

## RESEARCH ARTICLE

# Using unmanned aerial vehicles to estimate body volume at scale for ecological monitoring

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**Handling Editor:** Sarah Marley**Abstract**

1. Demographic data are essential to construct mechanistic models to understand how populations change over time and in response to global threats like climate change. Existing demographic data are either lacking or insufficient for many species, particularly those that are challenging to obtain direct measurements from that can be used to estimate demographic rates, like marine mammals. A method for collecting accurate demographic data to construct robust demographic models at scale would fill this knowledge gap for difficult-to-access species.
2. We introduce a novel, non-invasive method to estimate the 3D body size (volume) of pinnipeds (seals, sea lions and walruses) that will allow monitoring at high spatial and temporal scales. Our method integrates 3D structure-from-motion photogrammetry data collected via planned flight missions using off-the-shelf, multicopter unmanned aerial vehicles (UAVs). We apply and validate this method on the grey seal *Halichoerus grypus*, a pinniped species that spends much of its time at sea but is predictably observable during its annual breeding season. We investigate the optimal ground sampling distance (GSD) for surveys by calculating the success rates and accuracy of volume estimates of individuals at different altitudes.
3. Based on current technology, we establish an optimal GSD of at least  $0.8 \text{ cm px}^{-1}$  for animals similar in size to UK grey seals (~1.2–2.5 m length), making our method reproducible and applicable to other species. We found volume estimates were accurate and could be successfully estimated for up to 68% of hauled-out seals in study areas.
4. Our method accurately estimates individual body volume of pinnipeds in a time- and cost-effective manner while minimising disturbance. While the approach is applied to pinnipeds here, the method could be adapted to further taxa that are otherwise challenging to obtain direct measurements from. Our proposed approach therefore has the potential to fill demographic research gaps, which will improve our ability to protect and conserve species into the future.

**KEYWORDS**

demographic data, drone, photogrammetry, pinniped, structure-from-motion, UAV, wildlife monitoring

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## 1 | INTRODUCTION

Population modelling has produced key insights into the ecology (Goldberg et al., 2001), evolution (Grant & Grant, 2002) and conservation biology (Baxter et al., 2006) of multiple species. Indeed, using demographic data, one can parameterise mechanistic models to understand how populations change through time (Thomas et al., 2019), evolve (Barfield et al., 2011) and can be managed in the most cost-effective manner (Taylor & Hastings, 2004). In this context, demographic data describe the size, structure and/or trends through time of a population. These data are often used to parameterise structured population models (Caswell, 2000; Easterling et al., 2000). Such models can describe how different components of a population contribute differently to the population growth rate through birth, survival and migration (Sibly et al., 2002). Understanding these population changes is crucial given the increasing external threats populations face (IPBES, 2019), and as such these changes are integral metrics of the IUCN conservation status of species (IUCN, 2022).

Robust estimates of population trends emerge from demographic models often parameterised with data possessing four qualities. These qualities are long-term (White, 2019), individual-level (Merow et al., 2014), large sample size (Fiske et al., 2008) and, for species whose survival and reproduction are best described as a function of continuous variables (e.g. size, height, weight), data on those continuous traits (Easterling et al., 2000; Ramula et al., 2009). Longer time series of demographic data can help us understand how populations change and the consistency of trends over time (White, 2019). Individual-level data covering a high proportion of the population is important to capture the naturally occurring heterogeneity in vital rate values (e.g. survival, growth, reproduction), a key aspect of population viability (Fiske et al., 2008). Continuous traits such as body size (as opposed to discrete traits that can only take certain values or states, e.g. developmental stage or age) are good predictors of vital rates in a large number of species (Savage et al., 2004), as they tend to provide key insights into underlying mechanisms that shape fitness components. For example, body size is intrinsically linked to metabolic rate (Sparling et al., 2006) and competitive abilities (Whitman, 2008), which in turn shapes survival and reproduction (Brown et al., 2004; Savage et al., 2004). However, despite the preference for models based on data with these properties, we do not have such data for many species (Lebreton et al., 2012; Salguero-Gómez et al., 2015, 2016).

High-quality, continuous demographic data are lacking for many animal species because these species are not easily observed or approached (Cooke, 2008), or because time-consuming and invasive methods that could include capturing individuals or using sedatives may be required (Hodgson et al., 2020; Manning & Goldberg, 2010). Consequently, we do not have high-resolution demographic data for species such as many marine species that are challenging to observe (Davis, 2022). Examining data-deficient species is necessary to effectively protect them from threats,

particularly as less understood species are often more threatened or face different challenges to better-studied species (Borgelt et al., 2022). For example, marine mammals have faced more threats than their better-understood terrestrial counterparts (Schipper et al., 2008). However, novel technologies such as UAVs (unmanned aerial vehicles, drones) may help us overcome these challenges.

UAVs have diverse applications in ecology and conservation biology, ranging from crop monitoring to assessing forest health (Larsen & Johnston, 2023; Sun et al., 2021). Recent advancements have made UAVs suitable for collecting continuous state data (e.g. body size) that can be used to estimate demographic rates from populations that would otherwise be challenging to obtain direct morphometric measurements from (Christiansen et al., 2022; Krause et al., 2017). Indeed, UAVs can access remote areas, eliminating the need to approach, sedate and handle dangerous or threatened species (Krause et al., 2017; Shero et al., 2021). Disturbance to study organisms can also be minimised by using UAVs and by considering species-specific hearing sensitivity and operating UAVs at higher altitudes without sacrificing high resolution data (Duporge et al., 2021; Krause et al., 2021). Using UAVs is cheaper and quicker than traditional monitoring methods (Jackson et al., 2022) and can greatly expand the spatial scale of survey efforts (Bogdan et al., 2021). To date, UAVs have been used for 2D size estimates of individual animals, including at a colony scale (de Kock et al., 2021; Infantes et al., 2022). Some studies have also estimated 3D body size (volume) using UAVs, both indirectly by deriving volume estimates from 2D morphometrics (Carroll et al., 2024; Christiansen et al., 2019; Irschick et al., 2021), and directly by using structure-from-motion photogrammetry to take a series of overlapping images from a known altitude that are stitched to create a geometrically accurate 3D model (Hodgson et al., 2020; Shero et al., 2021). Recently, multiple studies have shown that 3D body size (body volume) estimates from UAVs are more accurate than 2D estimates, as the former are less sensitive to body position and posture (Hodgson et al., 2020; Shero et al., 2021). Despite this advancement, current methods have been limited to estimating the 3D body volume of a single individual or small group of individuals at a time, and so are not easily scalable to whole colonies (Hodgson et al., 2020; Shero et al., 2021). Therefore, there is need for a methodology to directly estimate body volume at a larger scale.

Here, we develop and validate a novel method to accurately estimate body volume at the colony scale and using commercially available and broadly affordable (<£6000) UAVs. We developed this method to assess body volume for a group of species, the pinnipeds (e.g. seals, sea lions and walrus), for whom it is challenging to obtain direct measurements that can be used to estimate demographic rates. We demonstrate our approach on the grey seal *Halichoerus grypus*, a cryptic marine species that spends much of its time at sea but is predictably observable annually during its breeding season when it hauls-out on land (Hall & Russell, 2018). We conducted fieldwork on two regionally important grey seal colonies in the UK: the Isles of Scilly and the Farne Islands. Our method obtains accurate (mean estimates not statistically different from

true values) body volume estimates for 68% of hauled-out seal individuals at the identified optimal ground sampling distance (GSD) of  $0.8 \text{ cm px}^{-1}$ . Finally, we propose the species' characteristics that may indicate suitability for future application of our methodology.

