:

$\hat{y}_i$ – estimated value.

The absolute root mean square error (RMSE) or relative root mean square error (rRMSE) is the standard accuracy estimate for the comparison of different methods of biomass estimation (Segura et al. 2006; Hyde et al. 2007; Popescu et al. 2011). Consequently this accuracy estimate was used in this study as well. The formula for the rRMSE is presented in Eq. 3:

$$\text{rRMSE} = \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}}{\bar{y}} \quad (3)$$

where:

$\bar{y}$ – mean value,

$n$ – sample size.

## RESULTS

### Study objects

Hedge bank 1 and 2 had an orientation from west to east while hedge bank 3 had an orientation from north to south. Typical width was 3.5 m for hedge banks 1 and 2. Hedge bank 1 was 1.5 m wide. All three hedge banks consisted of different species compositions as presented in Fig. 3. Blackthorn (*Prunus spinosa* Linnaeus), field maple (*Acer campestre* Linnaeus) and common hazel (*Corylus avellana* Linnaeus) were the most abundant species. Especially segments 6 to 10 of hedge bank 2 mainly consisted of blackthorn. Hedge bank 1 had the highest abundances of hawthorn (*Crataegus* sp. Linnaeus), elder (*Sambucus nigra* Linnaeus) and common hornbeam (*Carpinus betulus* Linnaeus). Hedge bank 3 was dominated by field maple.

### Reference data

Fresh biomass per segment varied between 150 and 2,250 kg with a mean of 1,060 kg and a standard deviation of 460 kg. Dry mass content varied between 47 and 62%. This resulted in harvested dry masses between 91 and 1,073 kg per segment with

