Using 3D models to quantify aboveground biomass in the cushion-forming species *Plantago rigida* in an Andean páramo peatland

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SUMMARY

Peatlands dominated by cushion-forming species have been recognised for their high rates of soil carbon storage, along with their crucial importance in local pastoral systems, and in water supply and regulation, in the tropical and subtropical Andes. Cushion-forming species in Andean peatlands are known to have high rates of aboveground productivity, but there have been few studies and direct methods for quantifying their productivity. Here we describe the use of 3D digital models to estimate the aboveground biomass of *Plantago rigida*, one of the most common cushion-forming species of the tropical Andes. Using Structure from Motion (SfM) photogrammetry we reconstructed high-precision 3D models and, using traditional methods, obtained the dry biomass and carbon contents of 13 *P. rigida* cushions in three peatlands in northern Ecuador. Linear regression models were performed to assess the relationship of cushion volume *vs*. dry biomass, and also the area *vs*. carbon content of cushions. We found highly significant (linear) relationships in both cases, indicating the potential use of SfM photogrammetry to evaluate the annual productivity, carbon and water storage of cushions, along with microtopography effects on plant–plant interactions, water flow routing, and disturbance effects in cushion-dominated peatlands.

KEY WORDS: 3D modelling, Structure from Motion, volume

INTRODUCTION

The tropical and subtropical Andes of South America are home to a vast system of mountain peatlands which play a disproportionate role in water regulation, food security, biodiversity conservation, and carbon storage (Squeo *et al.* 2006, Cooper *et al.* 2010, Hribljan *et al.* 2017). More specifically, peatlands dominated by cushion-forming species (e.g. *Distichia muscoides*, *Plantago rigida*, *Oreobolus obtusangulus*) have been recognised for their high rates of soil carbon storage (Benavides *et al.* 2013, Benfield *et al.* 2021), and their crucial importance in local pastoral systems - especially in Perú and Bolivia (Verzijl & Guerrero-Quispe 2013) - and in water supply and regulation in the northern Páramos of Colombia and Ecuador (Mosquera *et al.* 2015). Previous research on cushion-forming species in these Andean peatlands suggest high rates of aboveground and belowground productivity, which may explain the large stores of carbon in their peat, that can range from 300 to more than 1500 Mg ha^{-1} (Suárez *et al.* 2022). Despite the importance of these cushion-forming species and the peatlands which they form, there are few studies and direct methods for quantifying their productivity.

Previous research on individual cushion plant productivity used a modification of the cranked-wire method, often used in mosses (e.g. *Sphagnum* spp.) (Clymo 1970, Russel 1984, Camill *et al.* 2001). In this method, cranked wires are vertically inserted in the plant structure, with the hope that the lower end of the wire will firmly attach to the substrate, and a known length of wire is left protruding out of the plant. Then, plant growth is estimated by re-measuring the protruding end of the wire and relating that growth to estimates of plant biomass generated by harvesting layers of the plant with known thicknesses. Based on this method, Cooper *et al.* (2015) reported a height increase of *Distichia* *muscoides* that ranged from 0.96 to 5.37 cm yr^{-1} and carbon production of 1.5 to 4.0 kg m^{-2} y^{-1}, compared to the lower carbon productivities reported by Planas-Clarke *et al.* (2020) for *D. muscoides* (1.64 kg m^{-2} y^{-1}) and *Oreobolus obtusangulus* (0.91 kg m^{-2} y^{-1}), suggesting rapid growth and peat accumulation rates in all cases. This method, however, has limitations when used on vascular plants, particularly cushion forming species. Wires may sink because of low bulk density, animals sometimes pull wires from the ground or step on them, bending them over, and the ground surface is rarely perfectly flat. Moreover, this method does not take into account the complex architecture of cushion plants and the fact that they can grow not only vertically but also laterally, potentially leading to underestimation of plant productivity. Thus, non-destructive methods which do not require harvesting for estimation and monitoring of plant biomass (and other properties), and consider multi-dimensional growth, should produce high throughput and accuracy enabling more accurate plant modelling (Chen *et al.* 2022).