## 2 | METHODS

### 2.1 | Study species

The grey seal *Halichoerus grypus* is a long-lived (20+ years for males, 30+ years for females; SCOS, 2021) marine apex predator species that spends most of its time at sea (McConnell et al., 1999). Grey seals haul-out on land to rest and in larger colonies to pup and moult (Hall & Russell, 2018), so some of their key life history traits are predictably observable annually. The UK is home to ~35% of grey seals worldwide (SCOS, 2021), and UK populations are increasing in size from historic lows due to hunting (Russell et al., 2019). Grey seals have a polygynous mating system and mature females can give birth to one pup per year that is weaned at approximately 3 weeks (Hall & Russell, 2018). The pup then moults its white coat to gain adult pelage and after another 3 weeks leaves the colony (Hall & Russell, 2018). In this study, our objective was to develop a methodology that could be used to assess the body volumes of as many individuals in a seal colony as possible. We expected that it would be easier to estimate the volumes of larger individuals. We therefore split our sample into two discrete categories: (1) white coat pups, which are typically five- to tenfold smaller than adults (Hall & Russell, 2018), and (2) moulted pups and adults. This distinction allowed us to better assess the success of volume construction for adults, which are typically more important for population growth in long-lived species like pinnipeds (Franco & Silvertown, 2004). White coat pups also have distinct vital rates than older individuals, for example, higher mortality rates due to dependence on their mothers (Hall et al., 2001; Noren et al., 2008). Distinguishing between white coat pups and adult seals in a colony is also consistent with standard monitoring practices employed by marine management organisations (Hammill et al., 2017; Russell et al., 2019). We visually assessed surveyed seals and assigned any individual with a white coat to a 'white-coat pup' category, and any individual with adult pelage to an 'adult' category.

### 2.2 | Study sites

Grey seal colonies on the Isles of Scilly and Farne Islands (Figure 1a) both make important contributions to regional grey seal pup production (SCOS, 2021). Approximately 50% of Southwest England's grey seal pup production takes place in the Isles of Scilly, which on average is inhabited by ~600 individuals (Sayer & Witt, 2018). The Farne Islands' grey seal colony produces ~3000 pups annually, accounting for ~25% of England's grey seal pup production (SCOS, 2021).

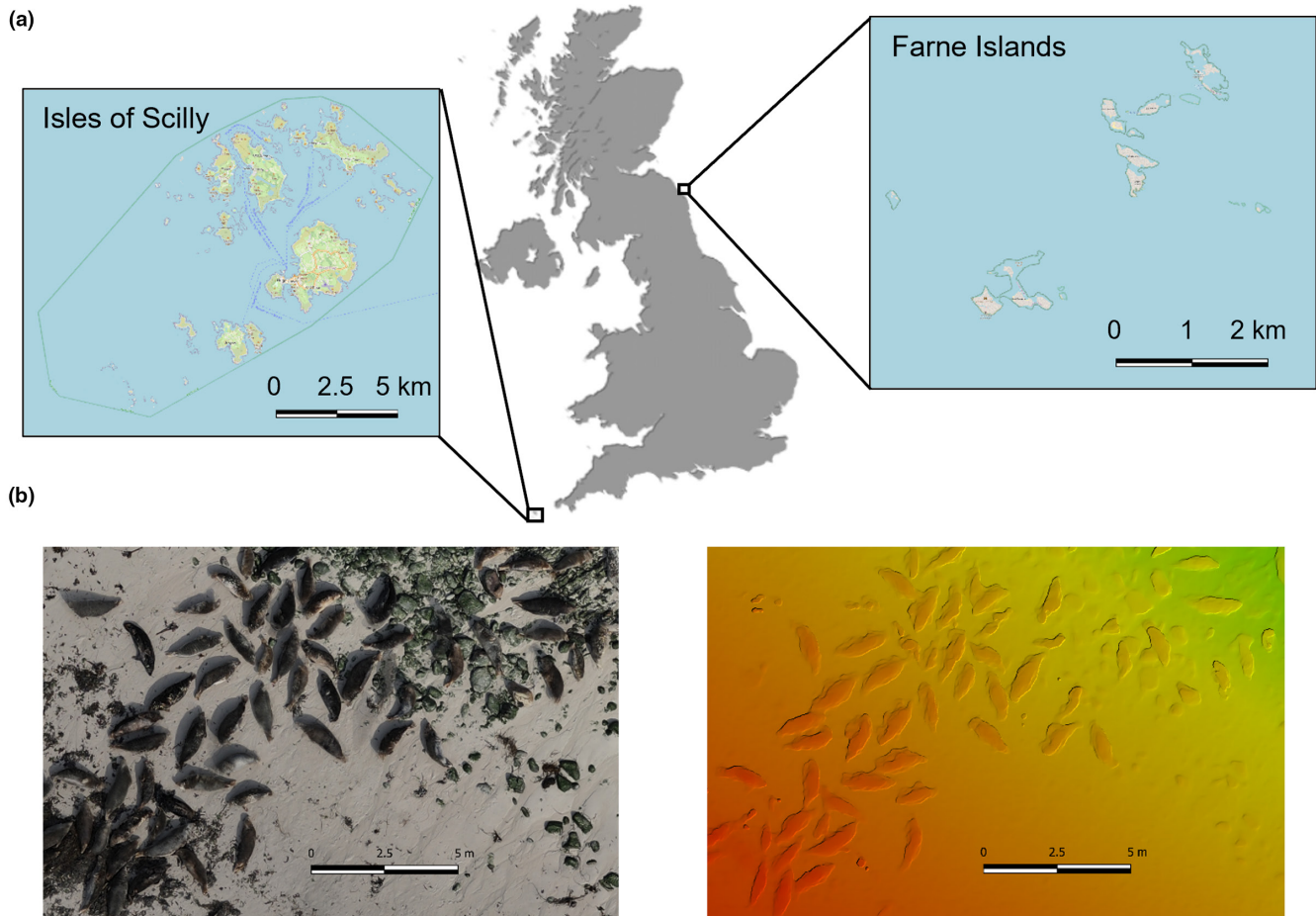
Seal haul-out sites in both locations are heterogeneous and are a mix of rocky intertidal areas and sandy beaches. Access to these sites is challenging, particularly in the Isles of Scilly, due to a lack of suitable boat landing sites and prevailing sea and weather conditions. Therefore, surveys are largely undertaken from sea (Sayer & Witt, 2018), with the use of visual aids such as binoculars. Visual surveys from sea will necessarily be limited in their ability to spot seals hidden from view or located in the centre of islands, potentially leading to inaccuracies in counts. Survey permissions for the current research were obtained from NE Natural England (NE 1208221126FG) for the Isles of Scilly and from the National Trust for the Farne Islands.

### 2.3 | Field technologies

We used two different off-the-shelf, multirotor UAVs to undertake survey missions. These UAVs were a DJI Mavic 2 Enterprise Advanced (DJI; Shenzhen, China; unfolded diagonal wingspan 354 mm, take-off weight 909 g, GPS accurate to  $\pm 0.5 \text{ m}$  vertically and  $\pm 1.5 \text{ m}$  horizontally, £5480) and a DJI Mavic 2 Pro (unfolded diagonal wingspan 354 mm, take-off weight 907 g, GPS accurate to  $\pm 0.5 \text{ m}$  vertically and  $\pm 1.5 \text{ m}$  horizontally, £1349). The visual-range camera on the DJI Mavic 2 Enterprise Advanced has a minimum ground sampling distance (GSD, a measure of image quality; Box 1) 20% lower than the DJI Mavic 2 Pro, meaning the DJI Mavic 2 Enterprise Advanced takes higher resolution images.