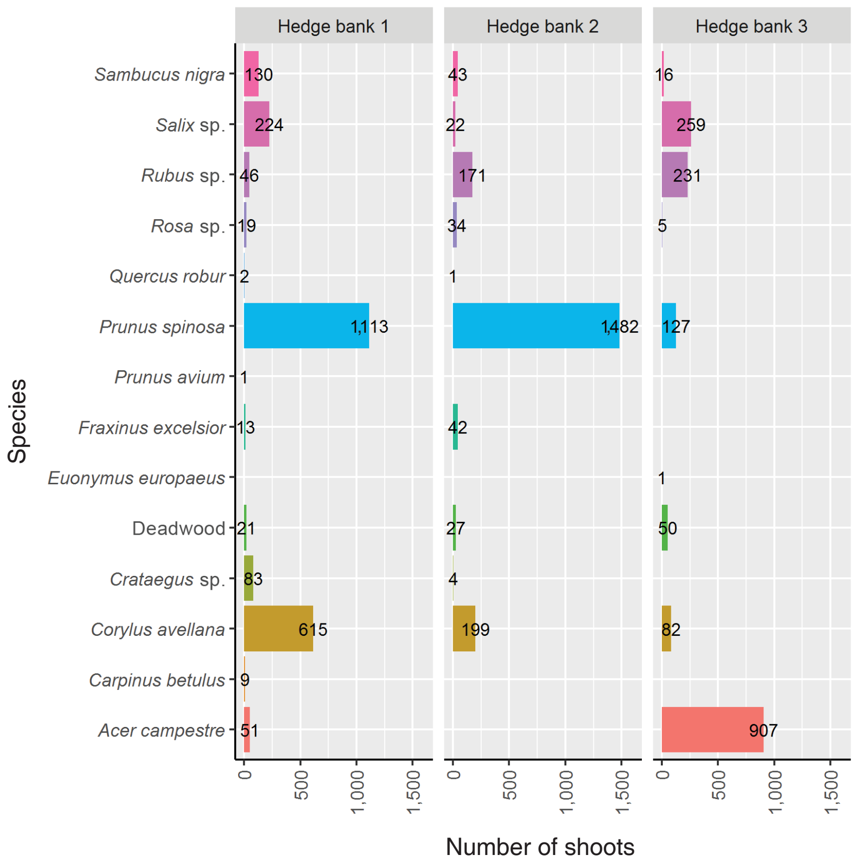


Fig. 3. Species composition of the three hedge banks

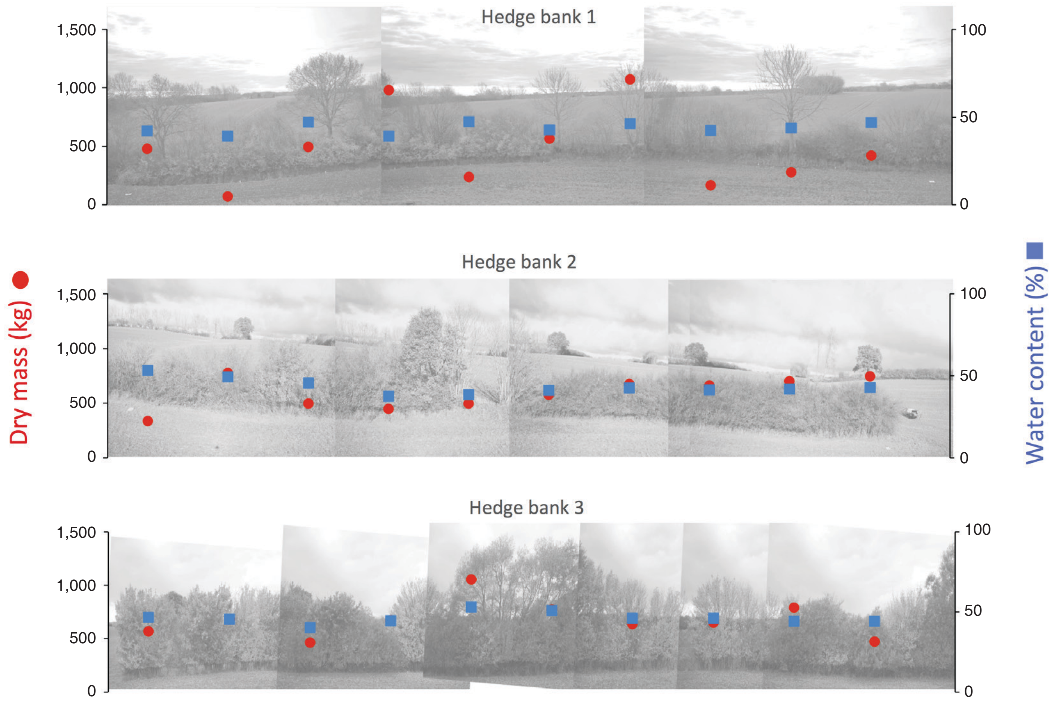


Fig. 4. Harvested dry masses (without trees left standing) and water content (water content = 1 – dry mass content) of the three hedge banks

a mean of 583 kg and a standard deviation of 236 kg (Fig. 4).

In total six trees with a DBH larger than 10 cm were left standing as presented in Table 2. Their dry masses were estimated using the equations listed in Table 2 and added to the harvested dry masses to gain reference dry masses. These reference dry masses varied between 280 and 1,660 kg with a mean of 758 kg and a standard deviation of 334 kg.

## Biomass estimation based on allometric equation

Estimated coefficients of Eq. 1 were $a$ = 0.01, $b$ = 2.98 and $c$ = 2.40. Fig. 5 shows the estimated and reference dry masses per segment. In the statistical non-intercept model the coefficient for estimated dry mass was 1.00 and had a significant effect (lin-

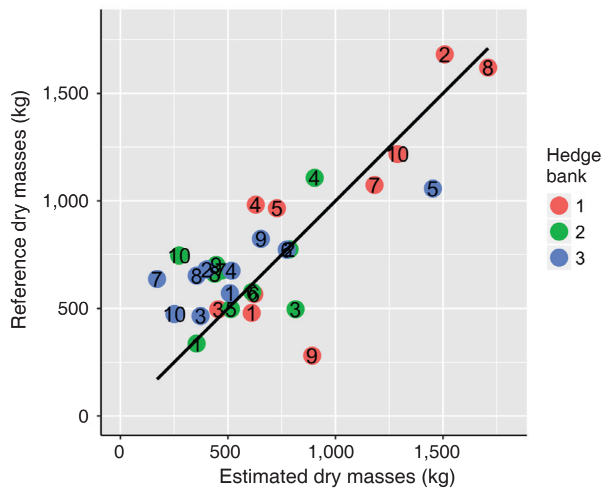


Fig. 5. Dry masses estimated by an allometric equation based on DBH vs. reference dry masses determined by weighing of 30 segments in three hedge banks. Estimated dry masses were predicted based on Eq. 1 with fitted parameters given in the text. The black line is a linear regression line

