Received: 27 September 2018 | Accepted: 26 August 2019 | Published: 17 October 2019
DOI:10.20870/oeno-one.2019.53.4.2310

OENO One
VINE AND WINE OPEN ACCESS JOURNAL

Evaluation of grapevine trunk size by use of a handheld camera and three-dimensional modelling

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ABSTRACT

Background and aims: Measurement of grapevine size is necessary to assess carbon reserves at the level of individual vines and to estimate the carbon sequestration potential of vineyards. Methods of measurement rely mostly on traditional dendrological techniques that may be prone to error. In this study, we examined the use of structure-from-motion with multiview stereophotogrammetry (SfM-MVS) to obtain accurate measurements of vine trunk thickness and volume. SfM-MVS enables the creation of scaled, georeferenced three-dimensional models based on a set of overlapping photographs.
Methods and results: The study was conducted using field-grown *Vitis vinifera* L. cv. Riesling vines aged 5, 22 and 46 years and pruned in a bilateral Guyot. Trunk diameter, cross-sectional area and circumference 10 cm above the grafting point were measured by traditional dendrometry, and the values obtained compared with corresponding estimates from reconstructed three-dimensional SfM-MVS models. SfM-MVS was also used to estimate total trunk volume. Correlation between measured values and modelled estimates was close to unity ($0.976 \leq R^2 \leq 0.988$). The estimates for 5-year-old vines had the largest errors.
Conclusions: Under adequate lighting conditions and with sufficient image resolution, SfM-MVS is able to produce accurate models of vine trunks.
Significance of the study: This work serves as proof of concept for the use of SfM-MVS to measure the trunk size of field-grown grapevines of different ages. This technique, which is relatively new, is cost-effective and easy to implement. Further research is necessary to determine specific applications of SfM-MVS, in which it could supplement or replace traditional dendrological techniques.

KEYWORDS

carbon storage, dendrology, photogrammetry, SfM-MVS, vigour, vine age, wood reserves

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INTRODUCTION

Information about stem volume is necessary to evaluate the carbon stocks of forests and orchards (Daudet *et al.*, 2005; Houghton, 2005; Nowak *et al.*, 2013; Mlambo *et al.*, 2017). This information is particularly significant in the context of climate change, because perennial plants provide important ecosystem services by acting as a long-term sink for atmospheric carbon (Pretzsch, 2009). Vineyards are a widespread agricultural system, covering 7.4 M ha of planted surface worldwide in 2018 (International Organization of Vine and Wine, 2019), and presumably represent large carbon stocks. However, measurement of carbon stocks in grapevines presents unique challenges. Unlike trees, grapevines are frequently trained on trellises to optimize canopy light interception (Reynolds and Vanden Heuvel, 2009), adapt to environmental constraints (Palliotti *et al.*, 2014), reduce the incidence of fungal infections (Austin *et al.*, 2011) and facilitate vineyard activities. Therefore, grapevine trunks grow in a variety of shapes as a result of different combinations of head/cordon and spur/cane pruning, sometimes with vertically or horizontally divided canopies (Reynolds and Vanden Heuvel, 2009).

Traditional dendrological techniques have been applied in viticulture to determine vine age and annual growth rate; however, they are usually destructive (Tyminski, 2013). For example, the most accurate method of evaluating trunk volume requires vines to be uprooted and plunged into water to enable measurement of the displaced volume of liquid (Keightley and Bawden, 2010). Simple and cost-effective methods, like measuring the trunk diameter at several heights to approximate the structure as a series of truncated cones, may be prone to error (Kitahara *et al.*, 2010). Trunk diameter and circumference are, by themselves, useful proxies for vine vigour (Santesteban *et al.*, 2010), but they do not account for the effects of vine training. For example, compared with a cane-pruned vine of the same height, a cordon-pruned vine often has a larger amount of wood reserves along the trellis wire, even if both vines have the same trunk circumference.

