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Contemporary Growth Curves for Individual Humpback Whales in Eastern Australia Using Aerial Photogrammetry

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ABSTRACT

Growth curves provide critical biological context for understanding life history, population dynamics, and responses to environmental change, yet our understanding of age–length relationships for humpback whales (*Megaptera novaeangliae*) remains largely based on measurements collected during commercial whaling operations from the mid-20th century. These measurements may not reflect the growth trajectories of present-day populations that have undergone substantial recovery and ecological change. Here, we establish contemporary, population-specific, growth curves for eastern Australian humpback whales (breeding stock E1) using noninvasive aerial photogrammetry coupled with photo-identification sighting histories. Total length measurements were collected from 865 individually identified whales between 2021 and 2024 and for a subset of these individuals, minimum age estimates were derived from long-term photo-identification sighting histories. Bayesian growth models were fitted to evaluate age–length relationships across multiple growth functions and age formulations. Growth was rapid during early life and approached an asymptotic adult length consistent with historical estimates for humpback whales in Australia. Predicted length at age 5 (median 10.93 m) and the age at which whales reached 90% of asymptotic length (median 6.58 years) indicated faster juvenile growth and earlier attainment of near-adult size than reported elsewhere for contemporary Northern Hemisphere populations. The growth parameters and length-at-age estimates provide a baseline for demographic inference. Further, they support long-term monitoring of growth and energetic constraints in a humpback whale population that has undergone one of the most rapid recoveries documented in a large whale species and is experiencing ongoing environmental change.

1 | Introduction

Body size and growth trajectories are fundamental components of mammalian biology, reflecting how energy is allocated to somatic growth, reproduction, and maintenance across an individual's lifetime (Adamczak et al. 2023; Lockyer 1981; Roff 2002). Growth trajectories represent a key life-history characteristic that influences the timing of maturation, reproduction, and generation time (Roff 2002; Stearns 1992). At the population level, growth curves serve as an important link between observed body size and inferred demographic processes (Caswell 2001; Heppell et al. 2000). Establishing reliable growth curves underpins demographic monitoring by enabling size-based inference of age structure, maturity rates, and reproductive potential, while

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providing a baseline against which future changes can be evaluated (Caswell 2001; Gaillard et al. 2000; Heppell et al. 2000).

The eastern Australian humpback whale (*Megaptera novaeangliae*) population (IWC breeding stock E1) was brought to the brink of extinction during the mid-twentieth century through a combination of shore-based whaling and large-scale illegal Soviet pelagic whaling on the Antarctic feeding grounds. Although regulated shore-based operations along the eastern Australian coast and in New Zealand contributed to initial population declines, it was clandestine Soviet factory-fleet whaling in the Southern Ocean that proved to be catastrophic. Soviet whalers killed at least 38,146 humpback whales from Antarctic Area V, the primary summer feeding grounds for breeding stock E1, between 1947 and 1973, as part of a global campaign of illegal Southern Ocean whaling (Clapham et al. 2009; Ivashchenko et al. 2011). Studies suggest that the population could have been reduced to as few as 100 individuals (Paterson et al. 1994). Following the cessation of commercial whaling and legislative protection, the population underwent a sustained recovery as documented by shore-based surveys from the 1980s onward (Noad et al. 2019; Paterson et al. 1994). The rate of population increase averaged 10.9% per annum over three decades (Noad et al. 2019), approaching the maximum plausible rate of increase of 11.8% per year estimated for the species from life-history data (Zerbini et al. 2010), and by 2015 the population was estimated to have reached ~94% of the estimated historical carrying capacity (Noad et al. 2019).

Despite their importance, growth curves for humpback whales remain largely based on whaling-era datasets (e.g., Chittleborough 1965). Foundational studies conducted during the mid-20th century, particularly those by Chittleborough, provided the first quantitative descriptions of humpback whale growth in the Southern Hemisphere and remain the primary historical benchmarks for size-at-age. However, these datasets were necessarily constrained by the structure of commercial whaling, with uneven age representation, a bias toward larger animals, and limited information on early life stages. Moreover, these growth curves predate the remarkable recovery of humpback whales in eastern Australia following exploitation (Noad et al. 2019) and therefore may no longer reflect the demographic characteristics of the current population.

Recent advances in noninvasive research methods provide new opportunities to revisit humpback whale growth using contemporary data from living animals. Aerial photogrammetry from unoccupied aerial vehicles (UAV; commonly called drones) enables researchers to collect accurate measurements of total body length in free-ranging live whales (Christiansen et al. 2019; Dawson et al. 2017; Russell et al. 2024; van Aswegen et al. 2025), while long-term photo-identification catalogues allow minimum ages to be assigned to individually identified whales. When combined with a Bayesian modeling framework, these data sources allow prior biological knowledge and measurement uncertainty to be explicitly incorporated into growth curve estimation, yielding length-at-age relationships that are well suited for demographic applications.

The aim of our study was to develop contemporary, population-specific, growth curves for eastern Australian humpback whales by integrating UAV-derived length measurements and photo-identification age estimates. Using Bayesian growth models, we estimated length-at-age relationships for whales of minimum age, including sex-specific growth curves for females. Our objective was to update growth parameters and derive size-at-age estimates intended for demographic inference and long-term population monitoring. By establishing contemporary length-at-age relationships for eastern Australian humpback whales, this study provides a demographic baseline for interpreting age structure, maturation, and population dynamics in one of the world's fastest recovering baleen whale populations.

2 | Materials and Methods

2.1 | Data Collection

Paired aerial morphometric and photo-identification data were collected from humpback whales on their southern migration along the east coast of Australia between 2021 and 2024. Aerial footage was collected annually between July and October in Hervey Bay, Queensland and in October 2023 in Eden, New South Wales (Figure 1). Data collection was conducted using nonsystematic surveys under favorable environmental conditions (Beaufort Sea State and Douglas Sea State ≤ 3), and UAV operations were attempted for all humpback whales encountered during a survey day, regardless of group composition or observed behavior.

