



# Recent Advances in UAV-Based Structure-from-Motion Photogrammetry for Aboveground Biomass and Carbon Storage Estimations in Forestry

Sercan Gülci, Abdullah Emin Akay, Burak Arıcak, and Temel Sariyildiz

## Abstract

Due to economical, ecological, and social changes over the last decade, managers and researchers in nature-based disciplines intend to use both traditional and innovative remote sensing (RS) technologies for best management practices. RS, which has grown interest in forestry, offers rapid and reliable assessment tool to monitoring and observing. Several successful studies in literature have indicated that the RS use in forestry is light the way of the most effective evaluating various forest ecosystems. Recent developing unmanned aerial platforms play as a low-cost and inexperienced user-based multi-image processing by using computer vision techniques for forestry studies. Forests, where are essential natural resources for the future, are the pool of biomass and carbon storage, and they need periodical monitoring to sustain. A sustainable management of carbon balance and biomass in mountainous forests includes exhausting effort in field-based studies. However, the RS as a tool for study on biomass and carbon storage can be received as the most effective prediction and nondestructive method in combination with structure-from-motion techniques. Considering recent opportunities in data science and unmanned aerial vehicles (UAVs), RS and photogrammetry in forestry have still played an indispensable role in the evolution of forests. This chapter aims to review the recent advanced knowledge on the progress of the use of UAV technologies in accordance with advanced photogrammetry-related applications in the quantification of forest aboveground biomass and carbon

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storage. A comprehensive literature search has been performed on the use of UAV-based SfM photogrammetry for UAV-based forest biomass and carbon storage studies.

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**Keywords**

UAV-SfM · Digital aerial photogrammetry · Remote sensing · Stand parameters · Timber volume · Carbon stock

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## 1 Introduction

Studies on forest biomass estimation can provide important results for determining the distribution and flow of materials in ecosystems and are necessary to understand the dynamics of the forest ecosystem (Andersson 1971). Estimation of forest woody biomass plays an important role in forestry for several reasons. Firstly, the planning of forest woody assortments production, for main commercial roundwood assortment and for assortments like “waste wood” or “recovered wood” as a potential for energy purposes (firewood, wood bricks, wood pellets, etc.). Secondly, the estimation of different parts of forest woody biomass as bole, branches, and foliage can be used to better manage forest resources. Thirdly, forest woody biomass estimations are useful to evaluate and understand (a) the stocks and fluxes of several biogeochemical elements and (b) the amount of net primary energy production from forests as a cleaner alternative to fossil fuels. In addition, forest biomass is an essential variable mostly used in several ecological and ecophysiological models (Brown 1997; Chave et al. 2005; Návar 2009a, b; Richardson et al. 2002). Finally, in last two decades, forest biomass estimation studies have received much attention due to its importance in the evaluation of carbon sequestration and the carbon balance capacity of forest ecosystems. It is well-known that forest ecosystems, being the most important carbon sink, are a good tool to reduce the carbon content of the atmosphere. Estimating the amount of carbon stored by forests is essential to support climate change mitigation and promote the transition to a low-carbon emission economy.

It is well-known by researchers, authorities, and publics that forests are major terrestrial C sinks and sequester large amounts of atmospheric carbon dioxide (CO<sub>2</sub>). Forest ecosystems contain large amounts of C in above- and below-ground biomass, dead organic matter, and soil and contribute to significant annual C exchanges with the atmosphere. All these components may play an important role in the carbon storage and cycling of forest ecosystems. Article 2.1 of The Kyoto Protocol addresses issues related to global warming and holds signatories accountable to protect sinks and reservoirs of greenhouse gases, increase afforestation and reforestation, and promote sustainable forest management (Yavaşlı 2012). Thus, in the last few decades, many local, regional, and national studies have been carried out to quantify the biomass of forest ecosystems and its potential carbon fixation. Those

studies have reported that both forest plants and soils can sequester 60–80% of the global terrestrial carbon (Perruchoud and Fischlin 1995).