The perennial structure of grapevines and their production capacity tend to increase with age, especially in the first few years after planting (Chiarawipa *et al.*, 2013; Grigg *et al.*, 2017; Bou Nader *et al.*, 2019). The magnitude of these changes depends on several environmental factors, such as soil profile and depth, water availability and regional climate (Keller, 2010), as well as management practices. Knowledge of the above-ground volume of grapevines allows estimation of a vineyard's biomass and carbon sequestration potential through allometric relations (Chiarawipa *et al.*, 2013; Miranda *et al.*, 2017). Estimates of trunk volume could also be used to improve on methods for assessing vegetative and generative capacity, since increased perennial wood is known to influence yield, fruit composition, and cold hardiness (Howell, 2001).

Structure-from-motion with multiview stereophotogrammetry (SfM-MVS) is a photogrammetric approach in which overlapping two-dimensional images are combined automatically to create three-dimensional models of captured objects. It does this by identifying and matching object features across the images, then using these features to infer camera location and orientation (James and Robson, 2012). The technique has already been tested successfully in urban forestry (Liang *et al.*, 2014; Morgenroth and Gomez, 2014; Miller *et al.*, 2015) and is a potential alternative to remote-sensing techniques, such as light detection and ranging (LiDAR), for describing the structure of trees and measuring their volume (Rosell and Sanz, 2012).

The present study was intended as proof of concept for the application of SfM-MVS in viticulture, which was assessed by comparing measurements of trunk circumference and cross-sectional area obtained in the field from grapevines of different ages with corresponding estimates derived from reconstructed three-dimensional models. In this article, the use of SfM-MVS to evaluate the total volume of pruned grapevines is also described.

MATERIALS AND METHODS

1. Plant material and field-measured trunk diameter and circumference

The trial was conducted in an experimental vineyard at Hochschule Geisenheim University in Geisenheim, Germany (+49°98′76.59″, +7°94′47.90″). The vineyard was initially planted in 1971 with *Vitis vinifera* L. cv. Riesling, clone Gm239-17, grafted on 5C Teleki rootstock. The vines were distributed along 68 rows in a north–south orientation and cane-

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pruned to form a bilateral, downward-arched Guyot. In 1995 and 2012, several rows were uprooted and replanted with the same planting material. The result was a vineyard with identical vines of three different ages divided along alternating rows. The number of nodes retained was adjusted to 10 per metre (equivalent to 14 nodes per vine) during winter pruning.

At the beginning of the growing season, trunk diameter in the direction of the row, 10 cm above the grafting point, was measured with a digital caliper. The selected vines were used in a separate trial on the effects of vine age on productivity and water stress tolerance (Bou Nader *et al.*, 2019). The present trial was conducted in 2017, when the yield and pruning mass of vines planted in 2012 was similar to those of older vines (Table 1).

When trunk diameter in the row direction had been measured, a thin plastic cord was tied to the trunk, just below the position of the caliper, to serve as a reference point for further measurements (Figure 1a and b). The diameter was measured again in the direction perpendicular to the row. The mean of the two values was used to compute trunk cross-sectional area (TCSA) by approximating the trunk to a circle (Lepsis and Blanke, 2006). Trunk circumference was measured with a flexible measuring tape at the same height.

2. Image acquisition for trunk reconstruction

When a picture is taken by a single camera, the three-dimensional space is compressed to two dimensions and therefore information about field depth is lost. To retain depth information and reconstruct the three-dimensional scene surrounding an object point, the object needs to be photographed from at least two different points of view. The location of the object point is then determined by a process known as digital image matching, which identifies and matches common points in the pictures (Luhmann, 2010).

Collections of object points, or *point clouds*, can be used to build models of complex objects by connecting adjacent points. This creates a three-dimensional mesh, whose accuracy increases with the density of object points (Luhmann *et al.*, 2014). Models built by photogrammetry have only relative information about scale (information about distances) and georeference (information about position in the original three-dimensional space) when they are first created. This information can be complemented by the use of markers or a fixed object of known dimensions placed close to the object of interest.