Data were collected using a DJI Inspire 2 UAV equipped with a Zenmuse X5S gimbal camera and 25 mm flat lens. The UAV was calibrated prior to data collection using protocols described by Dawson et al. (2017). High resolution videos (3840×2160) were recorded while the UAV was over a surfacing whale(s), with the camera in nadir (90 degrees) orientation. A custom-mounted SF11/C laser altimeter was used to measure UAV altitude above sea level following protocols described in Dawson et al. (2017). When photographing a whale, the UAV was flown at altitudes ranging from 22 to 54 m. Only flights with laser altimeter data available were used. Photo-identification images of the tail flukes were collected of the same individuals in the drone footage for individual identification of whales being measured.

2.2 | Length Measurements

The aerial videos were reviewed using VLC Media Player Software and a single screen-capture image was extracted for each whale, prioritizing full body extension, minimal pitch and roll, and a straight body axis. Photo quality was graded using a protocol adapted from Christiansen et al. (2018) by assigning scores of 1 (good quality), 2 (medium quality), and 3 (poor quality) in the following categories: camera focus, body roll, body pitch, body arch, and body length measurability. Images with a score of 3 in one or more categories were excluded from subsequent analysis.

Whales were measured by a single observer using the open-source software "Whalength" v7.4, which produced a measurement of each whale in pixels (Dawson et al. 2017). Images were then scaled using altitude, camera sensor size, lens focal length, and

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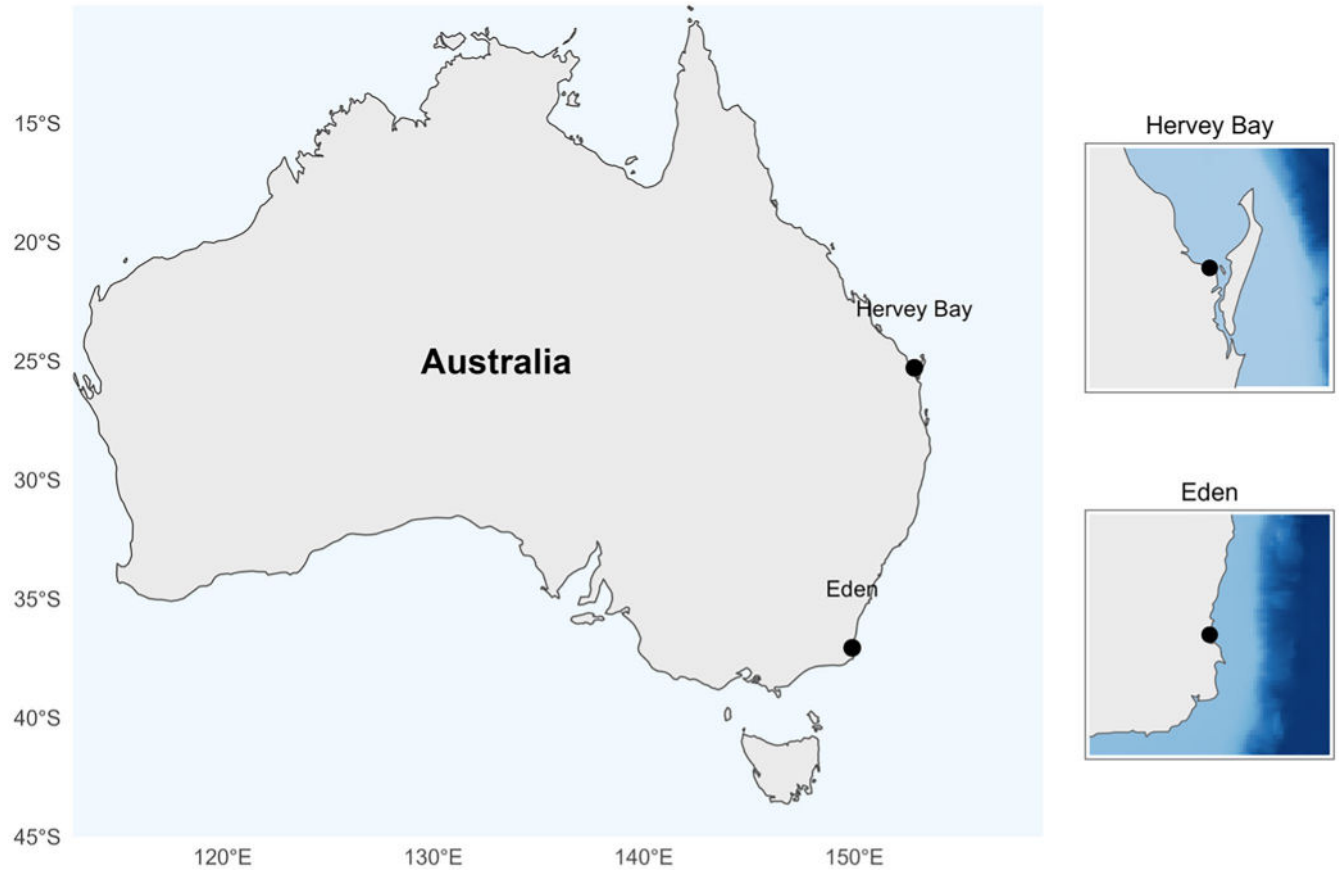


FIGURE 1 | Map of Australia showing the locations of Hervey Bay, Queensland, and Eden, New South Wales, where UAV photogrammetry data were collected between 2021 and 2024.

image resolution to convert these values to meters (Christiansen et al. 2019; Dawson et al. 2017). If an individual whale was measured more than once within a season, the mean length measurement was used for that individual. To quantify measurement error, we calculated the within-individual coefficient of variation and the coefficient of reliability (R) of total length from individual whales that had been measured on more than one date within the same season. Total length was measured as a straight line from the tip of the rostrum to the central notch of the tail flukes.