Most studies have focused on precise assessment of CO<sub>2</sub> emissions due to land-use changes, forest fire, degradation, and other anthropogenic activities in order to understand global carbon cycle and hence to make policies. So, biomass estimation studies of forest ecosystems all over the world have received much attention to reduce the uncertainties related to carbon cycle and emissions and find out the sources and sinks of carbon (C) as a result of forest to degraded land and vice versa as well as their temporal variations (Yavaşlı 2012).

In many studies, the standard methodology for the estimation of tree, plot, and regional aboveground biomass has been mostly allometric equations (Brown 1997; Lingner et al. 2018). Dry weight measurements conducted on harvested trees, fresh and dry weights of biomass components, and recording independent tree variables are required to construct allometric equations at the species, stands, or tree community levels. However, measuring forest biomass through field survey at a large spatial scale is time-consuming and cost-expensive and thus is difficult to popularize (Hermosilla et al. 2014; Van Leeuwen and Nieuwenhuis 2010; Dittmann et al. 2017). In addition to the large forest areas with the structural and geographical complexity and heterogeneity of forests and the conflicts in methods for forest measurements, precise mensuration of tree attributes with sufficient spatial and temporal resolution is also time-consuming and cost-intensive, especially in natural forest lands. Consequentially, the quantity, the frequency, and the parameter richness of in situ forest measurements reveal the constraints in accordance with the budget and the accessibility in forests.

The use of unmanned aerial vehicles (UAVs) both for small- and large-scale forest management inventories has become quite widespread and also produce accurate results (Wallace et al. 2012; Tuominen et al. 2015; Puliti et al. 2017, 2018b). The UAVs have high capacity to capture high- and ultrafine resolution information on the forest canopy and also their versatility and availability increase their uses for estimating forest management inventories. UAV systems represent a low-cost, agile, and autonomous opportunity and thus make them an alternative platform to satellites and aircrafts for forest inventory (Dandois et al. 2015; Sankey et al. 2017; Puliti et al. 2019). Considering recent applications of UAVs, demands on the usage of UAV-assisted surveys have increased suddenly in the last decade due to the technological advancements on various fronts such as structure-from-motion (SfM), machine learning, and robotics. The SfM photogrammetry provides surveys with little cost and low technical expertise. Therefore, the potential of using UAVs and consumer-grade cameras for terrestrial SfM-based surveys in forestry should be considered in measuring for large-scale forest inventories.

Within the scope of this study, researchers conducted on aboveground biomass and carbon storage in forest areas (coniferous or deciduous trees) were evaluated. Particularly studies in which UAV-SfM techniques are used in biomass and carbon measurements, which are the most important indicators for the reduction of pressures in forest areas, especially climate change, and the management of forests and the continuation of ecosystem services in a sustainable way have been reviewed.

Advanced research option under web of science search engines was used to identify the most up-to-date applications and researches. In the web of science core collection, the research area was chosen as “forestry.” A total of 15 recent publications related to aboveground biomass (AGB) and carbon storage estimations with UAV-SfM techniques were identified in the literature search made in the web of science database. In the review process, AGB and carbon estimation publications produced by manned flight, other than tree species, were excluded from the evaluation.

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## 2 A Very Brief Historical UAV Technology

Considering the history of remotely controlled unmanned aerial vehicles, hot-air balloons can be seen on the development of the first attempts for UAV before 1800s. The main technological development concepts of different type of UAV and mounted equipment or payloads (human, sensors, or weapons) have been used in the military and civilian purposes since early 1900s. In emerged unmanned flight platforms from past to today, inventors, manufacturers, and beneficiaries have used different terms, namely, “remote controlled aerial vehicles,” “remote controlled aircraft,” “remotely piloted aerial systems,” “unmanned air platform,” “unmanned aircraft,” “unmanned aerial systems,” “unmanned aerial vehicle” “drone,” “hexacopter,” “octocopter,” “quadcopter,” “delta-wing,” as well as other specific names such as “special purpose aircraft” and “unmanned combat aerial vehicle.” All mentioned terms have still been use in the history of continued UAV development in accordance with the technical usage function and the features of vehicles (Newcome 2004; Gupta et al. 2013; Keane and Carr 2013).

