**Seasonal- and age-dependent egg size variation in a polyandrous shorebird**

A key theory for the evolution of reduced male gamete size is sexual selection under male-male competition: sperm quality is traded off with sperm quantity to maximize fertilization success. Likewise, enlarged female gamete size is the evolutionary response to disruptive selection under reduced male gamete quality. The divergent gamete sizes of males and females (anisogamy) is a fundamental principle in sex role evolution, however, the effect of female-female competition on egg size variation in sex role reversed species remains unclear. Comparative analysis of birds has shown that a lineage’s egg size tends to decrease following the evolution of polyandry – supposedly due to the selective advantages that laying smaller eggs has on minimizing remating time and, hence, maximizing a female’s reproductive out given temporal constraints of her breeding schedule.

A female’s breeding schedule depends in part on her local resource availability to commence a breeding attempt – resources that include vacant space to conduct reproductive activities (e.g., courting, nesting, etc.), obtainable food to launch the physiological investments of egg production, and accessible males to seek copulations from and form pair bonds. In sequentially polyandrous species, females scramble competitively over these forms of breeding resources to maximize their opportunity for multiple breeding attempts, often resulting in high inter-female variation in reproductive success and breeding schedule. Females able to secure early nesting sites have more time to renest following failure of the first attempt and perhaps even enough time to pursue a sequential attempt. However, breeding early may come with the cost of physiological stress or increased likelihood of failure due to the higher environmental stochasticity associated with the early season, such as low food availability, inclement weather, or frequency-dependent predation risk. Taken together, a seasonal trade-off between quality and quantity exists for females: early nesting females may compromise the quality of an early investment in order to maximize time for prospective future investments.

In many organisms, reproductive productivity is age-dependent (Bouwhuis et al., 2009; Hammers et al., 2012; Lemaître et al., 2015; Zhang et al., 2015; Salguero-Gómez et al., 2016; Jankowiak et al., 2018; Dingemanse et al., 2020): an individual’s performance increases over early life to a maximum and is followed by a decline in older ages. The increase in breeding performance in early life is thought to be an indication of physiological or competitive inferiority of inexperienced breeders compared to their older conspecifics {Curio:1983fy}, whereas the decline in reproductive performance at old age is considered a sign of senescence – a within-individual age-specific decline in reproductive performance paired with an increase in the probability of death caused by the loss of physiological and cellular function (Medawar, 1952; Williams, 1957). A prominent hypothesis explaining the occurrence of senescence is the disposable soma theory (*sensu* Kirkwood, 1977), which states that individuals are constrained by the amount of resources they have to invest in survival and reproduction (Kirkwood & Austad, 2000). Therefore, senescence is the consequence of age-dependent trade-offs between energy investments in reproduction at the expense of somatic repair (Kirkwood & Rose, 1991; Kirkwood & Austad, 2000; Drenos & Kirkwood, 2005). Thus, an individual’s investment in current reproduction may exacerbate physiological and cellular damage, which might have knock-on effects on their capability for future reproductive investments at older ages – ultimately impairing performance.

A key issue for studying senescence in wild populations is that stochastic extrinsic mortality reduces the frequency of observable individuals in older age classes, hence making it challenging to disentangle among- vs. within-individual age-dependent variation – a phenomenon known as “selective disappearance” (Nussey et al., 2008; van de Pol & Wright, 2009). Investigations using longitudinal data to test for senescence are particularly powerful as they can quantitatively control for the confounding effects of selective disappearance through repeated measures of individuals as they age (Nussey et al., 2008; van de Pol & Wright, 2009; Dingemanse et al., 2020).

In oviparous organisms, egg size represents a fundamental measure of female reproductive investment (Kaplan, 1980; Fox, 1994; Williams, 1994, 2012; Starck & Ricklefs, 1998; Moran & Emlet, 2001; Xu et al., 2019) and is shown to be related to inter- and intra-specific variation in several life history traits. For example, egg size is associated with developmental mode with precocial species typically producing larger eggs than altricial species (Deeming & Reynolds, 2015). Within individuals, variation in egg size is shown to be highly repeatable (Christians, 2002), but notably, there is no clear association between egg size and female condition (Christians, 2002). Age-dependent changes in egg or clutch size are often consistent with senescence although complicated by considerable among-individual variation (Beamonte‐Barrientos et al., 2010; Dingemanse et al., 2020).

Among oviparous animals, shorebirds (part of the order Charadriiformes) produce some of the largest eggs in relation to body mass due to the needs of their precocial nidifugous young (Lack, 1968; Rahn et al., 1975). As a clade, shorebirds also exhibit a disproportionately high prevalence of polyandry (Oring, 1986; Colwell, 2010). Sexual and natural selection presumably act divergently on egg size with natural selection on offspring viability favouring larger eggs with more nutrients to enhance offspring survival (Blomqvist et al., 1997; Starck & Ricklefs, 1998; Williams, 2012) whereas sexual selection on polyandry favours smaller eggs that can be produced prior to peak seasonal food availability in order to maximize multiple nesting attempts (Liker et al., 2001; Andersson, 2004).