2.3 | Age and Sex Estimation

Age was estimated in one of two ways depending on the available sighting history. For individuals with only a single documented sighting (i.e., at time of measurement), a minimum estimate of age was assigned based on the age-class assigned in the field. Calves were defined as animals less than 1 year old, juveniles as animals of between 1 and 4 years old, and adults as animals 5 years of age or older. As the exact age of juveniles could not be determined from visual observations alone, all juveniles with a single sighting were assigned a minimum age of 1 year. Adults with a single sighting were assigned a minimum age of 5 years based on estimates of the youngest age of sexual maturity for humpback whales (Atkinson et al. 2026; Chittleborough 1955a, 1959, 1965; Clapham and Mayo 1987).

For individuals with two or more sightings, a catalogue-derived minimum age was calculated by subtracting the year of first sighting from the year the measurement was taken, and then adding the same minimum age values described above for each age-class. For example, a whale first sighted in 2010 as an adult and then measured in 2023 would be estimated to be at least 18 years old. Individuals classified as calves were assigned an age of 0 years (i.e., less than 1 year old), as age was modeled in whole years. This approach follows that of Stevick (1999), who assigned minimum ages to individually identified humpback whales from their age-class at first sighting and subsequent sighting history.

Individual humpback whales were identified from tail fluke photographs and added to a catalogue maintained by the Pacific Whale Foundation. The catalogue contains images collected in multiple locations along the east coast of Australia from 1984–present and contains over 8000 unique humpback whales (Kaufman et al. 1987; Stack et al. 2020). The photos were also uploaded to the Happywhale repository for matching against other photo-ID catalogues and citizen science contributions (Cheeseman et al. 2022). When possible, sex data based on genetic analysis, photographs of the genital region, and/or the presence of a calf were incorporated to explore potential size and growth differences in females and males.

2.4 | Growth Curve

A growth curve was modeled by relating UAV-derived total length measurements to the minimum catalogue-derived age

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of individually identified humpback whales. Two versions of the growth curve were fitted. In the first, a "minimum age" growth curve, all measured whales were included, and age was defined as the minimum possible age based on photo-identification history and age-class at measurement. In the second, a "catalogue-derived minimum age" growth curve, only individuals with two or more documented sightings were included, allowing age to be calculated directly from the interval between first sighting and measurement year. In both cases, age was treated as a fixed value in the growth models. All calculations assumed age in whole years and length in meters.

We adopted a Bayesian modeling framework to fit and compare three widely used growth functions: the von Bertalanffy growth function, the Gompertz growth model, and the Richards growth model (Adamczak et al. 2023). These models differ in their assumptions about the timing and symmetry of growth deceleration, allowing alternative biological growth trajectories to be evaluated within a unified statistical framework. The goal of fitting multiple growth models was not to identify a universally "best" mathematical form, but to assess the robustness of age–length relationships across biologically plausible growth formulations.

Bayesian models were fitted using nonlinear regression, in which total length was modeled as a deterministic function of age and growth parameters, with uncertainty propagated through prior distributions (probability distributions encoding pre-existing knowledge about plausible parameter values before observing the data) and the likelihood. This approach allows prior biological knowledge to be formally incorporated, yields full posterior distributions (updated parameter distributions reflecting both prior knowledge and the observed data) for all parameters, and facilitates robust model comparison while accounting for uncertainty (Gelman et al. 2013; Smart and Grammer 2021).

Priors for growth parameters were informed by published estimates of humpback whale length-at-age relationships, adult body size, and growth curve parameters derived from previous studies (Table S1). Where multiple estimates existed or uncertainty was high, weakly informative priors were specified to constrain parameters to biologically plausible ranges without exerting undue influence on posterior estimates (Table S2). Parameters shared across growth models (e.g., asymptotic length) were assigned consistent priors to ensure comparability among models.

All models were fitted using a Student-t likelihood to accommodate potential outliers and heavier-tailed residual distributions relative to a Gaussian error structure. A single residual error term (σ) was shared across models, representing observation-level variation in drone-derived length measurements and unmodeled biological variability. The prior for σ was informed by UAV photogrammetry validation studies using the same measurement platform and processing workflow, which report random length measurement errors on the order of 1%–1.5% of total body length (Currie et al. 2021; Vivier et al. 2025).

Model fitting was performed in RStudio (Posit Team 2024) using the "brms" package (Bürkner 2017) which interfaces with Stan for Bayesian inference via Hamiltonian Monte Carlo sampling (Stan Development Team 2023) following a Bayesian modeling framework (Gelman et al. 2013). Four Markov chain Monte Carlo (MCMC) chains were run per model, each for 4000 iterations with the first 2000 discarded as warmup, yielding 8000 postwarmup draws per model. Convergence was assessed using the potential scale reduction factor (Rhat; acceptable threshold: Rhat < 1.05) and effective sample size (bulk ESS and tail ESS; minimum threshold: > 400 per parameter). All parameters in all fitted models met these convergence criteria (maximum Rhat = 1.00; minimum bulk ESS = 2592; minimum tail ESS = 2313, across all candidate models fitted). Posterior predictive checks confirmed that model-predicted length distributions adequately reproduced the observed data. Model performance was compared using approximate leave-one-out cross-validation. All Pareto-k diagnostic values from the PSIS-LOO procedure were below 0.7, indicating that the leave-one-out approximations were reliable for all observations.

2.5 | Sensitivity Analysis: Propagating Uncertainty in Age Estimation

Accurate age estimation remains one of the principal challenges in studying humpback whale life history, and multiple approaches have produced differing estimates of age at sexual maturity, with the youngest reported ages ranging from 5 years in the Gulf of Maine (Clapham and Mayo 1987) to 6 years (Atkinson et al. 2026) and 7 years (Gabriele et al. 2007) in southeast Alaska. Age estimates derived from historical ear plug analyses depend on assumptions about the rate of growth layer group (GLG) deposition, with early studies assuming two GLGs were deposited annually (Chittleborough 1965) whereas more recent work supports a rate of one GLG per year (Best 2011; Gabriele et al. 2010). Similarly, although photo-identification histories provide robust minimum ages for individuals resighted over multiple years, the ages of adults photographed only once cannot be directly inferred and therefore depend on assumptions about the underlying age distribution of the sampled population.