### 2.4 | Survey planning and flight parameters

We present an overview of the key preparation, fieldwork, data pre-processing and finally outputs involved in estimating seal volumes using UAVs in Figure B2. Note that each of these steps is discussed in more detail in subsequent sections. Before undertaking surveys with UAVs in the field, UAV training should be completed and permissions from local landowners or site managers obtained (Figure B2, Step 1). To determine which islands to survey, we consulted site managers and conducted scouting missions in the field. We pre-programmed survey missions in DJI Pilot (DJI; Shenzhen, China. v2.5.1.15) or Fly Litchi (VC Technology; London, United Kingdom. V4.25.0-a) following transect routes to take a series of overlapping photos across a seal colony with the gimbal angled 90 degrees vertically down. This transect pattern is a key difference to previous pinniped body volume work that either used radial flight patterns circling a small group of seals (Shero et al., 2021) or focussed on a single individual at a time (Hodgson et al., 2020). Our transect method enables a wider area to be covered with a single survey. Early trials indicated no difference in accuracy between volume estimates from transect or radial survey patterns (Table S1). Sufficient overlap between images is required so images can be stitched together to create an orthomosaic (geometrically accurate 2D representation of the survey area, Figure 1b) and a digital surface model (DSM, 3D representation



**FIGURE 1** The locations of the two field sites used to test our method for estimating body volume using grey seals, *Halichoerus grypus*, as a case study, together with an example of what an orthomosaic (geometrically accurate 2D representation of the survey area) and a digital surface model (DSM, 3D representation of the survey area showing the elevation of objects above the Earth's surface) obtained following our method look like. (a) A map showing the location of our two field sites in the United Kingdom. The Isles of Scilly (left) consist of five inhabited and >100 uninhabited islands ~45 km off Southwest England. The Farne Islands (right) consist of 15–20 (tide-dependent) small islands ~2–10 km off Northeast England, uninhabited except for a ranger station on one island (Inner Farne). (b) Left: An orthomosaic generated from unmanned aerial vehicle (UAV) images taken from an island in the Isles of Scilly and Right: The corresponding digital surface model, with red colours indicating higher elevation and green colours indicating lower elevation.

of the survey area showing elevation of objects above the Earth's surface, [Figure 1b](#)). We set frontal image overlap at 80% and side overlap at 70% to exceed the minimum overlap of 75% frontal and 60% side recommended by the photogrammetry software we used, 'Pix4D Mapper' (v. 4.7.5; Pix4D S.A., Prilly, Switzerland). These values for overlap ensured 80% of the previous image was in the next image and 70% of the area covered in the previous transect was in the next transect, ensuring sufficient overlap was captured to reconstruct the survey area in three dimensions. However, some individuals will move between images in a survey, and this will always prevent a proportion of the colony from being reconstructed successfully in the 3D model. Therefore, being able to estimate the volumes of 100% of individuals in a survey is unlikely. The impact of seal movement can be reduced by programming transect routes to operate perpendicular to the longest edge of the survey area, commonly the coastline, as this minimises the time between successive flyovers

and so minimises the time in which individuals can move. Transect routes can also be saved and so are reproducible across years.

## 2.5 | Data collection

Ideally, censuses should be timed to maximise the number of individuals that can be captured within the survey, and when key vital rates are measurable (e.g. peak reproduction, juvenile to adult transition, etc.). For grey seals, surveying during the pupping season when much of the colony are hauled-out on land maximises the number of individuals captured in surveys (Sayer & Witt, 2018). In particular, breeding female grey seals and their pups can be captured in surveys during the pupping season. In the Isles of Scilly, the pupping season lasts from September to November (Sayer & Witt, 2018). We censused the Isles of Scilly grey seal colony by UAV in late-September

2022 over four consecutive days, covering every island with > five individuals based on previous surveys (Sayer & Witt, 2018). In total, we surveyed 21 islands over 23 individual missions in the Isles of Scilly. The Farne Islands' pupping season lasts from November to

December (SCOS, 2021). We censused every island in the Farne Islands with suspected seal presence (14 islands over 15 individual missions), as informed by local rangers.

For our UAV surveys of grey seals, we launched a combination of survey missions from land ( $n=12$ ) and from a small boat ( $n=26$ ). Launching missions from boats minimises disturbance to seals and precludes the need to make difficult landings on islands when conditions are poor. By contrast, launching UAV missions from land is generally safer for operators, quicker, and easier in poor weather conditions, allowing longer flight times since less battery reserves are needed for landing. We launched missions from land or boat depending on the accessibility of landing sites at a safe distance from seals for both researchers and seals. We maintained an in-flight altitude of  $\geq 40$  m when surveying and took-off and landed UAVs  $>50$  m from seals to avoid disturbance (Pomeroy et al., 2015). Seal and seabird behaviour were monitored during flights to ensure no disturbance. During the surveys, no abnormal seal behaviour was observed that could be attributed to our UAV missions. Different seal colonies may respond differently to UAV presence, and the potential for disturbance with local seal colonies should always be assessed before UAV work. Best practices in the field are discussed further in Box 2 and in Figure B2, Step 2.

### BOX 1 Ground sampling distance for estimating volume

Ground sampling distance (GSD) is a measure of the resolution of an image, representing the true distance between the centre of two adjacent pixels. A higher GSD, therefore, results in a lower resolution image. For example, if a camera's minimum GSD at a certain altitude is  $0.8 \text{ cm pixel}^{-1}$ , the smallest details that could be obtained from an image taken at said altitude would be  $0.8 \text{ cm}$  measured linearly (Figure B1). When planning surveys, GSD is dependent on flight altitude and three camera parameters: sensor width, focal length and image width. Because the GSD can be calculated for any UAV camera at a given altitude, once the maximum GSD that enables many accurate body volume estimates of an animal species to be obtained, one can determine whether any UAV can estimate the body volume of animals of that size at the altitude required to avoid disturbance. GSD is calculated as

$$\text{GSD (cm per pixel)} = \frac{\text{camera sensor width (mm)} \times \text{altitude (m)} \times 100}{\text{camera focal length (mm)} \times \text{image width (pixels)}}$$

For example, the DJI Mavic 2 Enterprise Advanced has a visual-range camera with a  $1/2$ " CMOS sensor, which has a sensor width of  $6.4 \text{ mm}$ , a focal length of  $4 \text{ mm}$  and an image width of  $8000$  pixels. Therefore, taking images at  $40 \text{ m}$  altitude gives a GSD of  $0.8 \text{ cm px}^{-1}$ ,

$$\text{GSD (cm px}^{-1}\text{)} = \frac{6.4 \times 40 \times 100}{4 \times 8,000} = 0.8 \text{ cm px}^{-1}$$

## 2.6 | Data processing

To estimate body volume on a colony scale, we aimed to find the most efficient way to process the image data we collected (Figure B2, Steps 3 and 4). This task involved establishing the optimal way to conduct pre-processing on the images collected, construct 3D models from these images, locate seals in the model and estimate their body volumes. Before processing the images collected, we removed blurry images ( $<5\%$  in our case) and ensured auto-collected image metadata including altitude and GPS coordinates were correct. We constructed 3D representations of the survey area using structure-from-motion photogrammetry with the software 'Pix4D Mapper'. As a series of overlapping photos were taken at known altitudes, every point in the survey area is present in many images from many angles meaning a geometrically accurate 3D model can



**FIGURE B1** Ground sampling distance (GSD) is a measure of the resolution of an image, representing the true distance between the centre of two adjacent pixels. Therefore, if each pixel represents  $0.8 \text{ cm}$  in real life, the GSD of the image is  $0.8 \text{ cm px}^{-1}$ . A GSD of  $0.8 \text{ cm px}^{-1}$  is illustrated here, with the width of each pixel representing  $0.8 \text{ cm}$  in real life.