With the development of technology, there are many types of UAVs used for civilian purposes today. This type of vehicle uses inertial measurement unit (IMU), Global Navigation Satellite System (GNSS) receivers, sensors (different type of camera, radar, and laser detection systems), digital memory cards for recording, and telemetry system that transmits a data back to ground control station (González-Jorge et al. 2017). Remotely controlled aerial platforms with many different features, produced for fully automatic or semiautomatic hobby purposes, have become widespread.

UAVs (capable of short-term flight with vertical or horizontal take-off feature), which are used for nonmilitary purposes, are widely used today in different studies in the field of science or social sciences, with the use of commercial or open source software or self-programming. There are multipurpose vehicles that are almost the size of a mobile phone and can be loaded with photogrammetric flight plans thanks to the microprocessors inside. In addition, even amateur users have appeared as “robots” with artificial intelligence that can safely return and land after the flight, without experiencing an accident, by overcoming obstacles.

### 3 UAV Photogrammetry in Forestry

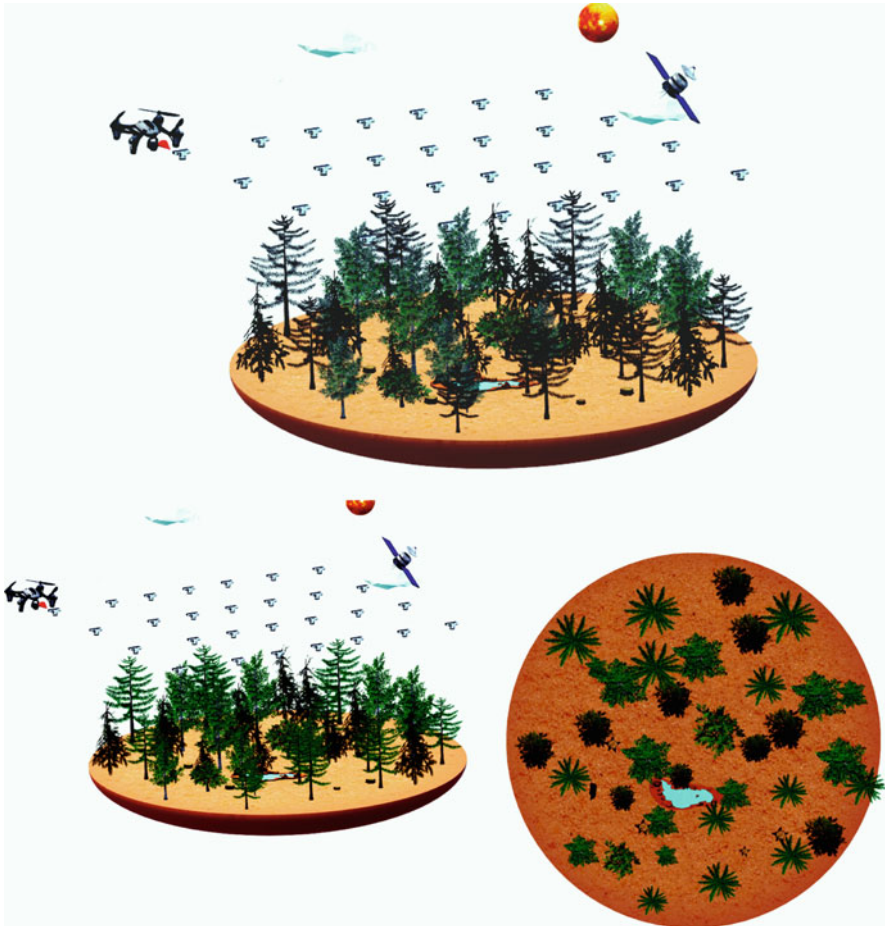
UAV usage techniques and terms have increased rapidly in forestry, which has become very popular in recent years. UAV-based SfM photogrammetry studies, which are considered new in terms of forestry, have been used in various countries in America, Europe, and Asia. With the widespread use of deep learning methods in photogrammetry (metric photography), its usage area has increased rapidly. The terms “close-range photogrammetry,” “digital aerial photogrammetry,” and “drone/UAV photogrammetry” are used for UAV photogrammetry, which does not comply with the definition of classical aerial photogrammetry classes. The term remote sensing has started to be used with the use of satellites and the development of technology. Similar methods can be applied for image processing and evaluation stages in digital photogrammetry, which is currently used.