Rather than adopting a single age-estimation framework, we explicitly propagated these sources of uncertainty through our growth analyses using a Monte Carlo outer loop around the Bayesian model-fitting procedure. We evaluated six scenarios defined by the combination of two assumptions about the youngest age at sexual maturity for this population, and hence the minimum age assigned to adults (5 years, following Chittleborough's two-GLG-per-year interpretation, and 10 years, following the one-GLG-per-year interpretation; Best 2011; Gabriele et al. 2010) and three alternative age distributions for single-sighting adults (uniform, moderate exponential decay, and steep exponential decay). In each of 50 iterations per scenario, catalogue-derived minimum ages for multiple-sighting individuals were held fixed, while ages for single-sighting adults were resampled from the relevant distribution. The best-fitting model was then refitted to each resampled dataset using the Bayesian framework described above, yielding 500 posterior draws per iteration. Posterior draws were first pooled within scenarios and then combined across all six scenarios to generate a single ensemble of 150,000 posterior draws that incorporated uncertainty associated with both the alternative minimum adult

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ages (5 and 10 years) and age estimation of single-sighting individuals. Median parameter estimates and 95% credible intervals for $L\infty$, K, t_0, predicted length at age 5, and t_{90} were calculated from this ensemble.

2.6 | Comparison of Growth to Other Published Studies

To facilitate a comparison of growth trajectories across humpback whale populations and modeling frameworks, we estimated (1) body length at age 5 years ($L(5)$) and (2) the age at which individuals reach 90% of asymptotic length (t_{90}). These values provide reference points that can be calculated from any fitted growth curve, allowing future comparison of other populations to eastern Australia.

Whereas the Richards growth model provided the best fit to our data and was used for the primary parameter estimates (see Results), the published growth curves used for cross-population comparison were based on von Bertalanffy models. To keep these comparisons free of differences in model structure, the comparison metrics $L(5)$ and t_{90} for the present study were derived from a von Bertalanffy growth function with an estimated theoretical age at zero length (t_0), fitted in the same Bayesian framework. Posterior distributions of asymptotic length ($L\infty$), growth coefficient (K), and t_0 were extracted from this fitted model. Predicted length at age 5 was calculated for each posterior draw as:

$$L(5) = L\infty\left[1 - \exp.\left\{-K\left(5 - t_0\right)\right\}\right].$$

In this equation, $L\infty$ is the asymptotic (maximum) body length, K is the growth coefficient (the rate at which length approaches $L\infty$), and t_0 is the theoretical age at which length equals zero. $L(5)$ therefore provides an age-standardized length estimate that can be compared directly across populations and modeling frameworks and t_{90} was calculated analytically for each draw as:

$$t_{90} = t_0 + \ln(10)/K$$

here t_{90} is the age (in years) at which an individual reaches 90% of its asymptotic length $L\infty$, and the formula is derived by solving $L(t) = 0.9 \times L\infty$ for t. This metric is independent of $L\infty$ and provides a growth-rate index directly comparable across populations and modeling frameworks with different asymptotic sizes. Median values and 95% credible intervals (the Bayesian analogue of a confidence interval: the range within which 95% of the posterior probability falls; reported as the 2.5th–97.5th percentiles of the posterior distribution) were then computed for both metrics.

To compare the current rate of growth in eastern Australia to that observed in other populations, we searched the literature for published growth curves using contemporary data. The published growth curve parameters from van Aswegen et al. (2025) and Blázquez et al. (2025) were used to calculate length at age 5 and t_{90} for humpback whales in the North Pacific Ocean and Northeast Atlantic Ocean, respectively. For studies reporting sex-specific growth curves, predicted length at age 5 and t_{90} were calculated separately for males and females, then averaged across sexes to provide a pooled estimate comparable to the sex pooled analysis in the present study.

3 | Results

Field surveys were conducted over 68 days across four field seasons from 2021 to 2024. The initial dataset comprised 892 individual whales. After excluding individuals without corresponding laser altimeter measurements and/or those that failed image quality criteria, the final analytical dataset included 865 whales. Of these, 338 individuals were matched to the photo-identification catalogue, and 294 whales had two or more documented sightings and were therefore eligible for minimum age estimation based on resighting data. Nineteen whales were each measured twice on separate occasions, between one and 20 days apart. No individual was measured more than twice, and no animal was sighted in more than one season. For the animals measured twice, repeatability was high, with a within-individual coefficient of variation of 1.4% and a coefficient of reliability of $R = 0.998$.

3.1 | Age and Sex Results

A minimum age was assigned to every measured whale from its age-class at the time of measurement ($n = 865$), refined upward using the resighting interval where photo-identification history was available. Age estimates ranged from 0 to 42 years old. This age range provides coverage of both early growth and mature adult sizes within the population, allowing key features of the growth curve to be directly informed by observations rather than extrapolated. Sex determination was available for 293 females and 86 males. Males were represented across a narrower range of estimated ages (0–11 years) than females (0–42 years).

3.2 | Length Results

Total lengths ranged from 4.33 to 8.26 m for calves, 7.24–11.51 m for juveniles, 10.55–14.59 m for lactating females, and 10.03–14.72 m for nonlactating adults (Table 1). Some overlap in length between adjacent age-classes is expected because age-class was assessed visually in the field from relative body size (with calves additionally identified by their close association with an accompanying mother) rather than from measured length. Mean total length was higher in females (11.9 m) than in males (10.1 m), and sex was undetermined for the remaining 486 measured individuals.

TABLE 1 | Summary of total length measurements for 865 humpback whales by age-class and reproductive status.

Age-class	Sample size	Length range (m)	Mean (m)	Standard deviation
Calf	247	4.33–8.26	6.18	0.56
Juvenile	226	7.24–11.51	9.26	0.73
Adult	184	10.03–14.72	11.82	1.01
Lactating female	208	10.55–14.59	12.64	0.68

Note: Values show sample size (n), observed length range, mean total length, and standard deviation for calves, juveniles, adults, and lactating females measured using aerial photogrammetry.