Table 2. Trees left standing. Dry masses were estimated based on species-specific allometric equations from Zianis et al. (2005)

| Hedge bank | Segment | Species | DBH (cm) | Equation | Dry biomass (kg) |
|---|---|---|---|---|---|
| 1 | 2 | *Fraxinus excelsior* Linnaeus | 52 | DM = 0.085 × $DBH^{2.4882}$ | 1,590 |
| 1 | 5 | *F. excelsior* | 38 | DM = 0.085 × $DBH^{2.4882}$ | 729 |
| 1 | 8 | *Quercus robur* Linnaeus | 51 | DM = 0.089 × $DBH^{2.4682}$ | 1,453 |
| 1 | 10 | *Q. robur* | 40 | DM = 0.089 × $DBH^{2.4682}$ | 798 |
| 2 | 4 | *Q. robur* | 37 | DM = 0.089 × $DBH^{2.4682}$ | 658 |
| 3 | 9 | *Acer campestre* Linnaeus | 11 | DM = 0.067 × $DBH^{2.5751}$ | 32 |

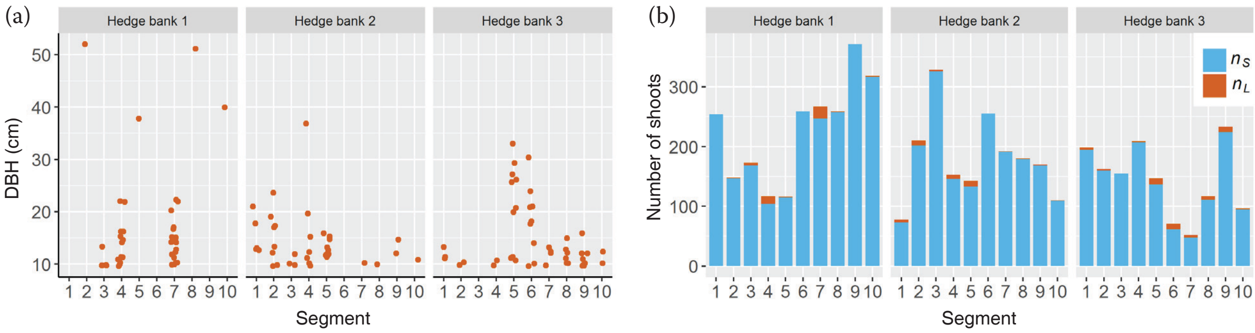


Fig. 6. Measured DBH of trees > 10 cm (a), number of shoots (b) in 30 segments

$n_S$ – number of shoots with a DBH < 10 cm, $n_L$ – number of shoots with a DBH > 10 cm

ear model, $F_{1,29}$ = 298.1, $P$ < 0.001). The different hedge banks had no significant effect. The model achieved an $R^2$ of 0.91 and an rRMSE of 32.4%.

Measured DBH and counted shoots per segment are presented in Fig. 6. About 98% of all shoots had a DBH smaller than 10 cm. Transferred into weight this equals 37% of total dry biomass if the fitting result of Eq. 1 is applied with 2.40 kg per shoot.

## Biomass estimation based on SfM volume

Calculated volumes based on SfM per segment varied between 95.5 and 957.2 m³. Volumes versus reference dry masses are presented in Fig. 7. In the statistical non-intercept model the interaction of volume and hedge banks was significant (linear model, $F_{3,27}$ = 10.8, $P$ < 0.001). The equation for the statistical model is presented in Eq. 4. The coefficients $d$ for hedge bank 1, 2 and 3 were 1.94, 2.43 and 1.42 kg·m$^{-3}$, respectively. This model achieved an $R^2$ of 0.95 and an rRMSE of 22.5%. A simpler model with a general coefficient for volume achieved an $R^2$ of 0.92 and an rRMSE of 30.0%. This general coefficient $d$ over all hedge banks was 1.79 kg·m$^{-3}$ (linear model, $F_{1,29}$ = 18.8, $P$ < 0.001).

$$\mathrm{DM} = d_i \times V \qquad (4)$$

where:
$d_i$ – estimated coefficients,
$V$ – volume.