The use of UAV platforms and their sensors is increasing rapidly due to the safety/security, cost, and time savings they provide in forested areas with difficult terrain conditions (Banu et al. 2016). Within the scope of forestry studies, preferred sensor combination expresses the use of both active and passive sensors. According to the intensity of use, visible range (RGB), multispectral, and LiDAR sensors are used in forestry (Dainelli et al. 2021). UAV-based forestry studies are carried out not only to collect data from hard-to-reach forest areas but also to use remote sensing techniques in all terrain conditions (Fig. 1).

As a result of recent advances and developments in UAV technology, the use of UAVs, especially for photogrammetry, is becoming even more common in forestry. In fact, the use of UAV photogrammetry has paved the way for the development of numerous methods, applications, research, and strategies by enabling to look at the problems that need to be solved in forestry from different perspectives. The diversity of data obtained from the scientific studies using UAV photogrammetry (observation, cartography, and 3D modeling) has carried the forestry research to whole new dimensions.

With various sensors mounted on UAV platforms, they have been used as spatial data production tools in many scientific researches and variety of applications in the field of forestry (Nex and Remondino 2014; Pajares 2015; Guimarães et al. 2020). In forestry, cameras in the RGB (R = Red, G = Green, and B = Blue) and NIR (Near infrared) spectral ranges are mostly preferred within the scope of UAV-assisted photogrammetry studies. Then, hyperspectral cameras and LiDAR sensors are preferred in the second place due to the cost constraints in applications. Currently, LiDAR sensor or hyperspectral camera and data processing costs are still higher than RGB and NIR band cameras (Torresan et al. 2017; Stone et al. 2016).

Aerial photography and satellite imagery, which have been used traditionally in forestry for many years, use of deep learning techniques (i.e., random forest, support vector machine, and convolutional neural networks) and UAV-imagery based photogrammetry, which can be evaluated within the scope of digital aerial photogrammetry, is structure-from-motion (SfM), paired with multi-view stereo algorithms provide significant advantages for forest practitioners and researchers (Iglhaut et al. 2019). The SfM technique, which includes traditional photogrammetric foundations,



**Fig. 1** Photogrammetric flight mission with drone

has led to an increase in measurement studies within the scope of close-range photogrammetry.

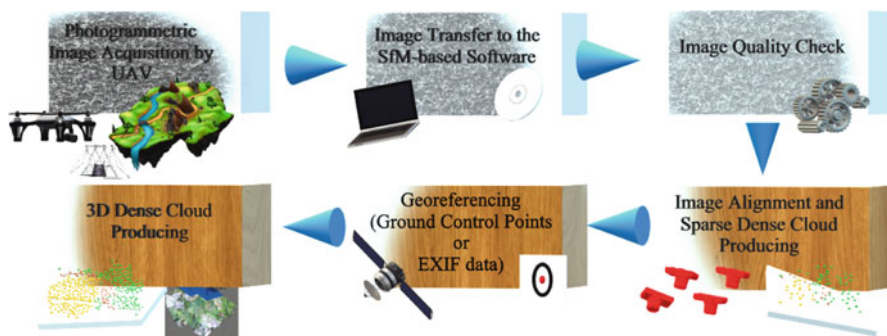
Through technological developments such as the development of more user-friendly photo processing algorithms and the production of various cost-effective sensors that can obtain various forestry-related data attract the attention of researchers in utilizing advanced remote sensing technologies in the field of forestry (Tang and Shao 2015). In the coming years, UAV photogrammetry use in forestry will increase its popularity especially in estimating individual tree parameters (used in tree recognition or disease detection in forests) with the decrease in the cost of camera and image processing programs in hyperspectral bands (Dainelli et al. 2021). For this reason, with UAV-SfM photogrammetry use in forestry, the next section focuses on studies using consumer-grade cameras in the visible range RGB and NIR.