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3.3 | Growth Curve Results

Our primary growth curves are based on catalogue-derived minimum age, restricted to individuals sighted two or more times ($n = 294$), for which age was determined directly from photo-identification resighting histories rather than from age-class alone; these are shown for all whales (Figure 2a) and for females only (Figure 2b). For comparison, we also fitted growth curves to the full set of measured whales ($n = 865$), which additionally includes individuals with a single documented sighting whose minimum age was assigned from age-class at measurement, shown for all whales (Figure 3a) and for females only (Figure 3b). A male-only curve was also fitted but, given the small, age-restricted male sample ($n = 86$), it is presented in Figure S1 and is not interpreted further. The two datasets yielded closely aligned length-at-age relationships, indicating

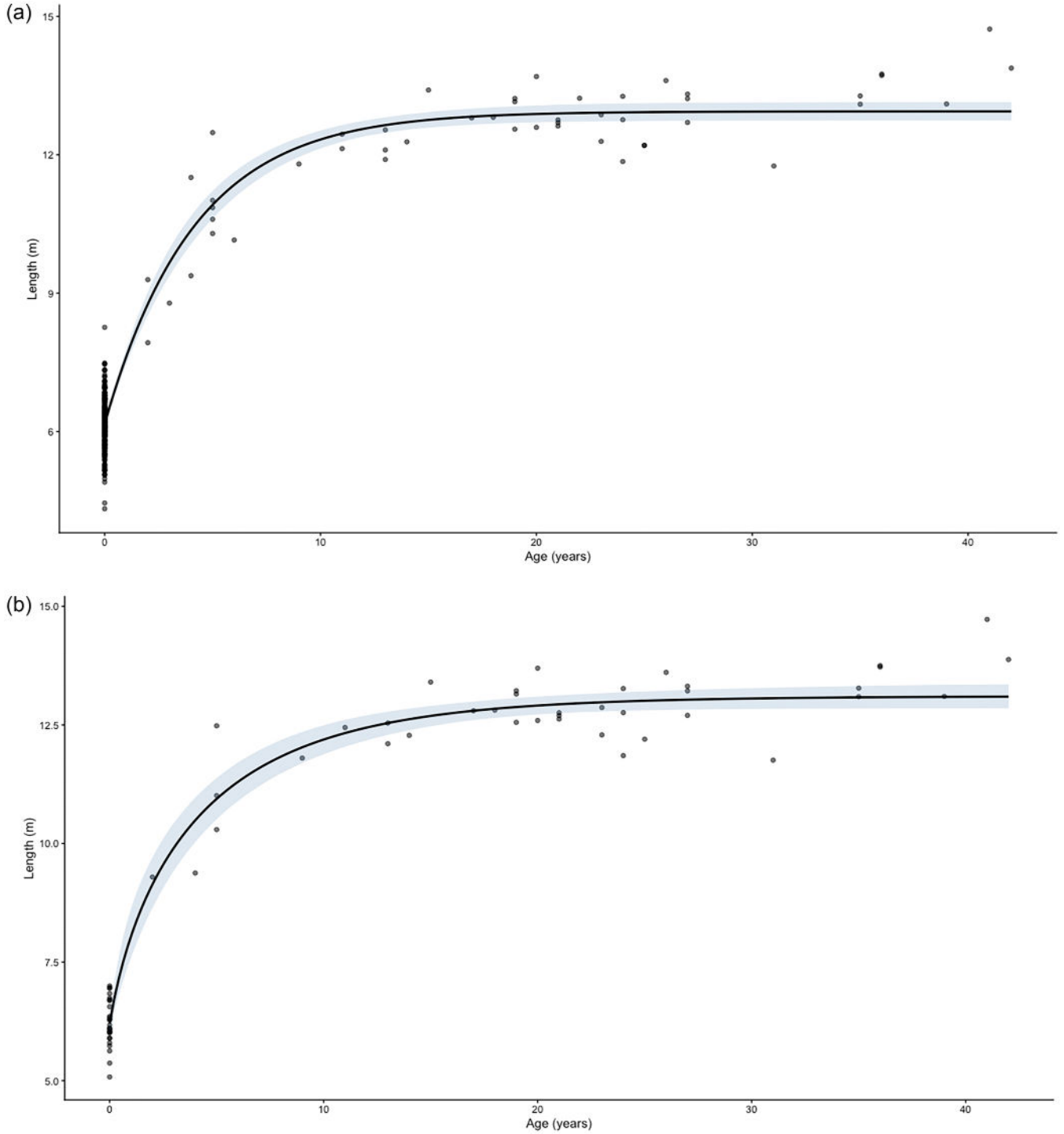


FIGURE 2 | Growth curves for eastern Australian humpback whales fitted using catalogue-derived minimum age derived from photo-identification histories of individuals sighted two or more times. Curves are shown for (a) all whales and (b) females only, restricted to individuals with sufficient resighting histories to allow for more precise estimates of minimum age ($n = 294$).