Studies of the measurement of plant traits using 3D methods have been increasing in recent years, mostly centred on monitoring crop architecture, composition and growth (Paturkar *et al.* 2021). In general, these methods are based on using digital photos to assemble a cloud of points in which each point corresponds to a detected point on the surface of the plant. This cloud is then processed to create a 3D model that can be used to calculate volume, distances and surface areas of the plant structure. Structure-from-Motion (SfM) photogrammetry is a technique that uses multiple overlapping images to determine both the camera positions and 3D geometry of a photographed scene, reconstructing high-resolution 3D natural environments and organisms with a cost-effective and automated method (Burns *et al.* 2015, Burns & Delparte 2017, Iglhaut *et al.* 2019, Paturkar *et al.* 2020, Chen *et al.* 2022).

Our objective is to evaluate the feasibility of using SfM photogrammetry to monitor several variables related with the ecology and biomass of individual cushion plants. In this article we describe the use of 3D digital models to estimate the aboveground biomass of *P. rigida*, one of the most common cushion-forming species of the tropical Andes.

METHODS

For this study, we selected 13 individuals of the cushion-forming species *P. rigida* from three peatlands in northern Ecuador's Cayambe-Coca National Park (4230 m a.s.l.). Individuals differed in size (0.02–0.27 m^2), capturing the natural variability of the local population. For each individual cushion plant, photographs were taken in a spiral pattern that simulated a dome-like structure above the plant (Figure 1A). About 200 42.4-megapixel (Mpx) photographs using a SONY® Alpha ILCE-7RMIII equipped with a SONY® 12-24 mm F4 G lens were required for each cushion. To define both the sampling space and the model's baseline, we set a wooden frame (70 × 70 cm) around each individual before photographing. This frame had coded targets on each corner that were used in a later step to set scale bars for subsequent calculations. To control for environmental light changes, pictures were taken during an overcast day, providing constant light conditions for reconstruction (approximately 10 min per cushion). Images were processed in Agisoft Metashape 1.8.3 (Agisoft LLC, St. Petersburg, Russia). For 3D model reconstruction, we aligned all images and identified common points to build a point cloud and later a 3D mesh (Figure 1A). We selected a medium-quality mesh reconstruction as it renders a better base geometry of the individual, automatically deleting noise generated by the pointed leaves of this species. A texture was applied to the resulting images so that photos with parts of the cushion were linked to the model's vertices and excluded what was not cushion. The resulting cushion model was then trimmed by deleting everything outside and below the wooden frame surface (Figure 1B). Two mesh model versions, one watertight (i.e. closed) and the other non-watertight (i.e. not completely closed) (Figure 1C), were exported as .OBJ files then imported into the Meshlab program for area and volume calculations, following the Million *et al.* (2021) protocol.

After the pictures were taken in the field, all individuals were harvested for biomass analysis using the wooden frame as a defined limit for the saw cut, ensuring compatibility between measured biomass and the 3D models' volumes. This was done to assess the relationships between measurable traits using the model (volume and surface area) and traits that would traditionally require harvesting (biomass and carbon content). For all individuals we weighed the freshly harvested material before drying subsamples at 65 ºC. We calculated bulk density and organic matter content for all samples, assuming that carbon constitutes 46.45 % of the organic matter weight (Ma *et al.* 2018). After this, linear regressions were performed to quantify the association between the calculated 3D model volume and the cushions' dry biomass and carbon content. All statistical analyses were made in R v.4.1.2 with the *lm* (Fitting Linear Models) function (R Core Team 2021).