The ground around the trunks was weeded manually to give direct visual access to the base of each trunk, and loose pieces of bark were removed to prevent volume miscalculations. A reference grid comprising seven equally spaced markers (Agisoft LLC, 2014) printed on cardboard was laid on the ground around the trunk before it was photographed (Figure 1). The distance between two adjacent markers was 10.5 cm.

Photography was done under cloudy conditions, because bright sunlight increases contrast between illuminated and shaded parts of the trunk, resulting in poor reconstruction of the latter. A commercial digital SLR camera (Sony α58; fixed focal length objective SAL35F18; Sony, Tokyo, Japan) was used. Use of a camera with fixed focal length is generally recommended, because variable focal length adds further complexity to the equation systems run by the software (Luhmann, 2010).

The images were captured in several concentric circles around the vine (Figure 2a). The first circle, a set of about 30 images, captured the whole vine. The three inner circles focused on the low, middle and crown parts of the trunk. Extra images were obtained at certain angles to capture specific structural features, such as the underside of an S-shaped trunk, giving a total of 80–110 images per vine. It took about 5 min to

TABLE 1. Characteristics of vines of three ages used in the present study.

Year planted	Age (years)	Variety, clone	Rootstock	Pruning system	Row ↔ vine distance (m)	Mean pruning weight (kg/m)[a]	Mean yield (kg/m)[a]
1971	46	Riesling, Gm239-17	5C Teleki	Bilateral Guyot	2.0 ↔ 1.4	0.78 ± 0.06	1.81 ± 0.20
1995	22	Riesling, Gm239-17	5C Teleki	Bilateral Guyot	2.0 ↔ 1.4	0.71 ± 0.09	2.23 ± 0.46
2012	5	Riesling, Gm239-17	5C Teleki	Bilateral Guyot	2.0 ↔ 1.4	0.67 ± 0.09	2.07 ± 0.33

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FIGURE 1. Experimental set-up on a vine planted in 1995.
(a) Vine with reference grid and point of measurement (white arrow). (b) Point of measurement of trunk circumference and trunk cross-sectional area 10 cm above the grafting point, highlighted by a plastic cord. (c) Reference grid around the base of the trunk.

prepare each vine and about 15 min to capture the necessary images.

Because the trial was conducted in a vineyard, the operator's movement around the vine was limited by neighboring plants. The distance between the outer circle and the vine was therefore approximate to the row distance of 2 m, and the inner circles had to be smaller than 1.4 m in radius to prevent obstruction by adjacent vines. The RAW format was used, with an ISO of 200, as well as a high aperture value and a shutter speed greater than 1/250 s to prevent motion blur, which would have reduced the quality of the models.

3. Three-dimensional model reconstruction by SfM-MVS

Three-dimensional models of individual vine trunks were reconstructed using Agisoft Photoscan software (Agisoft LLC, St Petersburg, Russia). First, the various positions of the camera were calculated automatically by matching common points on the images (Figure 2a) and aligning them to produce a sparse point model. Next, a dense point model, in which points are several times more numerous, was generated. At that time, the point cloud already resembled the original vine. The point cloud was then cleaned manually in Agisoft, removing the noise points from background elements, the ground, trellis wires and shadows. For the purpose of this experiment, the trunk was truncated at the grafting point and the bilateral canes were excluded. Finally, a polygonal mesh was fitted to the dense point model to form each three-dimensional trunk model.

As noted previously, the models lack information about scale or geographical position. Therefore, to measure distance or volume it was necessary to implement a coordinate system and a scale of measurement. Once the distance between markers have been specified on the referenced grid'., the software created a coordinate system that allowed data acquisition from various points. In a few cases, the software failed to automatically identify all markers; however, this problem was solved by referencing the missing markers manually.