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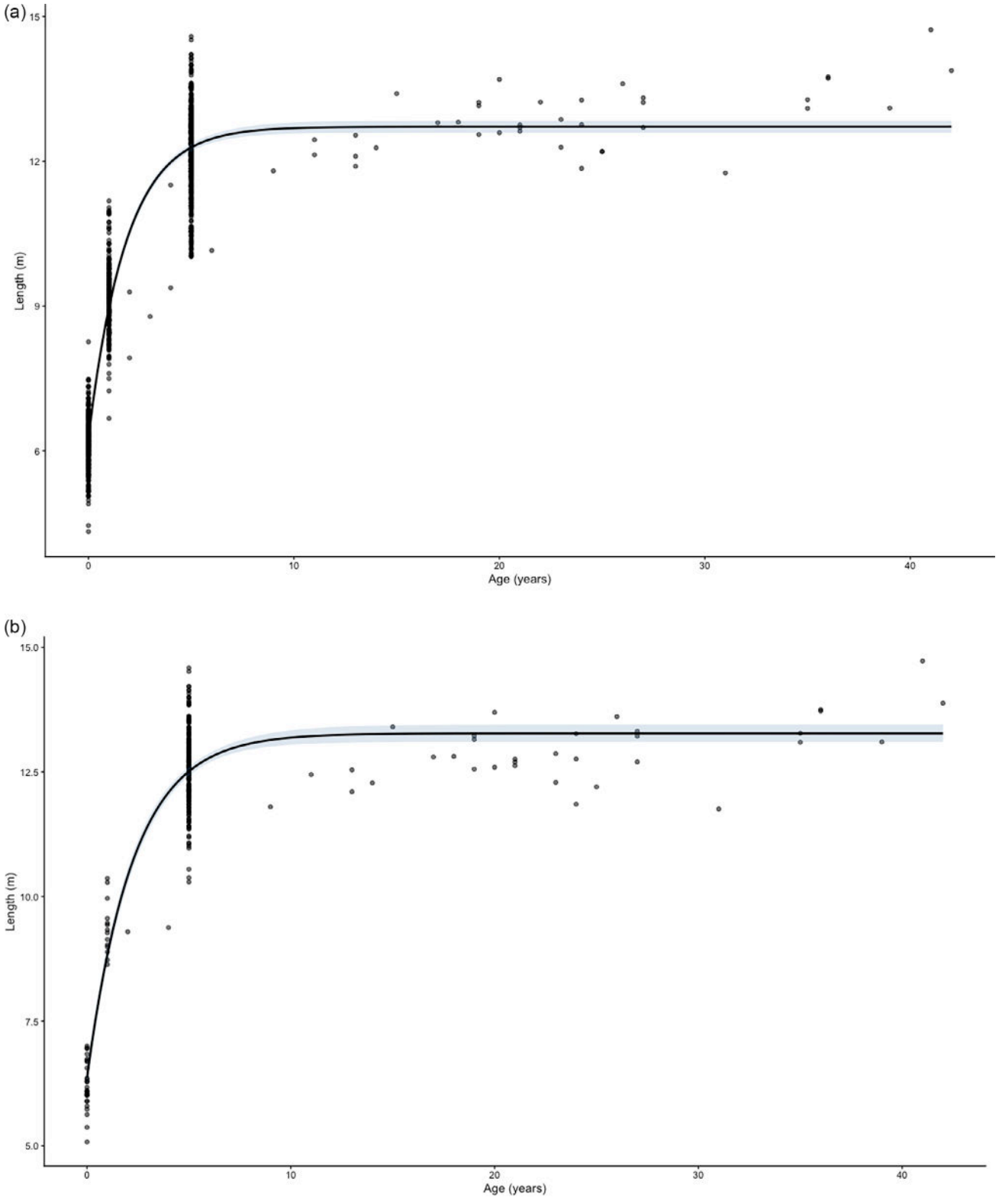


FIGURE 3 | Growth curves for eastern Australian humpback whales fitted using minimum age estimates derived from photo-identification sighting histories. Curves are shown for (a) all measured whales and (b) females only. Unlike Figure 2, this dataset additionally includes individuals with only a single documented sighting, whose minimum age was assigned from age-class at the time of measurement (total $n = 865$).

that including single sighted individuals did not materially change the growth trajectory and supporting the reliability of the age-assignment approach. Leave-one-out cross-validation indicated that the Richards model provided the best predictive performance. The von Bertalanffy model with estimated t_0 was closely comparable (Δ elpd = −7.0, SE = 6.0), while the Gompertz model and the von Bertalanffy model constrained by a fixed length-at-birth were less supported (Δ elpd = −73.7, SE = 11.8).

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3.4 | Growth Curve Parameters

Using the more restricted minimum-age dataset, growth parameters were estimated for males and females combined using the Richards growth model (Table 2). Posterior estimates indicated an asymptotic length ($L\infty$) of 13.14 m (95% CrI: 12.98–13.33 m), a growth rate coefficient (K) of 0.312 (95% CrI: 0.263–0.364), a theoretical age at zero length (t_0) of −0.33 (95% CrI: −0.44 to −0.25), and a shape parameter (p) of 0.325 (95% CrI: 0.278–0.388). The value of p confirmed rapid early-life growth followed by a gradual approach to asymptotic length.

3.5 | Sensitivity Analysis: Propagating Uncertainty in Age Estimation

Growth parameter estimates were robust to uncertainty in humpback whale age estimation. Incorporating uncertainty associated with both the alternative minimum adult ages (the youngest age at sexual maturity for this population) and the age distribution of single-sighting individuals produced an ensemble of 150,000 posterior draws from which the primary parameter estimates were derived. The asymptotic length was estimated as $L\infty = 12.84$ m (95% CrI: 12.65–13.04 m), the growth rate coefficient as $K = 0.25$ (95% CrI: 0.21–0.30), and the theoretical age at zero length as $t_0 = -2.62$ (95% CrI: −3.11 to −2.20). Predicted length at age 5 was 10.93 m (95% CrI: 10.52–11.34 m) and the estimated age at which whales reached 90% of asymptotic length (t_{90}) was 6.58 years (95% CrI: 5.49–7.90 years). These uncertainty-propagated estimates are reported as the primary results throughout this study.

Parameter estimates were highly consistent across the alternative age-estimation scenarios. Applying a direct uniform-resampling correction for age-class assignment produced near-identical estimates (length at age 5 = 10.87 m; $t_{90} = 6.73$ years), indicating that assigning fixed minimum ages to juveniles and adults did not materially influence the fitted growth curve. Similarly, alternative assumptions about the minimum age of sexual maturity (5 vs. 10 years, corresponding to the two- and one-GLG interpretations) yielded negligible differences in parameter estimates ($L\infty$: 12.85 vs. 12.84 m; K: 0.250 vs. 0.253; t_{90}: 6.66 vs. 6.57 years), demonstrating that the inferred growth trajectories were robust to plausible variation in age-estimation assumptions.

TABLE 2 | Posterior estimates of parameters from the Richards growth model fitted to pooled-sex (males and females combined) length-at-age data for eastern Australian humpback whales, derived from photo-identification histories of individuals sighted two or more times (catalogue-derived minimum age; $n = 294$), using Bayesian inference.