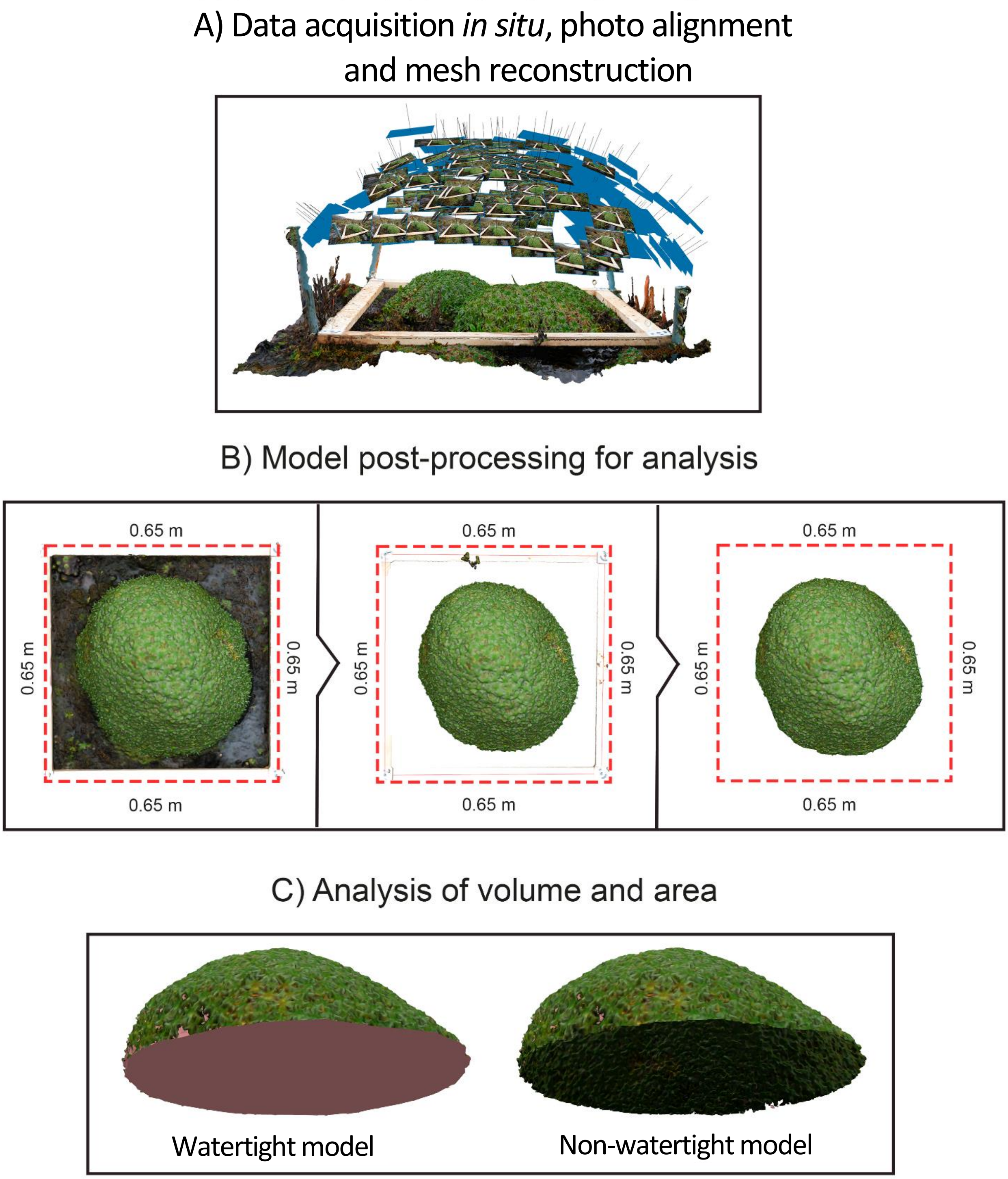

Figure 1. Outline of processing and analysis stages for 3D plant modelling.

RESULTS

The modelling process used between 121 and 261 images for each cushion, producing high precision 3D models using an average of 50000 ± 17000 (mean ± SD) points per individual, with a mean resolution of 0.14 ± 0.008 mm px^{-1}, a spatial error of 1.6 ± 0.1 mm, and a reprojection error of 0.73 ± 0.04 px.