Here, we investigate seasonal- and age-dependent egg size variation using a 15-year longitudinal mark-recapture dataset of snowy plovers (*Charadrius nivosus*) breeding at Bahía de Ceuta – a wild sub-tropical population in western Mexico. The snowy plover is a long-lived shorebird (Colwell et al., 2017) exhibiting a rare breeding behaviour characterized by sex-role reversal including facultative sequential polyandry (Eberhart-Phillips et al., 2017; Kupán et al., 2019). The prominent variation of reproductive investment within the same sex provides a highly suitable study system to investigate how scramble competition shapes female reproductive output and scheduling in a species with non-conventional sex roles. Our aims were to 1) examine whether age-related dynamics in egg size and breeding schedule follow a pattern typical for senescence and 2) assess the seasonal relationship between egg size and polyandry potential in regard to reproductive trade-offs associated with female-female scramble competition. Following others (i.e., Bouwhuis et al., 2009 and Jankowiak et al., 2008), we hypothesized that a pattern of early-life increase in egg size and advance in lay date, followed by a peak maximum, and a decline thereafter, would be indicative of age-related changes associated with senescence. Furthermore, we hypothesized that the likelihood of polyandry and egg size would be inversely associated with lay date: early breeding female would have the highest rates of seasonal polyandry and would also lay the smallest eggs.

MATERIALS AND METHODS (2062 words)

*Data collection*

We studied the reproductive effort and breeding schedules of female snowy plovers (Figure 1a) at Bahía de Ceuta – an important breeding site located on the coast of Sinaloa, northwest Mexico (23o54’N, 106o57’W). Details on the study site and population are provided elsewhere (e.g., Cruz-López et al., 2017; Eberhart-Phillips et al., 2020a). In brief, we annually monitored breeding birds from mid-April until early July, and collected mark-recapture data following the methods described in Székely et al. (2008). We exhaustively searched for nests using telescopes and mobile hides to minimize disturbance. Upon finding a nest, we measured each eggs’ length and width to the nearest tenth of a mm to determine egg size (Figures 1b and 1c). Using these egg dimensions, we calculated egg volume (Figure 1d) following Hoyt (1979) as:

Eq. 1 ,

where *K* is 0.486, a volume-index constant for snowy plovers determined by Székely et al. (1994) through the use of an egg volumeter (Hanson, 1954). The modal clutch size of snowy plovers is three (87%) and is the maximum number of eggs we have observed in this population (Eberhart-Phillips et al., 2020b). We regularly checked incomplete nests until the clutch was completed and assigned the age of these nests according to the lay date of the last egg laid (Plaschke et al., 2019). If the clutch was complete upon discovery and had not been incubated longer than 10 days, we determined its lay date by floating the egg and estimating the stage of embryonic development {Nosaly:1993uz}. For successful clutches found after 10 days we assumed an incubation period of 25 days and back-calculated the laying date based on the hatching date (Plaschke et al. 2019). In the rare case that the nest did not hatch and we discovered it after day 10 of embryonic development, we simply used the nest’s found date as a crude approximation for lay date.

We identified nesting adults that had been previously marked based on their unique colour ring combination. We captured unmarked adults on their nests during incubation using funnel traps and assigned a unique colour combination for subsequent recognition (Hall & Cavitt, 2012). Because snowy plovers have circadian sex roles during incubation (Vincze et al., 2017), we generally targeted females for captures during the day and males during the night. In the rare circumstance when we were unable to identify parents before hatching, we attempted capturing parents whilst they tended chicks. As snowy plovers only show a small degree of sexual dimorphism (Küpper et al., 2009), we determined sex of all captured plovers in the field through a combination of plumage characteristics (Argüelles-Ticó et al., 2016), time of capture, and other behavioural cues (e.g., sex-specific brood care; Kupán et al., 2019). Furthermore, we confirmed sex molecularly from DNA extracted from blood samples through PCR amplification of Z and W specific DNA regions with two sex-typing markers: P2/P8 and Calex-31 (Griffiths et al., 1998; Küpper et al., 2007; Dos Remedios et al., 2010).

We visited known active nests every four or five days to determine the status of the nest (e.g., active, abandoned, predated) until the 20th day and thereafter daily until the eggs hatched or the nest failed. We weighed chicks as soon as possible after hatching and marked them with an alphanumeric metal and a single colour ring for subsequent identification in the chance that these individuals recruited into the breeding population as adults in future years. To evaluate the relationship between egg volume and chick hatching weight, we ran a mixed effect model predicting a nest’s average chick weight at hatch from the nest’s average egg volume, with mother identity and year as random intercepts. Nest averages were used in this model because we were unable to assign individual eggs to individual chicks in the field.