## 4 UAV-SfM Photogrammetry Use in Forestry

Structure from motion (SfM) paired with multi-view stereo (MVS), namely, SfM, is a technique that converts stereopairs taken with a UAV from a 2D plane to a 3D point cloud. UAV-mounted consumer-grade RGB cameras or NIR cameras have been used in the generation of image-based 2D or 3D models using various software (i.e., Photoscan, Pix4D, MicMac, ReCap, VisualSFM, etc.), which effectively run SfM-based algorithms (Lisein et al. 2013). To generate self-calibrated image-derived products, UAV-SfM pipeline involves four basic steps: (1) image acquisition, (2) sparse dense cloud producing, (3) georeferencing, and (4) 3D dense cloud producing. Then, the generation of high-resolution models (orthophoto, mesh, texture, and digital elevation models) can be derived by using 3D dense point clouds (Fig. 2) (Remondino et al. 2014; Smith et al. 2015).

There is no standard for the values of the image processing quality that must be entered by the user in the image processing steps with SfM. UAV-SfM imagery-based derivation of 3D point clouds, which are LiDAR-like point clouds, can be prepared for further processing in forest stand parameters (i.e., individual tree detection, canopy cover, or canopy height model). To obtain stand-specific estimations, image-derived point clouds can be processed by using local maxima, marker-controlled watershed algorithm, template matching, valley following, scale-space theory, and Markov random fields (Wallace et al. 2016; Mohan et al. 2021).

Cost-effectiveness, temporal resolution, and flexibility in working within the scope of forestry increase the use of UAV-SfM method. Estimation of individual tree parameters (i.e., tree height and crown widths) with UAV-SfM photogrammetry has promising accuracy. Many variables are being investigated to increase the quality of 3D point cloud. For example, closure, species, species compositions, topographic structure, and other factors affecting locality can be taken into consideration. The carrier platform and system features used in photogrammetric flights, photogrammetric flight plan (such as flight altitude, flight speed, overlapping rates, camera calibration), environmental conditions during flight (such as stand feature and meteorological birds), image processing methods, and parameters are still being



**Fig. 2** Simplified workflow of UAV-SfM



investigated (Gülci 2019; Yurtseven et al. 2019; Kameyama and Sugiura 2020; Eker et al. 2020; Nasiri et al. 2021; Swayze et al. 2021). Studies on the variables and conditions that affect the prediction success of the UAV-SfM technique continue to increase. Therefore, the success of estimation of stand parameters has been increasing gradually.

The SfM techniques are effectively used in following subjects in forestry: (1) individual tree detection and inventory parameters; (2) aboveground volume estimations; (3) pest and disease detection; (4) species recognition and invasive plant detection; (5) conservation, restoration, and fire monitoring; and (6) setting and accuracy of imagery products (Dainelli et al. 2021). Among these subjects, the most popular research topics are individual tree detection and inventory parameters such as basal area, number of trees, diameter, and volume, which are crucial in decision making process, and followed by the pest and disease detection.

There are recent examples of UAV-SfM-based forestry-related researches, which mostly involve visible and NIR bands photogrammetry derived 3D point clouds. These researches were conducted on forest uniformity (Michez et al. 2016; Hentz et al. 2018); the characterization of vertical and horizontal variations of the forest canopy (Jayathunga et al. 2020); an assessment of the estimation success in tree height; tree crown cover and tree count for young stone pine stand and comparison of SfM processing quality (Gülci 2019); tree crown parameter estimations by using object-based image classification (Yurtseven et al. 2019); the mapping and classification of forest tree species comparing field- and UAV-SfM-based timber volume estimations by using allometric formulas (Gülci et al. 2021); mapping forests at the species level (Grybas and Congalton 2021); monitoring health status in priority riparian forests and detection of infects (Woellner and Wagner 2019; Guerra-Hernández et al. 2021; Miraki et al. 2021); tree-stump detection, segmentation, classification, and measurement (Puliti et al. 2018a); and forest road construction and earthwork (Bugday 2018; Akgul et al. 2018).

Based on the results derived from the previous studies, the success in estimated tree parameters of UAV imagery has great potential to use in forestry. For example, biomass estimations of tree parameters determined by UAV-SfM have been carried out with the help of allometric formulas for more than a decade (Dandois and Ellis 2010). On the other hand, UAV-SfM-derived orthophotos with high resolution provide as a basis of image classification techniques (i.e., unsupervised or supervised) for land cover analysis.