Parameter	Estimate	95% credible interval (CrI)
Linf (pooled)	13.14 m	12.98–13.33 m
K	0.312	0.263–0.364
t_0	−0.33	−0.44 to −0.25
p	0.325	0.278–0.388

Note: Shown are posterior mean estimates and 95% credible intervals for asymptotic length ($L\infty$), growth rate (K), theoretical age at zero length (t_0), and the shape parameter (p).

3.6 | Comparison to Other Published Studies

For direct comparability with previously published growth curves, predicted length at age 5 and t_{90} for this study were derived from a von Bertalanffy growth function with estimated t_0 ($VBGF_{t0}$), rather than the Richards model used elsewhere in this study. Although the Richards model provided the best fit to the eastern Australia data, the von Bertalanffy model with estimated t_0 performed well (Δ elpd = −7.0, SE = 6.0) and was within approximately one standard error of the Richards model. As the published growth curves used for comparison were based on von Bertalanffy models, using the same form ensured that cross-population comparisons were not confounded by differences in model structure. These parameter estimates were subsequently compared with published growth parameters derived from both historical whaling-era data and contemporary UAV-based studies of other humpback whale populations (Table 3).

In the present study of humpback whales from the east coast of Australia, predicted length at age 5 was 10.93 m (95% credible interval: 10.52–11.34 m), indicating rapid juvenile growth. Whales in this population were estimated to reach 90% of asymptotic length by a median age of 6.58 years (95% credible interval: 5.49–7.90 years). In contrast, historical estimates for Southern Hemisphere humpback whales from the east and west coasts of Australia (Chittleborough 1965) gave

TABLE 3 | Predicted length at age 5 and age at 90% of asymptotic length (t_{90}) for humpback whale populations derived from this study and previously published growth curves.

Study/whale population	Length at age 5 (m)	t_{90} (years)
This study (eastern Australia pooled, age-class uncertainty propagation)	10.93 (10.52–11.34)	6.58 (5.49–7.90)
Chittleborough (1965) (West and eastern Australia, pooled by averaging outputs)	10.51	8.29
van Aswegen et al. (2025) (North Pacific, pooled by averaging outputs)	10.57	8.73
Blázquez et al. (2025) (NE Atlantic, published parameters)	9.60	20.24

Note: For this study and comparison populations, length at age 5 and t_{90} were derived from a von Bertalanffy growth function with estimated t_0 ($VBGF_{t0}$) to facilitate direct comparison with published estimates. For this study, values represent the pooled posterior distribution from a Monte Carlo sensitivity analysis in which individual ages were resampled from plausible class ranges in each of 50 iterations per scenario across six age-estimation scenarios (juveniles: 1–4 year; adults: 5–42 year; 150,000 draws total). Values for comparison studies were derived from published VBGF parameters. 95% CrI = 95% credible interval.

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a predicted length at age 5 of 10.51 m and t_{90} of 8.29 years (Table 3).

4 | Discussion

Using UAV-derived morphometric measurements integrated with photo-identification based age estimates, this study provides contemporary growth curves for humpback whales along the east coast of Australia across a broad range of ages. Growth models fitted to the catalogue-derived minimum age dataset produced nearly identical length-at-age relationships to those fitted using estimated minimum ages, indicating that the inferred growth trajectory was robust to alternative age-assignment approaches. This close agreement supports the reliability of assigning minimum ages from age-class at the time of measurement. Sex-specific models for females further demonstrate that biologically meaningful stratification can be accommodated within the Bayesian framework while retaining stable parameter estimates.

Across all models, growth was rapid during early life and gradually approached an asymptotic adult length, consistent with expectations for most species of large baleen whales (Adamczak et al. 2023; Lockyer 1981). Estimated asymptotic lengths were similar among growth formulations and broadly aligned with historical values for Australian humpback whales, while uncertainty increased at older ages where sample sizes were lower. The inclusion of calves and juveniles allowed early-life growth to be directly informed by observed lengths rather than inferred from adult sizes. Overall, these results show that noninvasive measurements of living whales can be used to produce robust growth curves for this population. The resulting parameter estimates and size-at-age relationships establish a contemporary baseline for somatic growth in eastern Australian humpback whales that can support demographic interpretation and future comparative studies. More broadly, this study demonstrates how integrating aerial photogrammetry with longitudinal photo-identification data and Bayesian modeling provides a robust framework for estimating growth in free-ranging cetaceans.

4.1 | Historical Benchmarks for the Growth of Australian Humpback Whales

Age–length relationships for humpback whales in Australia were first quantified using extensive whaling-era datasets and remain the primary historical benchmark for growth in these populations (Best 2011; Chittleborough 1955a, 1965). Working with whales taken from both the west and east coasts of Australia between the late 1940s and early 1960s, Chittleborough combined morphometric measurements with reproductive and anatomical indicators of age, including counts of ovarian corpora, ear plug lamination layers, and vertebral fusion (Chittleborough 1965). These data provided foundational insights into humpback whale growth, including adult body size, evidence that somatic growth may continue beyond sexual maturity, and indications of long lifespan.

The nature of commercial whaling affected the age composition of the samples available to Chittleborough. There was not much information available on very young animals, because taking of calves was not permitted and a minimum legal length of 35 ft. (10.7 m) applied. Of 12,276 whales taken off Western Australia between 1949 and 1962, only 118 were recorded as shorter than this limit (Chittleborough 1965), and under-sized whales may have been reported as being of legal size (Stevick 1999). As a result, Chittleborough's growth curves were developed for whales estimated to be between approximately 5 and 19 years of age, and early-life growth was inferred rather than directly observed and measured (Stevick 1999). Nevertheless, these data captured adult size and late juvenile growth effectively and established expectations for asymptotic length in Australian humpback whales, with mean adult lengths of approximately 45 ft (13.72 m) and individual measurements exceeding 50 ft. (15.24 m) in a large female that had not yet reached physical maturity (Chittleborough 1965).