4. SfM-MVS measurements and model validation

Trunk diameter in the direction of the row and perpendicular to the row were estimated on the three-dimensional models at the level of the plastic cord. The trunk was truncated at the point

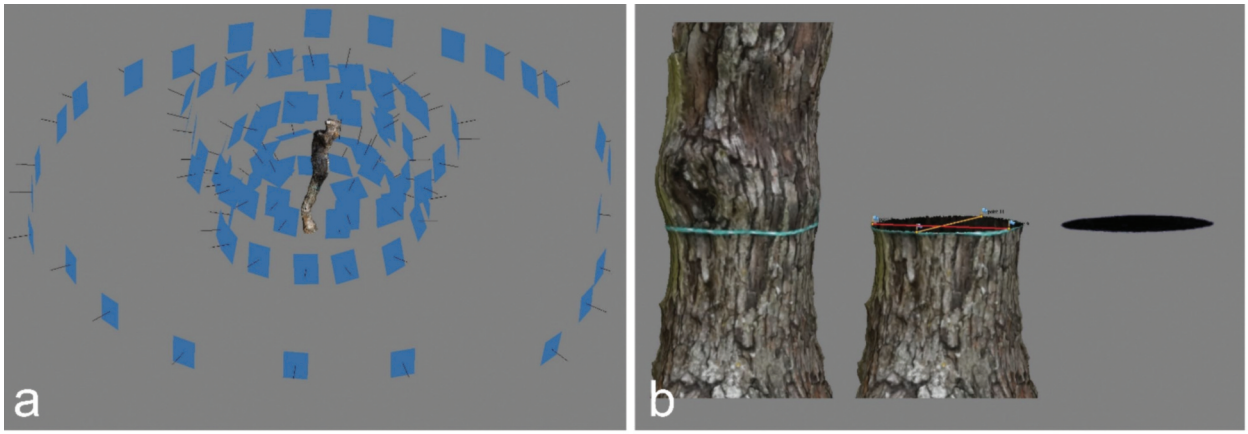


FIGURE 2. Reconstruction of images of a vine by structure-from-motion with multiview stereophotogrammetry.
(a) Squares and black lines representing camera position and direction, respectively, when taking photographs. (b) From left to right: intact trunk with point of measurement 10 cm above the grafting point (in green), the two orthogonal diameters (in red and yellow) of the trunk cross-sectional area (TCSA), and the modelled TCSA.

of measurement, and point markers were added based on the position of the referenced grid relative to the trunk (Figure 2b). For TCSA and trunk circumference, it was necessary to create a surface at the cross-section. This was done with the 'close holes' tool provided in the software, which generates a 'watertight' mesh by connecting the points at the periphery of holes with a flat surface. It was then possible to measure the trunk circumference and TCSA directly on the surface, without having to rely on the orthogonal diameter (Figure 2b). The estimates obtained were then validated by comparison with field-measured values.

5. Estimation of trunk volume

Computation of total trunk volume also required use of the 'close holes' tool. However, it was not possible to validate trunk volume estimates calculated by the model by comparison with field-measured values. Accurate values for trunk volume could only have been obtained by uprooting the vines (Özçelik *et al.*, 2008), which was not possible due to ongoing trials on the 72 selected vines.

6. Statistical analysis

For each dendrological metric, estimates derived from the three-dimensional models were compared with corresponding traditional field measurements by linear regression with calculation of the coefficient of determination (R^2). Additionally, the root mean square error (RMSE) and bias were calculated for each vine, as defined by equations 1 and 2:

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

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

In these equations, n is the number of estimates, y_i is the estimate obtained by model reconstruction, and $\hat{y}_i$ is the value measured directly in the vineyard. Calculations were made with R (version 3.5.1; R Core Team, 2018) and RStudio (version 1.1.419; RStudio, 2015).