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## 5 UAV-SfM Studies in Aboveground Biomass and Carbon Estimation

Precise measurement of a tree biomass includes felling, weighing, and costly and difficult stages. This cost will increase exponentially in forested areas depending on the rough conditions of the land structure. In addition, ecological bases may not be appropriate in many studies, depending on the amount of sample tree use. For this



reason, more cost-effective biomass and carbon measurement techniques, which can be alternatives in tree mass measurement, are used (Dittmann et al. 2017).

The techniques generally used in biomass estimations include (1) allometric equations (field- and laboratory-based equations), (2) optical images (aircraft- and satellite-based passive sensors), (3) radar (aircraft- and satellite-based active sensors), (4) LiDAR (aircraft- and satellite-active sensor), and (5) SfM (UAV-based passive sensors) techniques.

Alonzo et al. (2018) carried out inventory studies in coniferous and broad-leaved forest areas. Tree density, basal area, and AGB estimates were made for white spruce, black spruce, birch, and aspen species in the study, which was carried out for a total of five different lands. In the study carried out with UAV-SfM photogrammetry, oblique and vertical photogrammetric image acquisitions were performed with a DJI Phantom 4 Pro quadcopter with a 20 megapixel camera. In oblique acquisitions, the nadir angle is set to  $90^\circ$  at a 90% overlapping rate at 100 m flight altitude. In their vertical flights, they flew with the camera at a narrow angle ( $20^\circ$  off nadir) from a height of 70 m. The total duration of single grid flights for 100 m and double grid flights for 70 m was 12 min. They have established a total of five ground control points (GCPs). In the study, firstly, with the RGB point cloud from UAV-SfM, it was investigated how accurately boreal forest tree species could be classified at the crown scale. Five basic steps have been followed to achieve this goal: (1) identifying the crown areas from the point cloud; (2) estimating structural and spectral variables for each segment; (3) classifying each segment as birch, aspen, white spruce, black spruce, or shrub; (4) calculating crowns at USDA FIA subplot level to estimate tree density (TD), basal area (BA), and AGB; and (5) comparing the TD, BA, and AGB model without segmentation at the subplot level. In the study application, Pix4D software was used for digital photogrammetric processes. They preferred watershed segmentation and then mean-shift segmentation methods in generating canopy height model (CHM) from point clouds. Except for one of the trial areas, the height errors were calculated to be below 1 m. With the help of allometric formulas, estimations were made for conifers by using tree height values ( $R^2 = 0.75$ , RMSE = 2.5 cm). On the other hand, the diameter at breast height (DBH) estimates based on crown width was lower ( $r^2 = 0.35$ , RMSE = 5 cm). Segment volumes substantially improved modeled AGB compared to subplot-level height metrics ( $R^2 = 0.92$ , RMSE =  $13.5 \text{ Mg ha}^{-1}$ , %RMSE = 27.1) in their study, where they stated that the TD values calculated on a single tree basis and on a trial area basis varied.

Otero et al. (2018) obtained CHM from the point cloud produced by the UAV-SfM technique. Biomass estimations of *Rhizophora apiculata* Blume and *R. mucronata* Lamk species were performed. They produced orthomosaic and digital surface model (DSM) with Photoscan software. Tree height information was estimated with CHM, in which Gaussian filter was applied. The package program "rLidar" (Silva et al. 2015) in R was used to process the CHM. CHMs have been introduced with the local maximum function with a fixed window size application. According to forest inventory, different values for Gaussian filter and a window size were compared for the best thresholds. A quadratic formula ( $R^2 = 0.75$ ) that explains

the relationship between height and AGB by making use of allometric formulas was used in the calculations of AGB ( $\text{Mg ha}^{-1}$ ) (Eq. 1):

$$\text{AGB} = 23.5 - 6.5 \times \text{Height} + 0.8 \times \text{Height}^2 \quad (1)$$