The contemporary growth curves presented here align closely with this historical benchmark while using noninvasive measurements of living whales. Estimates of asymptotic length are consistent with those reported in Chittleborough (1965), supporting the conclusion that adult body length in this population has remained relatively consistent across decades. Importantly, the inclusion of calves and juveniles, and animals of catalogue-derived minimum age, in the present study allows early life growth to be informed directly by observations rather than extrapolated from adult size. Because the priors were weakly informative, these estimates were shaped primarily by the observed length-at-age data and were not strongly constrained by the prior values. Together, these results establish age–length relationships for humpback whales in Australia using modern data and analytical approaches, providing an updated biological baseline that complements and builds upon the foundational work of Chittleborough. Rather than replacing Chittleborough's work, these results extend it by providing contemporary growth trajectories derived from living whales across the full range of early life.

4.2 | Hemispheric Differences in Growth

Predicted length at age 5 and the age at which 90% of asymptotic length is reached varied markedly among populations, highlighting substantial population-specific differences in growth trajectories. Humpback whales from the east coast of Australia exhibited both a larger predicted length at age 5 and an earlier t_{90} than whales from both Northern Hemisphere populations, indicating that a greater proportion of somatic growth is completed early in life. This is consistent with recent bioenergetic modeling, which similarly assumes that most structural growth is completed within the first 5 years of life in humpback whales (Christiansen et al. 2025), although that model was parameterized from life-history assumptions rather than fitted to empirical length-at-age observations.

When considered alongside population-level indicators, faster growth in Australian humpback whales is biologically plausible. Australian humpback whale populations have exhibited among the highest rates of postwhaling recovery globally, with rapid increases in abundance documented following the cessation of commercial whaling (e.g., Bejder et al. 2016; Best 1993; Fleming

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and Jackson 2011; Noad et al. 2019). While age at maturity was not directly estimated in this study, the growth patterns observed here are consistent with life-history strategies that promote rapid population recovery. Accelerated somatic growth may facilitate earlier attainment of sexual maturity, thereby shortening generation time and contributing to higher population growth rates (Roff 2002; Stearns 1992).

Somatic growth and sexual maturity in humpback whales are not defined by a single body length or age. Both whaling-era and contemporary studies have reported wide variation in age and size at maturity, with substantial overlap between immature and mature individuals (Best 2011; Chittleborough 1955b; Clapham 1992; Gabriele et al. 2007; Robbins 2007; van Aswegen et al. 2025). As a result, faster growth does not automatically imply earlier maturity for individual whales and understanding how growth influences reproductive timing remains an important focus for future work.

4.3 | Life History Significance

Although age at sexual maturity was not directly estimated in this study, the rapid early growth observed in eastern Australian humpback whales has important demographic implications. Individuals in this population reached 90% of asymptotic length by approximately 6.6 years of age, indicating that much of somatic growth is completed relatively early in life. Faster attainment of adult size may facilitate earlier sexual maturity, thereby shortening generation time and increasing the potential rate of population growth (Roff 2002; Stearns 1992).

These findings are particularly relevant in the context of this whale population, which has experienced a remarkable recovery following the cessation of commercial whaling (Noad et al. 2019). Growth represents one of the fundamental demographic processes underlying population recovery from severe depletion because it influences the timing of recruitment into the breeding population and contributes to generation time (Caswell 2001; Gaillard et al. 2000). Contemporary growth curves therefore provide an important reference point for understanding the vital rates of a population that has largely recovered from historical exploitation and is now transitioning toward a more stable demographic state (Caswell 2001).

4.4 | Management Implications for Demographic Monitoring

The growth curves developed here provide a contemporary, population-specific demographic baseline for eastern Australian humpback whales. Because the age of free-ranging cetaceans is rarely known (Best 2011; Clapham and Mayo 1987; Gabriele et al. 2007), length-at-age relationships provide a valuable tool for interpreting population age structure, maturity schedules, and generation time. These growth trajectories therefore establish a reference against which future studies can evaluate demographic change and characterize life-history patterns in this population.

The combination of UAV-based photogrammetry, long-term photo-identification, and Bayesian growth modeling provides a robust framework for long-term demographic monitoring. UAV photogrammetry enables repeated, noninvasive measurements of healthy individuals across multiple life stages, while photo-identification provides longitudinal information on known whales that can be used to refine growth trajectories over time. Incorporating uncertainty in age assignment and measurement within a Bayesian framework further provides transparent and reproducible estimates suitable for demographic applications (Smart and Grammer 2021). Together, these growth curves provide an important demographic reference for future studies of growth, reproduction, survival, and population dynamics, supporting continued monitoring of a population that has undergone rapid recovery from historical exploitation.

Author Contributions

S. H. Stack: conceptualization, methodology, formal analysis, funding acquisition, writing – original draft, writing – review and editing. **T. Fettermann:** data curation, writing – review and editing, investigation. **B. McGovern:** writing – review and editing, investigation. **S. M. Bengtson Nash:** conceptualization, supervision, writing – review and editing.

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Ethics Statement

Research in Hervey Bay, QLD was conducted under a Marine Parks Research Permit P-MPR-100853077, Scientific Purposes Permit P-SPP-100853084, and approval from the Animal Ethics Committee of the Queensland Government. Research in Eden, NSW was conducted under a DCCEEW Cetacean Permit 2023-0007, Scientific License SL102792 and approval from the Animal Ethics Committee of Griffith University. The UAV was operated under a UAV Operator Certificate issued to Pacific Whale Foundation and the UAV pilots held a Remote Pilot License (RePL) in accordance with regulations from the Australia Civil Aviation Safety Authority (CASA).

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Figure S1:** Male-only growth curve for eastern Australian humpback whales ($n = 86$), fitted using minimum age estimates derived from photo-identification sighting histories (as in Figure 3). Owing to the small male sample, this curve is presented for completeness and is not interpreted further. **Table S1:** Literature-derived values relevant to humpback whale growth priors. **Table S2:** Priors used in Bayesian growth models for humpback whales measured using UAV photogrammetry in eastern Australia.

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