RESULTS AND DISCUSSION

Overall, SfM-MVS succeeded in modelling the trunks of vines of all three ages. The number of pictures taken was sufficient to produce accurate three-dimensional models of the trunks. Because of the small size of grapevines relative to trees, they were easy to capture from low as well as high angles. Although the 2-m row distance limited movement around the vine of interest, it was large enough for satisfactory results to be obtained. The best results were obtained under cloudy conditions, because model reconstruction works best with images characterized by diffuse light and minimal contrast between illuminated and shaded parts (Miller *et al.*, 2015).

Across the three vine ages, regression analysis showed high correlation for trunk diameter both in the direction of the row (d_{row}) and perpendicular to the row (d_{per}) ($R^2 = 0.98$; Figure 3a and b). The correlation was similar for TCSA when comparing the value calculated

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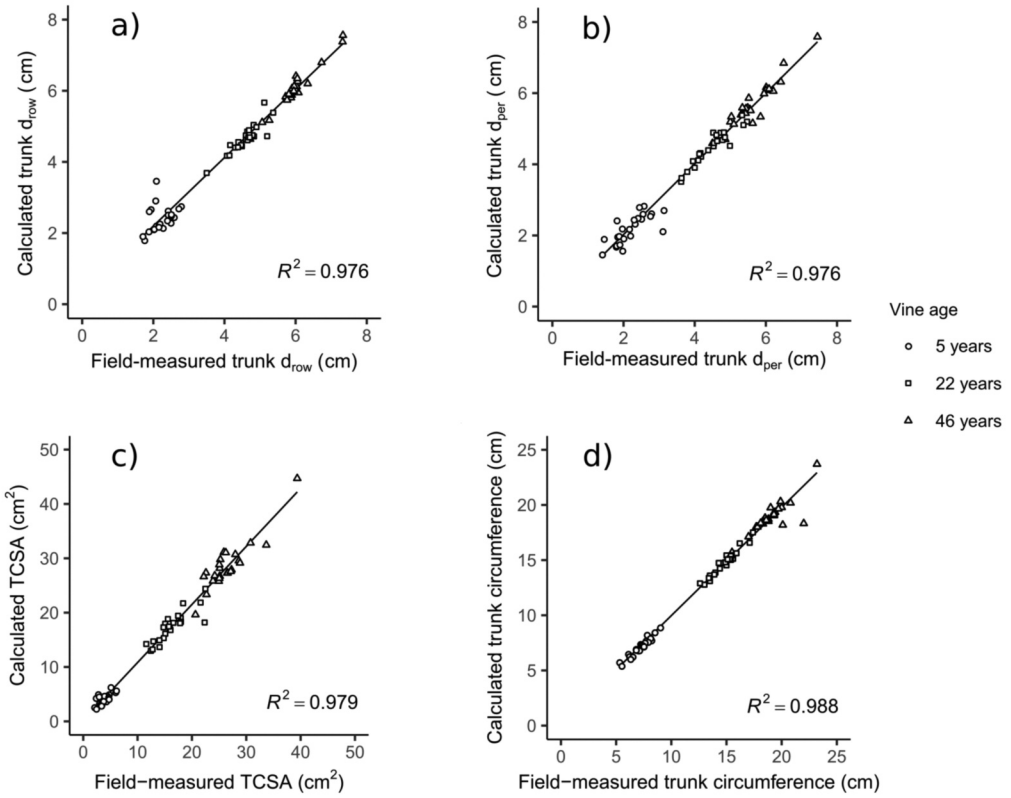


FIGURE 3. Regression analysis of estimates obtained using structure-from-motion with multiview stereophotogrammetry against field-measured values for vines of three ages.
(a) Trunk diameter in the direction of the row (d_{row}); (b) trunk diameter perpendicular to the row (d_{per}); (c) trunk cross-sectional area (TCSA); (d) trunk circumference.

TABLE 2. Field-measured values and modelled estimates of dendrological metrics for 5-, 22- and 46-year-old vines, with root mean square error (RMSE) and bias of modelled data.