## BOX 2 Method and best practices

Our method has five key stages (Figure B2), starting with the pre-fieldwork stage to ensure the appropriate training and planning have been carried out, including selecting the appropriate GSD. The second stage describes best practises in the field. When in the field, UAV batteries are a key limiting factor due to cost and transportability issues (e.g. one DJI Mavic 2 Enterprise Advanced battery is £160), as sufficient batteries must be taken into the field for the day's activities. Therefore, optimising the number of UAV batteries required in the field is important. In the field, keeping a flight log detailing survey flight times, locations, and SD card used makes post-field processing easier. The third stage is the pre-processing stage, which helps to make the subsequent processing stage easier. When undergoing data pre-processing, removing blurry images or images where a large number of seals were moving can allow 3D models to be reconstructed where reconstruction would otherwise be impossible. In stage four, the processing stage, images are stitched together to form a geometrically accurate 3D model, seals are identified and counted, and individual volumes are estimated. Exporting the orthomosaic into manual counting software such as 'DotDotGoose' (v1.5.3; Ersts, 2022) helps to accelerate the seal identification and counting step. Finally, in stage five, the resulting body volume estimates can be used for their intended purpose.

be reconstructed from the 2D images taken using structure-from-motion photogrammetry (Hodgson et al., 2020; Shero et al., 2021). We used the default settings of the '3D Maps' Processing Option in Pix4D, except for changing the minimum number of matched keypoints (points Pix4D can easily recognise and match between multiple images) from three to five (Shero et al., 2021). As a point must be matched in five individual images before being included in the final model, sensitivity to seal movements between photos is reduced as small movements will not be included in the final model. We processed projects in Pix4D Mapper to create an orthomosaic (Figure 1b) and a digital surface model (DSM, Figure 1b) for each discrete area we surveyed. In Pix4D Mapper, the resolution of the DSM is equal to the ground sampling distance (GSD, Box 1) by default. We manually located each seal within each orthomosaic. Any seals in the water were counted but their volumes were not estimated as it is currently only possible to estimate the volume of seals on land (but alternative methods and techniques have emerged that may contribute in this context: Chirayath & Earle, 2016; Chirayath & Li, 2019; Hirtle et al., 2022).

Next, we estimated the volume of each seal in Pix4D Mapper using the 'Volume' function by manually marking vertices around a seal. The base of each individual seal was constructed using the

'Triangulated Plane' setting by triangulation of all marked vertices. Pix4D calculates volume as the difference in altitude between the base and the top of the seal using the DSM. We estimated the volume of 196 individual adult seals (out of a possible 437) and 48 white-coat pups (out of a possible 183) from 21 islands in the Isles of Scilly and one island (Inner Farne) in the Farne Islands (Table 1). Our ability to estimate seal volumes depended on whether they were reconstructed successfully in the 3D model (see 'Success of estimating seal volumes' section for more information). The accuracy of volume estimates was tested by applying our method to a large, inflatable object of known volume (see later section 'Verification of accuracy').

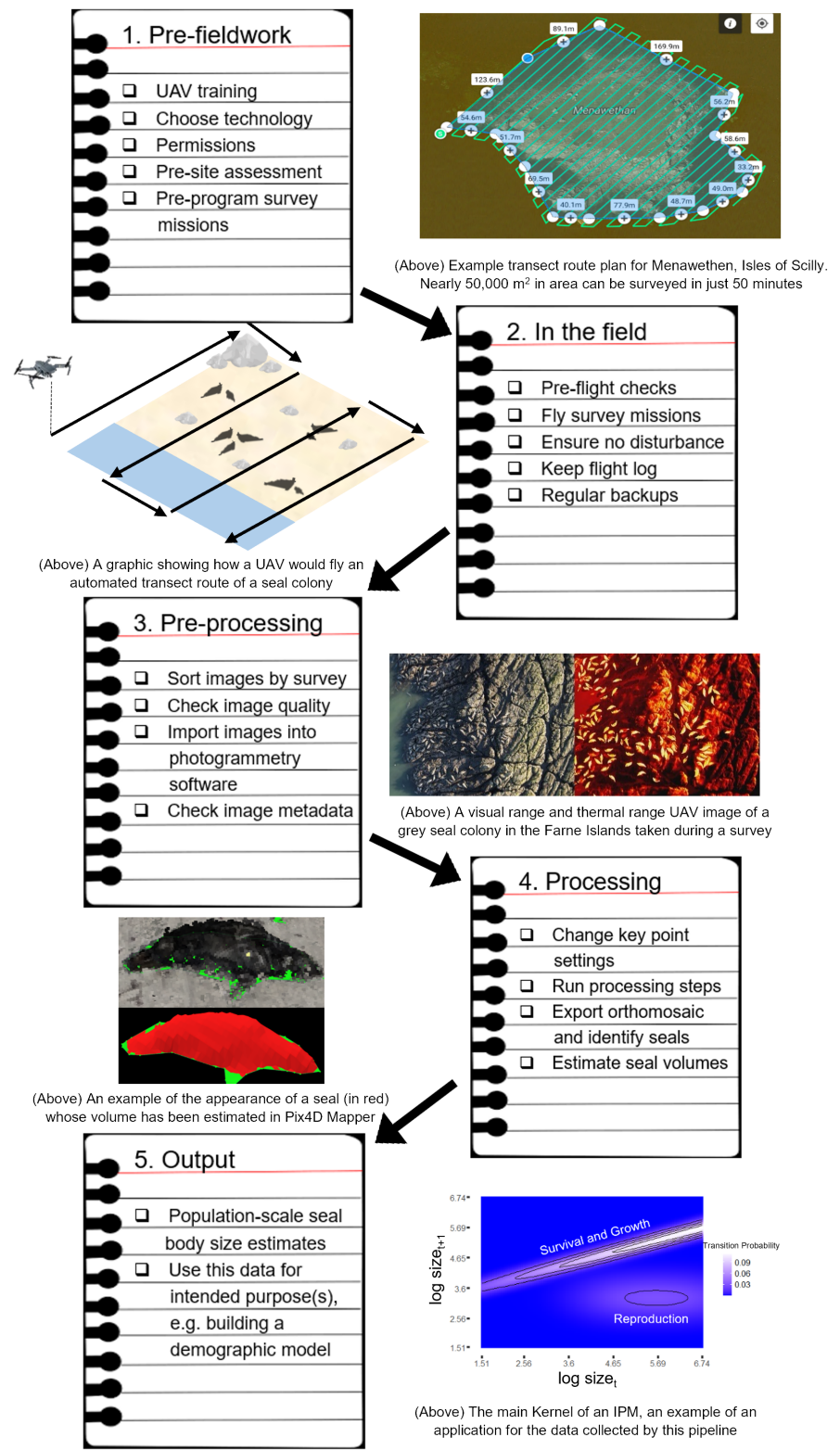
## 2.7 | Determining optimal ground sampling distance

Most fieldwork activities typically operate under a delicate data quality versus cost trade-off, whether costs be time and/or financial (McDonald-Madden et al., 2010). Here, the key components of data quality were the percentage of individuals that could be reconstructed within Pix4D so their volumes could be estimated, and the accuracy of those volume estimates. Both qualities are dependent on ground sampling distance (GSD, Box 1), which is optimised with lower flight altitudes or a UAV that takes higher resolution images. However, UAVs that take higher resolution images are more expensive (e.g. DJI M300 RTK with DJI Zenmuse P1 camera, £13,330; compared to the DJI Mavic 2 Enterprise Advanced, £5480). Conducting missions at lower altitudes means surveying takes longer as less area is captured per image. This trade-off between data quality and cost is highlighted by the difference in total mission time for the Isles of Scilly census. If all survey missions were planned to be undertaken at a minimum GSD of  $0.8\text{cm px}^{-1}$  (40m altitude with the DJI Mavic 2 Enterprise Advanced), the time required to be spent in the field would have increased by 35% compared to surveying at a GSD of  $1.2\text{cm px}^{-1}$  (60m altitude, see Table S2 for further details). Extra time in the field incurs higher financial costs. We flew missions at a range of altitudes (40–60m; Table 1) to allow us to assess the optimal GSD, given current technology, to enable successful volume estimation at the colony scale while minimising time and financial costs.

## 2.8 | Success of estimating seal volumes

To help determine the optimal minimum GSD for resolving the data quality against cost trade-off with currently available technologies, we calculated the percentage of seals that could be successfully reconstructed in Pix4D to obtain volume estimates at different GSDs (Figure 2). To do this, we visually assessed the reconstruction of each seal in the 3D model to determine if the reconstruction of the seal appeared to be the correct shape or if the seal had moved significantly between images. We tested GSDs of  $0.8\text{cm px}^{-1}$  (40m altitude with DJI Mavic 2 Enterprise Advanced;  $n=154$  adults, 88 white-coat pups),

**FIGURE B2** Overview of the UAV method we developed to estimate the body volume of pinnipeds at scale, from pre-fieldwork to output stages.