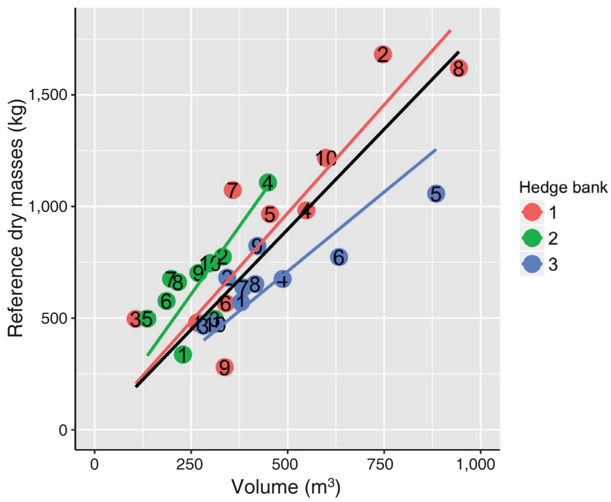


Fig. 7. Structure from Motion based volume vs. reference dry mass of 30 segments in three hedge banks. Coloured lines represent linear regression lines per hedge bank with fitted parameters given in the text. The black line represents a general regression line

## DISCUSSION AND CONCLUSIONS

The selected hedge banks in the present study differed in orientation, species composition, width and wood yield. These differences indicate that the selection of heterogeneous hedge banks was successful. The samples appear to be representative of hedge banks in the Schleswig-Holstein Uplands, northern Germany.

Estimated dry mass based on allometric equations had a significant effect on reference dry mass in the statistical model. The estimated coefficient was 1. This value does not surprise since it was modelled to be 1. Different coefficients per hedge bank did not significantly improve the model. The model resulted in an rRMSE of 32.4%. This is a lot less precise than allometric equations in literature like 9% in Segura et al. (2006) (shade trees of coffee plants) and 13% in Annighöfer et al. (2016) (seedlings and saplings of European tree species). Plus in the present study the same data were used for model generation and valuation. It is likely that the model fit would decrease if independent data for model generation and valuation were used. One possible reason for the relative low precision of the allometric equation approach in the present study is surely the diverse growth habit of trees in hedge banks. However the major reason is probably the weight of shrubs and trees with a DBH smaller than 10 cm. All three hedge banks had a large proportion of shoots with a DBH smaller than 10 cm. In Eq. 1 all shrubs and trees with a DBH smaller than 10 cm were assumed to have the same weight. This assumption surely does not apply. One example is the 9th segment of the 1st hedge bank. The reason for its poor fit is its low weight but the large number of shoots with a DBH smaller than 10 cm. No shoot with a DBH larger than 10 cm was present in this segment. To create more realistic models it would be necessary to assess the DBH of shrubs and trees with a DBH smaller than 10 cm as well. However this would result in an enormous effort for data collection.

Volume had a significantly different effect on reference dry mass depending on the hedge bank. This pattern indicates that the relationship between volume and mass additionally depends on other factors like species composition. However due to the sample size these effects could not be tested sufficiently in the present study. The statistical model assuming a general coefficient for volume resulted in an rRMSE of 30.0%. This rRMSE is larger than the rRMSE from Miller et al. (2015), who used SfM to calculate the volume of 30 single bald trees and received an rRMSE of 19%. In Miller's study the single trees were photographed side-on all around. Dandois and Ellis (2010) used SfM for biomass estimation at a larger spatial scale and received an rRMSE of 54%. However, due to the large spatial scale they used top-down photos only.

In the present study the rRMSE of the SfM approach was slightly lower than the rRMSE of the allometric approach. The $R^2$ was better in the volume models as well. The results of the comparison indicate that SfM approaches are generally suitable for dry mass estimations of hedge banks. SfM approaches appear to be reasonably precise and are a lot less time consuming than approaches based on allometric equations. However, technical requirements are higher when applying SfM.

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