We found a strong relationship between the volume of cushions obtained by the SfM 3D models and their dry biomass ($R = 0.97$, $p < 0.001$, $n = 13$, Figure 2A). Also, as expected, the volume and area of the cushions had a strong positive relationship ($R = 0.98$, $p < 0.001$, $n = 13$), as well as the area of cushions and their carbon content ($R = 0.91$, $p < 0.001$, $n = 13$, Figure 2B).

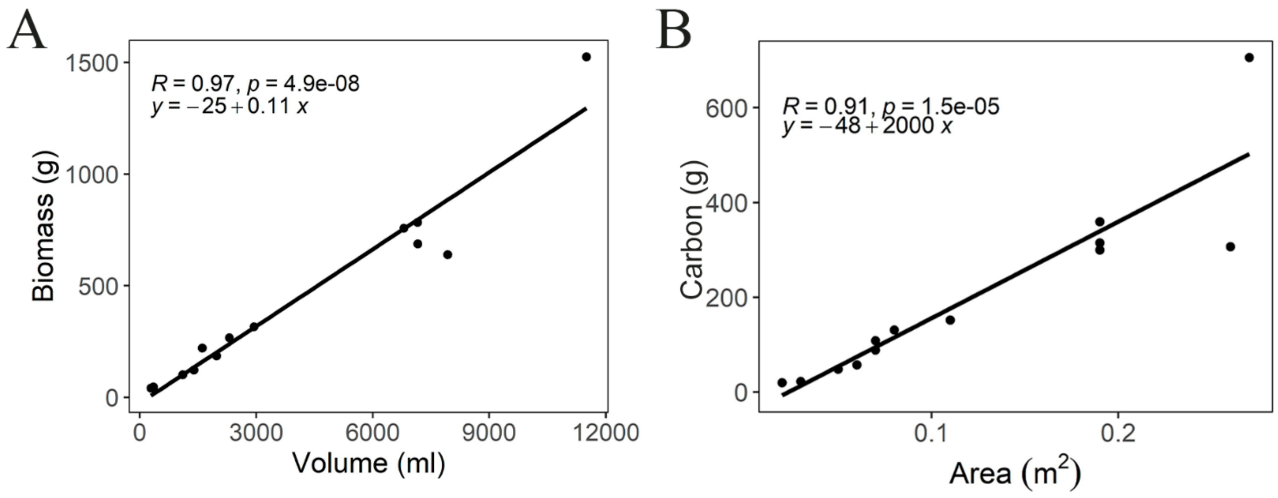

Figure 2. Relationships between (A) calculated 3D model volume and cushion biomass, and (B) calculated 3D model area and carbon content per square metre, for 13 individual cushions of *Plantago rigida*.

DISCUSSION

Usage of SfM modelling techniques to estimate and quantify ecological traits in plants in airborne and terrestrial inventories has been validated by several studies (Iglhaut *et al.* 2019, Paturkar *et al.* 2021). Airborne inventories have been used in different forest types producing high-accuracy model outputs (Kachamba *et al.* 2016, Feduck *et al.* 2018, Lin *et al.* 2018), with even better performance compared to airborne laser scanning (ALS) and field assessments (Puliti *et al.* 2019). Terrestrial forest studies have focused on linear measurements such as DBH, tree position, height, and stem curve (Mikita *et al.* 2016, Piermattei *et al.* 2019, Chen *et al.* 2022), but single-plant approaches have also demonstrated high accuracy when evaluating plant volume (Cunliffe *et al.* 2016, Schittek *et al.* 2018) and aboveground biomass (Zhang *et al.* 2016, Cooper *et al.* 2017, Paturkar *et al.* 2019, 2020).