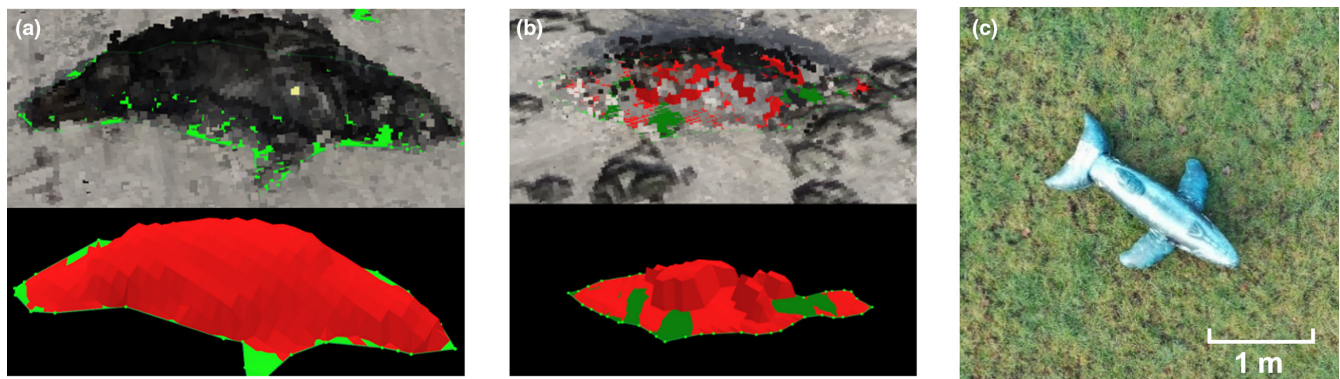
1.0 cm px<sup>-1</sup> (50m; n=178 adults, 27 white-coat pups), 1.2 cm px<sup>-1</sup> (60m; n=87 adults, 59 white-coat pups), and 1.4 cm px<sup>-1</sup> (70m; n=18 adults, 9 white-coat pups; Table 1). We did not test altitudes lower than 40m to avoid disturbing seals (Pomeroy et al., 2015). All 23 missions from the Isles of Scilly and one mission from the Farne Islands were analysed here. We introduced the mission from the Farne Islands to balance the

sample size at a GSD of 0.8 cm px<sup>-1</sup>. We assessed whether there were significant differences between the percentage of volume estimates possible for adult and white-coat pup grey seals at GSDs of 0.8, 1.0<sup>1</sup> and 1.2 cm px<sup>-1</sup>. We expected the success rate for reconstructing seals would be higher at lower GSDs with higher resolution images. The sample size is lower at a GSD of 1.4 cm px<sup>-1</sup> because accuracy tests

**TABLE 1** The success rate of reconstructing grey seals *Halichoerus grypus* in 3D so their volumes could be estimated following our method was 2.5 times higher at smaller ground sampling distances (GSDs, [Box 1](#)) and overall 1.7 times higher for adults compared to white-coat pups.

GSD (cm px <sup>-1</sup> )	DJI Mavic 2 enterprise advanced altitude (m)	DJI Mavic 2 pro altitude (m)	<i>n</i> adults	% success adults	<i>n</i> pups	% success pups	<i>p</i> value adult versus pup success
0.8	40	N/A	154	68	88	41	<0.001
1.0	50	40	178	27	27	11	0.12
1.2	60	50	87	28	59	10	0.019
1.4	N/A	60	18	44	9	0	NA

*Note:* Volume estimates were attempted at the different GSDs listed above, along with the altitude corresponding to these GSDs with the two different UAVs used for surveys. The number of grey seal white-coat pups and adults whose volume we attempted to estimate, and the percentage success rates of estimating their volumes, at the different GSDs we tested. The altitude at which the DJI Mavic 2 Enterprise Advanced achieves a GSD of 1.4 cm px<sup>-1</sup> and the DJI Mavic 2 Pro achieves a GSD of 0.8 cm px<sup>-1</sup> are listed as 'N/A' because we did not undertake any surveys with these UAV at these GSDs. The rate of successfully estimating adult seal volumes was significantly higher for adults compared to white-coat pups at GSDs of 0.8 and 1.2 cm px<sup>-1</sup>.



**FIGURE 2** To establish the optimal ground sampling distance (GSD, [Box 1](#)) at which to undertake surveys of grey seals, *Halichoerus grypus*, to estimate their body volumes, we calculated the success rates of being able to estimate seal volumes and the accuracies of volume estimates at different GSDs. We used the software Pix4D Mapper to reconstruct seals from UAV photographic data so that their volumes could be measured. Here, we compare a seal that has been successfully reconstructed so its volume can be measured to a seal where the programmatic reconstruction failed. As validation, we also used an inflatable object of known volume to test the accuracy of volume estimates made following our method. (a) A successfully reconstructed seal that has had its volume estimated. The images used had a GSD of 0.8 cm px<sup>-1</sup>. Note that the upper image appears pixilated because the step of marking the base of the object to estimate the volume of objects is performed in the dense point cloud. (b) A seal that has not been reconstructed successfully, because it moved between images in the survey. The images used had a GSD of 0.8 cm px<sup>-1</sup>. The volume of this seal could not be estimated. (c) Unmanned aerial vehicle (UAV) image of a large inflatable object of known volume, which we used to test the accuracy of volume estimates obtained following the method we developed.

showed that even at a GSD of 1.2 cm px<sup>-1</sup>, the resolution of images was insufficient to accurately estimate volumes (see 'Verification of Accuracy' section). We therefore did not carry out any statistical tests at a GSD of 1.4 cm px<sup>-1</sup>, although we still attempted to estimate the volumes of seals at this GSD for completeness.

## 2.9 | Verification of accuracy

We tested the accuracy of volume estimates from UAVs using a large, inflatable, plastic object of known volume with a comparable size and shape to that of an adult seal (Figure B2. Note: a realistic inflatable seal was not available) following the same survey and processing methodology used in the field. We carried out 30 UAV surveys of the inflatable with the DJI Mavic 2 Enterprise Advanced, 10 at each

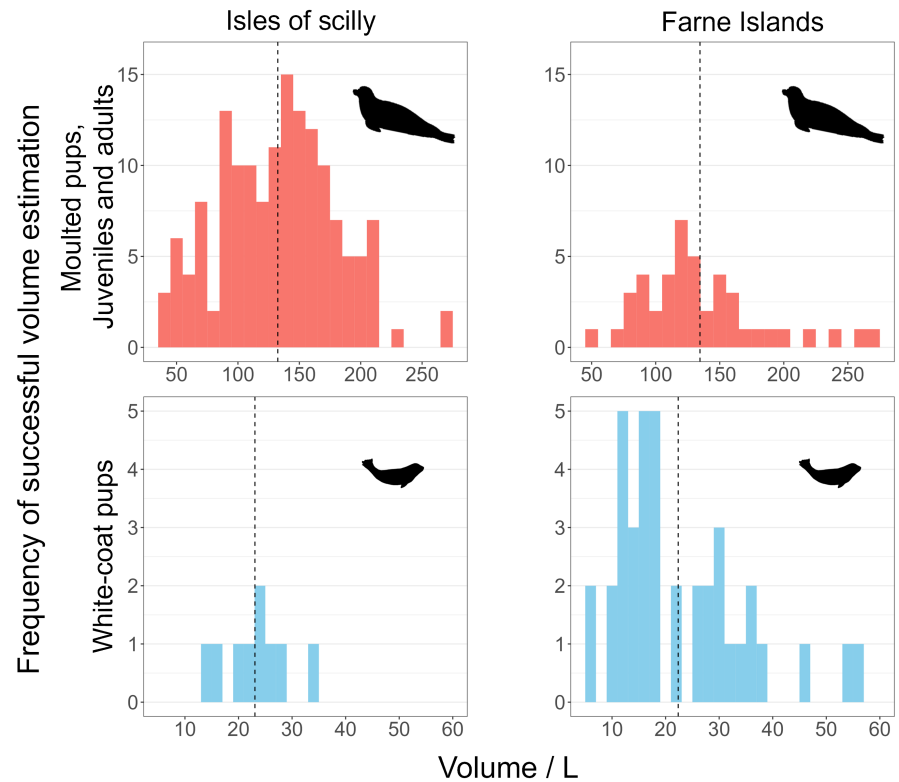
planned GSD of 0.8 cm px<sup>-1</sup> (40 m), 1.0 cm px<sup>-1</sup> (50 m) and 1.2 cm px<sup>-1</sup> (60 m). We compared the mean volume estimated by UAV to the true volume of the object to assess the accuracy of volume estimates. We also calculated the mean absolute error (MAE) of volume estimates at each GSD (Figure S1).