Metric	Field-measured value (mean ± SD)	Modelled estimate (mean ± SD)	RMSE[a]	Bias[a]	RMSE (%)	Bias (%)
5-year-old vines						
d_{row} (cm)	2.21 ± 0.29	2.40 ± 0.36	0.41	0.19	18.59	8.67
d_{per} (cm)	2.21 ± 0.46	2.20 ± 0.40	0.31	0.00	14.19	–0.20
TCSA (cm^2)	3.90 ± 1.10	4.16 ± 0.97	0.82	0.26	20.97	6.61
Circumference (cm)	7.23 ± 0.96	7.18 ± 0.85	0.25	–0.04	3.40	–0.60
Total trunk volume (cm^3)	ND	327.0 ± 64.2	ND	ND	ND	ND
22-year-old vines						
d_{row} (cm)	4.59 ± 0.40	4.67 ± 0.40	0.19	0.07	4.22	1.61
d_{per} (cm)	4.50 ± 0.52	4.50 ± 0.49	0.17	0.00	3.79	0.02
TCSA (cm^2)	16.34 ± 3.80	17.45 ± 2.81	1.85	1.11	11.34	6.80
Circumference (cm)	14.85 ± 2.44	14.76 ± 1.18	0.28	–0.09	1.90	–0.59
Total trunk volume (cm^3)	ND	2120.7 ± 349.0	ND	ND	ND	ND
46-year-old vines						
d_{row} (cm)	5.97 ± 0.57	6.03 ± 0.62	0.14	0.07	2.42	1.12
d_{per} (cm)	5.65 ± 0.62	5.69 ± 0.65	0.21	0.04	3.76	0.67
TCSA (cm^2)	26.64 ± 4.36	28.62 ± 4.46	2.72	1.97	10.21	7.41
Circumference (cm)	19.08 ± 1.87	18.91 ± 1.42	0.89	–0.17	4.69	–0.87
Total trunk volume (cm^3)	ND	3740.9 ± 729.3	ND	ND	ND	ND

ND, no data; TCSA, trunk cross-sectional area.
[a]Units for RMSE and bias are the same as their respective metric.

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from the two diameters measured in the field with the area of the reconstructed surface modelled by the software (R^2 = 0.98; Figure 3c). Trunk circumference showed the strongest linear relationship between measured values and modelled estimates, approaching unity (R^2 = 0.99; Figure 3d).

Although linear regression for the three vine ages combined showed a good fit of the data, the RMSE and bias of the modelled data were generally greater for younger vines (Table 2). This may be due to the greater difficulty of applying SfM-MVS to small objects such as slender tree branches (Kankare *et al.*, 2013; Morgenroth and Gomez, 2014). The density of point clouds generated by the software depends on image resolution, and it is also affected by the camera and the distance at which the images are obtained (James and Robson, 2012).

All metrics except trunk circumference were slightly overestimated by the models, as shown by their positive bias. RMSE values for d_{row} were consistently higher than those for d_{per}, possibly due to systematic errors when measuring in the two positions with the digital caliper. Nevertheless, the level of accuracy obtained in the present study was similar to that obtained in previous studies in which SfM-MVS was used to assess tree size (Kankare *et al.*, 2013; Liang *et al.*, 2014; Miller *et al.*, 2015). Estimates of total trunk volume obtained from SfM-MVS models varied widely across vine ages, with 46-year-old vine trunks being 1.7 times larger than 22-year-old vines trunks and more than 10 times larger than 5-year-old vine trunks (see Table 2).

CONCLUSION

With SfM-MVS, it was possible to build realistic three-dimensional models of vine trunks of different ages, from which accurate estimates of trunk diameter, area and circumference could be obtained. The technique was able to accommodate complex trunk structures on old Guyot vines and is cost-effective and easy to apply in the field. However, its accuracy in shaded environments, and when the object captured does not generate enough points (due to low image resolution), requires improvement. SfM-MVS is relatively recent, and its future development in the areas of automation and object detection could provide new opportunities for its use in forestry, ecology and viticulture to assess the carbon sequestration potential of landscapes.

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