The models produced during this study also demonstrate high accuracy, with resolution values and spatial and re-projection errors similar to those in other studies that used similar techniques on organisms with complex morphologies. Burns *et al.* (2015) used SfM to evaluate structural complexity in coral reefs (configuration, conformation, contour, form, and shape of the coral reef environment) with a lower resolution (1.09 mm px^{-1}) and a slightly smaller re-projection error of 0.501 px. Similar error values were also obtained by Burns & Delparte (2017), who assessed the performance of SfM modelling in creating 3D reconstructions of coral reefs using commercial software packages. Interestingly, Lange & Perry (2020) found that the reconstruction accuracy in colonies of the hard coral *Porites lobata*, a species resembling the cushion-like morphology of *P. rigida*, was below 0.2 mm, making the models developed in this study the closest point of reference available.

Previous research by Schittek *et al.* (2018) calculated the exact volume of a 10 m diameter *Distichia muscoides* cushion in the Peruvian Andes using terrestrial laser scanning (TLS). However, this method is light sensitive and the resulting model included some areas without data because of shading effects and open water areas. We addressed this in our work by taking the pictures during an overcast day.

The strong relationship we found between cushion volume from SfM 3D models and dry biomass indicates that SfM models can be used as a non-destructive, cost-effective and high-precision tool to quantify biomass and annual productivity of *Plantago rigida* cushions. The relationships and regressions presented in this article allow for future biomass and carbon estimations without the need for additional harvesting. Also, since cushion area and carbon content were strongly related, this technique could be scaled up using unmanned aerial vehicles (UAVs) to survey carbon stocks in large areas covered with cushion-forming plants such as high-elevation tropical peatlands.

The high precision of the 3D models that we built for *P. rigida* has at least three relevant implications. First, our data showed that 84 % of the weight of our cushions was water, the rest being organic matter and a small amount of soil. Given the high accuracy of the volume calculations for our individual cushions, the 3D models could be used to study water dynamics and storage in cushion plants under different environmental conditions. Second, since the volume-biomass relationship has been developed (Figure 2), repeated 3D models of the same cushion over time will allow precise estimation of productivity by relating the changes in volume to the changes in biomass and carbon content. It would be necessary to include geotags during the data-acquisition workflow to set a baseline for comparison. And third, by using 3D models to map and describe the distribution of other species on the microtopography of the cushions, plant–plant interactions could be explored, as well as the effects of microtopography on water flow routing, saturation areas, and disturbance effects in cushion-dominated peatlands (Holden 2005).

Despite the wide use of passive techniques such as SfM models for a wide range of organisms and approaches (Iglhaut *et al.* 2019, Paturkar *et al.* 2021, Chen *et al.* 2022, Taugourdeau *et al.* 2022), there are some drawbacks that need to be considered when SfM modelling. Paturkar *et al.* (2021) point out that wind can move plant structures during the photographic process displacing key features spatially, which may result in noise around the point cloud. Similarly, isolating individual plants for 3D reconstruction may be difficult in structurally complex habitats where plant leaves and branches overlap each other. Moreover, environmental light may change over the course of data acquisition leading to the appearance of hard shades and bright edges under direct sunlight that may hide key features for 3D reconstruction in sequential images, especially if the angle of reflection within the picture varies significantly. However, the packed cushion-like shape of *P. rigida* makes this plant robust against wind gusts and its relatively simple structural environment - the Andean peatland - facilitates individual isolation and reconstruction. Finally, there is an inverse relationship between the number of images taken for 3D modelling and the image-processing time (Paturkar *et al.* 2020, 2021). A small number of photos would decrease the time to render a 3D model at the cost of accuracy, although the number of photos per individual of *P. rigida* in this study (120–261) rendered accurate 3D models. In conclusion, SfM is an efficient, cost-effective and non-destructive approach for the 3D reconstruction of objects with high resolution, allowing long term monitoring of ecological traits and potential applications for conservation and management of these ecosystems.

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AUTHOR CONTRIBUTIONS

RJ and ES devised the work; AM-G carried out the 3D plant modelling and análisis; RJ, LGD and SC carried out fieldwork and sample processing; RJ, LGD, AM-G and ES wrote and revised the article.

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