## 3 | RESULTS

### 3.1 | Determining optimal ground sampling distance

To test the accuracy and applicability of our method to estimate body volume on a colony scale, we calculated (A) the percentage success rate of reconstructing a seal so its volume could be estimated

**FIGURE 3** We estimated the body volume of grey seals, *Halichoerus grypus*, in the Isles of Scilly ( $n=161$ ) and Inner Farne, the Farne Islands ( $n=83$ ) using 3D structure-from-motion photogrammetry from UAV imagery. The histograms show the variation in body volume estimated by UAV following our method, in Litres, for adult and white-coat pup grey seals in each location. Seals were assigned to either adult or white-coat pup categories, meaning the adult category includes moulted pups and juvenile individuals. The dashed lines represent the mean volumes. The top two panels correspond to adult seals in the Isles of Scilly (left), and the Farne Islands (right), while the two bottom panels correspond to white-coat pups in the Isles of Scilly (left) and the Farne Islands (right).



(Figure 2) and (B) the accuracy of volume estimates at different ground sampling distances (GSDs; Box 1; Figure 3).

### 3.1.1 | Success of seal reconstruction

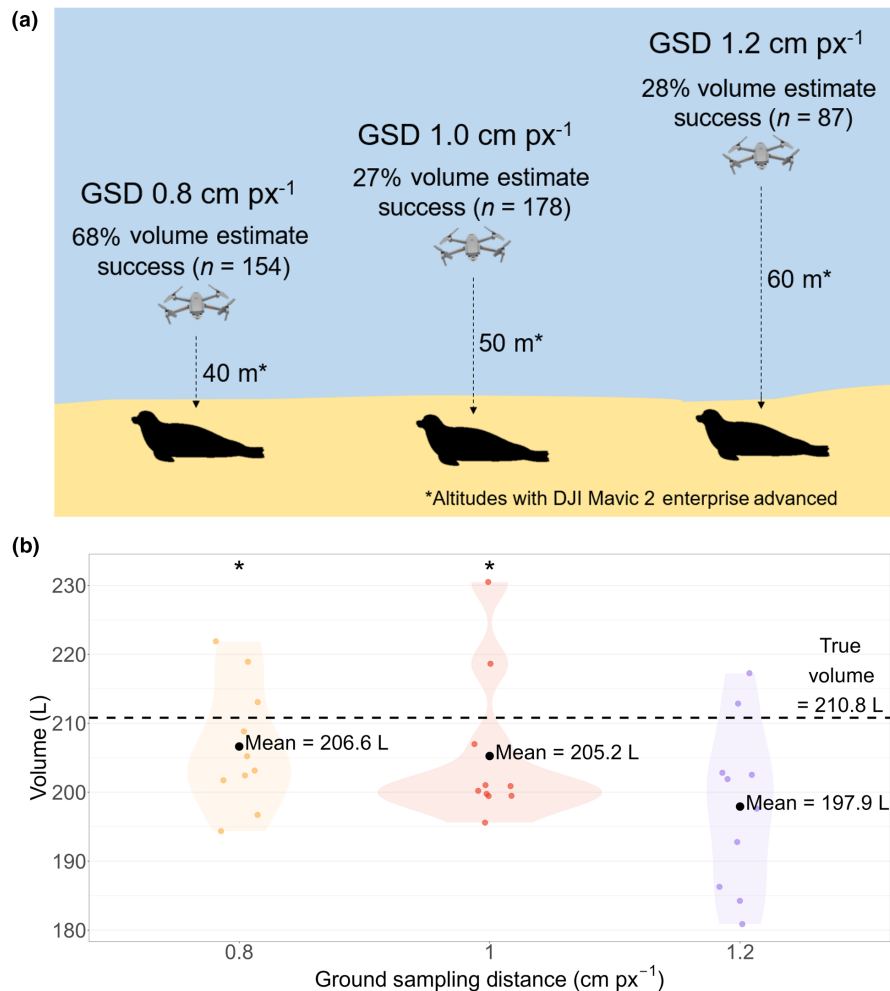
The percentage success rate of reconstructing individual seals decreased as GSD increased (Figure 4a; Table 1). At a GSD of  $0.8 \text{ cm px}^{-1}$ , the volume of 68% of adult seals ( $n=154$ ) and 41% of white-coat pups ( $n=88$ ) could be correctly estimated. The success rate decreased to 27% for adults ( $n=178$ ) and 11% for white-coat pups ( $n=27$ ) at  $1.0 \text{ cm px}^{-1}$  and was 28% for adults ( $n=87$ ) and 10% for white-coat pups ( $n=59$ ) at  $1.2 \text{ cm px}^{-1}$ . The sample size for a GSD of  $1.4 \text{ cm px}^{-1}$  is low at 18 adults and nine white-coat pups. Of these, the volumes of 44% of adults and 0% of white-coat pups were estimated successfully. Successful estimation of volumes was much more likely for adults than white-coat pups at GSDs of  $0.8 \text{ cm px}^{-1}$  ( $p_{df=1}=0.0000624$ ,  $n=242$ ) and  $1.2 \text{ cm px}^{-1}$  ( $p_{df=1}=0.0189$ ,  $n=205$ ; Table 1). At a GSD of  $1.0 \text{ cm px}^{-1}$  volume estimates were equally (un)successful for adults and white-coat pups ( $p_{df=1}=0.124$ ,  $n=146$ ), although the sample size for white-coat pups was relatively low at this GSD. Given the camera resolution of the UAVs used here, a GSD of  $0.8 \text{ cm px}^{-1}$  is optimal for surveying animals the size of UK grey seals (typically  $\sim 1.2\text{--}2.5 \text{ m}$ ) with currently available and affordable technologies. This GSD achieves an optimal trade-off between data quality and costs, despite the longer time required to survey at this lower GSD (see Section 3.1). Alternatively, if time is the limiting factor, a more expensive UAV (e.g. DJI M300 RTK with DJI Zenmuse P1 camera, £13,330) that can survey at the same GSD from a higher altitude could be purchased.

### 3.1.2 | Verification of accuracy

We tested the accuracy of volume estimates by comparing estimates obtained following our method to the true volume (210.8L) of a large inflatable object (Figure 4b). A one-sample t-test showed there was no statistically significant difference between the mean volume estimates obtained by UAV and the true volume of the inflatable at GSDs of  $0.8 \text{ cm px}^{-1}$  ( $p=0.178$ ,  $n=10$ ) and  $1.0 \text{ cm px}^{-1}$  ( $p=0.142$ ,  $n=10$ ). However, at  $1.2 \text{ cm px}^{-1}$ , the mean volume estimated by UAV was significantly different to the true volume of the inflatable ( $p=0.008$ ,  $n=10$ ). Therefore, estimates of volume accuracy decrease with increasing GSD and thus altitude, as expected. In addition, the standard deviation of volume estimates increased from 9.04L at  $0.8 \text{ cm px}^{-1}$  to 10.91L at  $1.0 \text{ cm px}^{-1}$  and 12.01L at  $1.2 \text{ cm px}^{-1}$ . This result was expected, as lower resolution images should lead to more variable volume estimates. Values for mean absolute error (MAE) are presented in Figure S1. Based on these results, we conclude that volume estimates of a stationary object similar in size to grey seals obtained following our method are accurate at GSDs of 0.8 and  $1.0 \text{ cm px}^{-1}$ , whilst accuracy decreases with GSD.