Fernandes et al. (2020) used a combined field and multispectral imagery approach to assess C stock of three dominant species (i.e., *Acacia dealbata* Link, *Alnus glutinosa* (L.) Gaertner, and *Salix salviifolia* Brot.), understory, and soil biomass in the Mediterranean riparian. Object-based image analysis (OBIA) was performed for species classification and segmentation from unmanned aerial vehicle (UAV)-based images. UAV SenseFly eBee platform is used as an aerial platform with RGB camera and Sequoia Parrot (multispectral camera). The photogrammetric flight height was 120 m with 80% of forwarding and side overlaps for RGB and 100 m for multispectral images. In the data acquisition, a total of 12 GCPs were used. Working with SfM logic, Pix4DMapper was used to process block images. Then, the aboveground biomass was calculated based on the allometric formula. A simple nonlinear model ( $R^2 = 0.94$ ,  $\text{MSE} = 4.5$ ) was developed for *Salix salviifolia*, an endemic species (Eq. 2). A coefficient of 0.5 ( $\text{tC ha}^{-1}$ ) was used as the carbon conversion factor:

$$\text{AGB} = 0.1758 \times \text{DBH}^{2.1314} \quad (2)$$

In their study, based on image classification, it was concluded that multiband UAV image data directly supports the conservative ability to classify in-forest waterfront species and indirectly predict tree AGB. No metrics are specified for the estimated carbon content and AGB prediction accuracy.

Wang and Lin (2020) performed photogrammetric flight with a RGB sensor platform mounted on a fixed-wing type UAV and performed biomass estimations. DSM, DEM, and CHM were obtained by processing the 3D point clouds produced with SfM in an area with sparse coniferous species. Tree crown widths were determined using the OBIA technique on the orthorectified map. Tree heights were estimated using CHM. Photogrammetric flight plans used SONY ILCE-5100 brand camera from 400 m height with 60% side and 80% front overlap. In the processing of photo blocks, point cloud and orthorectified map were obtained with Acute3d context capture. They have established 24 GCPs in the field. TerraScan software with the gradual encryption algorithm was used to generate CHM from point cloud. They used new height estimates using a linear regression model between tree height measurements and estimates. In tree height estimations,  $R^2 = 92$  and RMSE value was calculated as 1.08 m.

Castellanos-Galindo et al. (2021) studied comparison of ground-based, UAV-based, and radar-based measurements in estimation of stand characteristics. They performed a photogrammetric flight from 100 m using the DJI Phantom Mavic Pro and the Drone Deploy app. GCPs could not be established in the mangrove forest, which is very densely closed. Point cloud and orthomosaic were produced from block images taken at nadir angles with Agisoft Metashape. Tree diameter



(Gülci et al. 2021) and thus the carbon amount will increase. In addition, since even the same species may show different morphological characteristics in different forest ecosystems, it is necessary to develop site-specific formulas by classifying them (Tiwari and Singh 1984).

There are difficulties in performing biomass estimations with UAV-SfM due to the presence of trees of different closures, ages, and types in protected areas:

- Detection of errors caused by point cloud estimations due to tree crown forms.
- Preferring UAV platforms with sensitive GNSS modules (such as D-RTK or RTK) in difficult conditions where GCPs cannot be obtained.
- Reducing the losses incurred when processing images.
- SfM-based programs should be designed in an easier and more understandable way, as it can be complex for people who are not experienced in processing point cloud.

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## 6 Conclusion

AGB and carbon storage in forestlands cannot be directly measured by using UAV-SfM; however, some of biophysical attributes can be obtain by using UAV-mounted optical sensors considering SfM technique. Our findings show UAV-SfM photogrammetry can provide individual tree attributes such as tree height and canopy cover area via processing 3D point clouds. On the other hand, SfM-based generated orthomosaics can be classified by using supervised or unsupervised classification techniques. To improve image classification accuracies, different vegetation indexes, which can be derived from multispectral camera, can improve AGB estimations in forests with high canopy cover or riparian zones. Furthermore, research on carbon storage will be increased in forestry when the cost of hyperspectral camera and LiDAR sensor reduce by time. UAV-SfM-based AGB estimation, which is a nondestructive method, will be increased with the help of developed computer vision technology as well as experts.

**Authors' Contributions** All authors performed the same effort in this study. All authors wrote, read, reviewed, and decided to submit as chapters of a book.

**Conflict of Interest** No conflict of interest

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