## 4 | DISCUSSION AND CONCLUSIONS

We introduce a method to estimate the body volume of pinnipeds at a colony scale in a time- and cost-effective manner while minimising disturbance, using grey seals as a case study species. We show that body volume estimates are accurate (mean estimates not statistically different from true values) at ground sampling distances (GSDs,



**FIGURE 4** The optimal ground sampling distance (GSD; [Box 1](#)) at which to undertake surveys was 0.8 cm px<sup>-1</sup>, from the GSDs we tested. This conclusion was reached because the highest success rate of estimating seal volumes was at a GSD of 0.8 cm px<sup>-1</sup>, and because volume estimates are accurate at this GSD. (a) A visualisation of the different percentage success rates at reconstructing seals within Pix4D Mapper so their volumes can be estimated at the different tested ground sampling distances of 0.8, 1.0 and 1.2 cm px<sup>-1</sup>. The highest success rate of 68% was obtained at a GSD of 0.8 cm px<sup>-1</sup>, followed by 27% at 1.0 cm px<sup>-1</sup> and 28% at 1.2 cm px<sup>-1</sup>. Although we carried out some surveys at a GSD of 1.4 cm px<sup>-1</sup>, this GSD is not represented here because of a low sample size. (b) We tested the accuracy of volume estimates obtained following our method at different GSDs by comparing the mean volume estimates obtained to the true volume of a large, inflatable object using a one-sample t-test. The mean, standard deviation and spread of volume estimates at the different ground sampling distances tested of 0.8, 1.0 and 1.2 cm px<sup>-1</sup> are shown here. \*: Volume estimates at that ground sampling distance are not significantly different ( $p < 0.05$ ) from the true volume, 210.8 L, represented with the dashed horizontal line. We also calculated the Mean Absolute Error at each ground sampling distance ([Figure S1](#)).

[Box 1](#)) achievable with off-the-shelf, multirotor unmanned aerial vehicles (UAVs) operated at altitudes that do not cause disturbance. Moreover, we establish that planning UAV surveys at a GSD of 0.8 cm px<sup>-1</sup> optimises the trade-off between data quality and costs when estimating the body volume of grey seals, or other species of similar size (~1.2–2.5 m length). Our method is highly adaptable to other pinniped species, and our approach has the potential to be adapted for species that possess similar traits to grey seals. The ability to obtain body volume estimates at the colony scale for pinnipeds opens many possibilities for new research, including parameterising demographic models to help fill existing demographic knowledge gaps.

Our method enables individual pinniped body volumes to be estimated at the colony scale. [Figure B2](#) presents an overview of our

method, and the five stages of the method are described in more detail throughout the *Methods* section. Key insights include that a UAV that can survey at a GSD of 0.8 cm px<sup>-1</sup> whilst at  $\geq 40$  m in altitude (ensuring no disturbance to animals; Krause et al., 2021; Pomeroy et al., 2015) is optimal for resolving the trade-off between data quality and the cost of data collection for species the size of UK grey seals, with technologies that are currently available and affordable. In addition, using a transect survey pattern instead of a radial pattern obtains volume estimates on a much wider-scale (e.g. colony vs. small group). This new pattern allows an area of nearly 50,000 m<sup>2</sup> to be surveyed in just 50 min, as shown in the first stage of [Figure B2](#).

Based on our findings, we can conclude that our method may be suitable for estimating the volume of additional plant and animal taxa

exhibiting traits similar to pinnipeds, although proper tests would be needed to validate this method for any new species. For terrestrial animals, we expect such traits include a low-to-the-ground profile, volume >80L, high population density, predictable geographic distribution, periods of limited mobility and inhabiting areas UAVs can fly over. Examples of animal taxa that we believe may fit many of these traits include larger reptiles such as crocodiles and mammals such as the hippopotamus, in addition to a range of ungulate species when resting. Many plant taxa possess all the traits that we believe would make a species well-suited to our method, particularly bushes or shrubs in systems without much elevational structure such as deserts or Mediterranean habitats (Mao et al., 2021). UAVs have already been used to estimate the volume of plants such as desert shrubs (Mao et al., 2021), estimate the body length of Nile crocodiles (*Crocodylus niloticus*) using a transect survey pattern (Ezat et al., 2018) and assess the population sizes of ungulates (Hu et al., 2020). Given the widespread lack of high-quality demographic data for many of these species, such as many large reptile species (Briggs-Gonzalez et al., 2017), our method presents a promising potential approach to collect high quality data to fill these data gaps.

Using UAVs to estimate body size can offer advantages over traditional methods of measuring animal body size (Allan et al., 2019). Traditional methods for measuring animal body size are often time-consuming and invasive. Typically, these methods involve capturing a single individual at a time and measuring them by hand, often requiring sedatives (Hodgson et al., 2020). Using UAVs to estimate body size eliminates the need to catch or sedate animals, thus avoiding risks for the target species and the researcher (Krause et al., 2017), and enables multiple individuals to be measured simultaneously (Shero et al., 2021). Therefore, using UAVs is faster, safer for both researchers and animals and less invasive compared to traditional methods that use sedatives to measure body size.

Studies have estimated animal 2D body size at scale using UAVs (de Kock et al., 2021; Infantes et al., 2022), but recent research has shown that 3D body volume estimates are more accurate than 2D estimates (Hodgson et al., 2020; Shero et al., 2021). However, previous research only estimated the body volume of a single individual or small group of individuals at a time. Our research builds on this previous work by adopting a transect flight pattern for UAV surveys. This transect flight pattern enables the body volumes of individuals in an entire colony of taxa with similar traits to grey seals to be estimated in a single field survey. Our approach therefore offers a faster method to estimate body volume at the colony scale. The overall mean adult body volume (133L) we obtained is comparable to the mean body volumes estimated by UAV by Shero et al. (2021) for grey seals at Sable Island, Canada, when adjusted for the known difference in size between the Eastern and Western Atlantic grey seal populations. In addition, our recommended GSD of 0.8 cm px<sup>-1</sup> is achievable with a variety of affordable, off-the-shelf UAVs at altitudes that do not disturb grey seals (≥40m altitude; Pomeroy et al., 2015). As the UAVs required are off-the-shelf, relatively little training is required to operate them compared to the training required for traditional methods to estimate pinniped size involving

sedative usage (e.g. Hodgson et al., 2020). These practical improvements mean our method is highly applicable for those responsible for managing or researching pinniped populations.

One limitation of our method when surveying animal populations is that successfully estimating the volume of 100% of individuals captured in a survey is highly unlikely. Previous studies investigating body volumes of individuals on a range of substrates, including sand and rock, found no impact of body position or posture on volume estimation (Carroll et al., 2024; Krause et al., 2017; Shero et al., 2021). Therefore, posture is unlikely to affect volume estimation. However, individuals can move between images, preventing them from being reconstructed successfully in photogrammetric software—this makes it unlikely that the success rate of estimating volumes can reach 100%. For example, at our highest resolution GSD (0.8 cm px<sup>-1</sup>), the volume of 68% of adult seals could be estimated. After GSD, seal movement between images was the second most important factor preventing successful seal reconstruction in the 3D model. However, reconstruction was always possible at 0.8 cm px<sup>-1</sup> when using our stationary inflatable object to verify the accuracy of volume estimates. We can therefore assume that movement was a major factor preventing a greater percentage of volumes from being estimated at 0.8 cm px<sup>-1</sup>. Other factors that can influence the success of reconstructing a seal in the 3D model include weather conditions that cause shadow, and light levels. Shadows can make it more difficult to spot seals in the images and can make it harder for Pix4D Mapper to successfully reconstruct seals. In addition, low light levels can reduce image quality. This means cloudy weather around midday, or when the sun is not low in the sky, are optimal for surveys. However, the realities and constraints of fieldwork means that it is rarely possible to wait for optimal weather conditions to conduct surveys.

In cases with large amounts of movement between images, the less accurate methods based on 2D photogrammetry from UAV imagery may be more appropriate, as they only require a single photo and so do not rely on the subject remaining stationary (de Kock et al., 2021; Krause et al., 2017). Alternatively, if budget allows, multiple UAVs could be synchronised in parallel so multiple images are obtained at the same time. A further limitation of our method is that it would be difficult to assess aquatic species using our methods. The variable visibility and movement of the water would impair the collection of different images of the same objects required for 3D photogrammetry, although novel techniques such as fluid lensing and multispectral imaging, detection, and active reflectance (MiDAR) show this problem can be overcome in shallow waters (Chirayath & Earle, 2016; Chirayath & Li, 2019). In addition, the study species would have to remain stationary during surveys, in high densities, and in a predictable location for some period of time, which is unlikely in dynamic aquatic environments. However, it is possible to use UAVs to estimate the 2D body size of fully aquatic species such as cetaceans (Gray et al., 2019), and alternative methods exist for estimating the 3D body size of stationary aquatic species such as corals (e.g. using remotely operated vehicles, ROVs; Price et al., 2019). It is also possible to estimate body volume in cetaceans by creating

a 3D model of the study species and scaling the model to different individuals using 2D body size estimates (Christiansen et al., 2019). Such methods present alternatives to our method for some fully aquatic species.

Finding the optimal GSD at which to undertake surveys with currently available and affordable technologies is important to resolve the trade-off between data quality and costs (Tziavou et al., 2018). Despite its importance, relatively little research has focussed on determining optimal GSDs for estimating body size, although studies have investigated the optimal GSD for wildlife detection (Frąckowiak & Goraj, 2023). When applying our method to species of similar size to grey seals (mean volume 133L, standard deviation 47.5L), we recommend a maximum planned GSD of  $0.8\text{cm px}^{-1}$ . At this GSD, the volume of 68% of adult seals ( $n=154$ ) could be correctly estimated, decreasing to 27% ( $n=178$ ) at  $1.0\text{cm px}^{-1}$ . This 25% decrease in GSD therefore led to a 41% decrease in successful volume estimates—a greater decrease than we expected given that we found volume estimates to be accurate at GSDs of 0.8 and  $1.0\text{cm px}^{-1}$ . The percentage of successful volume estimates was similar at 1.0 and  $1.2\text{cm px}^{-1}$  (28%,  $n=87$ ), indicating a plateau in feasibility above  $1.0\text{cm px}^{-1}$ . No other factor that would affect the results was found, such as the order of sampling, the time of day or increased shadows during certain surveys. We therefore infer that the increased resolution at a GSD of  $0.8\text{cm px}^{-1}$  enables Pix4D Mapper to better identify and match points between images to successfully reconstruct seals, meaning lower GSDs offset the increased potential for seal movement at these GSDs. For animals larger than grey seals, surveying at  $0.8\text{cm px}^{-1}$  will give high enough quality data to obtain accurate volume estimates at scale, but further research may determine surveying at a higher GSD is possible. We recommend further research on the optimal GSD for species smaller than grey seals, as lower GSDs are likely to be required for smaller species. Our optimal GSD of  $0.8\text{cm px}^{-1}$  is higher than the average GSD used in previous work estimating body volume of pinnipeds using UAVs (Hodgson et al., 2020; Shero et al., 2021), demonstrating a wider range of UAVs or altitudes can be used for this research than have been used previously. Whilst we did not test GSDs  $<0.8\text{cm px}^{-1}$ , we expect GSDs  $<0.8\text{cm px}^{-1}$  would further improve the accuracy and success rate of estimating seal volumes. However, we were limited to surveying at  $\geq 40\text{m}$  altitude to ensure seals were not disturbed during surveys (Pomeroy et al., 2015) and because we wanted to use relatively affordable technologies ( $< \text{£}6000$ ) to give those responsible for managing local populations the best chance of applying our method. Ensuring seals were not disturbed is important both for animal welfare and because if seals are disturbed during the survey, the success rate of estimating seal volumes will be lower because more seal movement will take place during the survey. UAV and camera technologies are rapidly advancing and becoming more affordable, meaning higher resolutions will be possible in the future. Future work will therefore be required to establish whether improved technologies that can capture GSDs lower than  $0.8\text{cm px}^{-1}$  provide sufficient increases in data quality to overcome the costs of additional time and money.

The colony- scale, continuous body size data collected following the method presented here have a wide range of uses. Data obtained via our method can facilitate research into tracking energy-flow dynamics (Shero et al., 2021), assessing individual health (Hodgson et al., 2020) and fitness (Stevenson & Woods Jr., 2006) across populations, comparing health of different populations (Sweeney et al., 2014) and detecting how environmental conditions affect body size (Berger, 2012). In addition, a time series of such continuous data could be used to parameterise demographic models such as integral projection models (IPMs; Easterling et al., 2000) using inverse techniques (González et al., 2016). To the best of our knowledge, though, no IPMs have been constructed using body size data for our case study species, the pinnipeds, or other species (such as the hippopotamus) that we believe our method is appropriate for. Continuous body condition indices can also be developed using body volume data (Christiansen et al., 2018; Krause et al., 2017; Moya-Laraño et al., 2008). Such indices could be improved by taking into account other data that can be obtained from UAV imagery. For example, thermal imagery could be used to give a score of animal health or reproductive ability (Jeelani & Jeelani, 2019), given the importance of metabolic rate to key processes such as survival and reproduction (Brown et al., 2004; Savage et al., 2004). A continuous body condition index could also be used to parameterise demographic models like IPMs. To make best use of the data collected following our method when developing such demographic models, a promising area for future work is the automation of sex and stage distinctions from UAV images, as currently this task must be done visually by experts.

Currently, bottlenecks exist in our method at the seal identification and volume estimation stages of the method, which are performed manually. To date, machine learning has been used to successfully automate or semi-automate the process of estimating 2D body size or identifying animals from images, for example, in cetaceans (Gray et al., 2019) and pinnipeds (Infantes et al., 2022). Therefore, we expect future work taking advantage of machine learning technology will be able to overcome these bottlenecks in our method to greatly decrease the time taken to identify and estimate the volume of individual seals.

## 5 | CONCLUSIONS

Our method enables accurate estimation of body volume in a time- and cost-effective manner using off-the-shelf, multirotor UAVs while minimising the disturbance caused to the study species. The ability to obtain accurate body volume estimates of taxa like pinnipeds that are otherwise challenging to obtain such measurements from at scale enables the development of continuous, size- or body condition-structured demographic models. This work will therefore help to fill demographic research gaps (Lebreton et al., 2012; Salguero-Gómez et al., 2015, 2016) by enabling demographic studies that will improve our ability to protect and conserve species into the future.

## AUTHOR CONTRIBUTIONS

Thomas C. Stone and Katrina J. Davis developed the original idea; Thomas C. Stone and Katrina J. Davis conducted the fieldwork; Thomas C. Stone implemented all analyses under the supervision of Katrina J. Davis; Thomas C. Stone wrote the first draft of the manuscript. Katrina J. Davis contributed to writing, structure and edits of the manuscript. We have communicated with the local land and wildlife managers from the start of our work, and our results have been shared with them.

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## CONFLICT OF INTEREST STATEMENT

All authors declare no conflicts of interest.

## PEER REVIEW

The peer review history for this article is available at <https://www.webofscience.com/api/gateway/wos/peer-review/10.1111/2041-210X.14457>.

## DATA AVAILABILITY STATEMENT

Data required to recreate analysis with ground truthing images are available at the FigShare Digital Repository <https://doi.org/10.6084/m9.figshare.24771129> (Stone & Davis, 2024).

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## SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

**Table S1.** There is no clear difference between the absolute error between radial and transect surveys.

**Table S2.** The time for surveys increases with decreasing ground sampling distance (GSD; Box 1).

**Figure S1.** The mean absolute error (MAE) decreases with decreasing altitude.

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