For the years 2006 to 2016 all longitudinal data collected has been compiled as part of the *CeutaOPEN* project – an open-access database for individual-based field studies in evolutionary ecology and conservation biology (Eberhart-Phillips et al., 2020a). We accessed these data directly from the open source repository (Eberhart-Phillips et al., 2020b) and supplemented them with data from four additional field seasons: 2017, 2018, 2019, and 2020. The *CeutaOPEN* database is composed of five tables that correspond to our routine data collection in the field. Here we used the “Captures”, “Resights”, and “Nests” tables. The “Captures” and “Resights” tables contain information about all the individuals captured and observed, whereas the “Nests” table contains the morphometric and spatiotemporal information related to each nest monitored. Please refer to our RMarkdown vignette that connects to *CeutaOPEN* and reproduces all analytical methods and results discussed below (Supplementary File 1).

*Statistical Analyses*

*Age estimation of individuals with unknown origin*—Investigating age-dependent processes of marked populations in the wild is challenging as they are often composed of a mix of individuals that are of known or unknown age (Colchero et al., 2012) – with the former being individuals initially marked at birth (i.e., ‘uncensored’), and the latter being immigrants of unknown age or those that were born before the study’s first marking occasion (i.e., ‘left-truncated’). To estimate the ages of unknown individuals in our marked population we employed a capture-mark-recapture analysis using the ‘Bayesian Survival Trajectory Analysis’ (BaSTA) package in R (v1.9.4, Colchero et al., 2012), which uses a Bayesian hierarchical framework to fit parametric survival functions of the marked population while accounting for imperfect detection. BaSTA derives birth year estimates of left-truncated individuals from the population mean of the projected survival function. As snowy plovers show prominent sex differences in survival (Eberhart-Phillips et al., 2017, 2018), we estimated female-specific survival functions for this study. Due to high natal dispersal we could not confidently determine the fate of juveniles marked in our population. To acknowledge this uncertainty, our capture-mark-recapture sample only included individuals that survived to their first breeding season, i.e. we constrained first-year survival probability to 1.

In total, our capture-mark-recapture data comprised of 450 uniquely marked females, of which 45 hatched locally and subsequently recruited into the adult population as known-age individuals (Fig. 1a), and the remaining 405 individuals were adults of unknown age and origin. Over the 14-year study period we monitored the presence or absence of marked individuals annually by recapturing or observing them in the field, amounting to a total of 916 post-birth detections of the 450 females in our sample (median detections per adult = 2; mean = 2.04 *±* 1.45 SD). In short, BaSTA determined that a logistic bathtub-shaped mortality model best fit our data – revealing that female mortality rate increased until age 5 years, after which it became constant (Fig. 1a; see Appendix S1 for detailed methods). Using this model, we extracted the birth year estimate posteriors for each unknown-age individual in the capture-mark-recapture sample. Note that three individuals (one first encountered as an adult [CA1579] and two local recruits [CA2036 and CA1526]; Fig. 2) had been already marked two years prior to the start of our monitoring period (i.e., pre-2006) and were thus added to our sample after running BaSTA on the 2006–2020 capture-mark-recapture data.

*Modelling seasonal variation in polyandry potential (“Polyandry model”)*—Our sample for studying seasonal polyandry dynamics included 425 females for which the identity of their mates had been verified through observation of unique leg-ring colour combinations. We defined observed polyandry as a binomial variable that scored an individual as being monogamous or polyandrous in a given year based on our observations of them having one or multiple breeding partners, respectively (see Fig. 2 for sampling distribution). Following this, our sample included a mixture of females that were observed breeding once or mutiply within the season – by definition, all polyandrous cases bred at least twice, but also 12.4% of monogamous cases were observed breeding multiply (i.e., remained with the same partner between breeding attempts within the same season). To assess the relationship between the likelihood of polyandry and lay date, we fitted a binomial linear mixed effects model that tested the likelihood of polyandry predicted by the fixed effect of lay date (i.e., of an individual’s first nest of the season), with individual and year included as random effects.

*Modelling individual variation in egg volume (“Egg volume model”)*—Our sample for studying egg volume dynamics included 2391 eggs from 840 nests of 425 females. 34 (13.2%) of females had three or more years of repeated measures, 83 (19.5%) had two years of repeated measures, and 286 (67.3%) were measured in a single year. Furthermore, 43 (10.1%) individuals in our sample were marked as hatchlings but later recruited as breeding adults in subsequent years (i.e., known age; Fig. 2a), with the remaining 382 (89.9%) individuals being initially marked as adults (i.e., unknown age; Fig. 2b). We followed common statistical approaches to investigate senescence in birds (e.g., Bouwhuis et al., 2009, 2010; Schroeder et al., 2012; Herborn et al., 2016; Graham et al., 2019; Dingemanse et al., 2020) by fitting a quadratic function of age to model age-specific trends in egg volume. This model controlled for selective appearance and disappearance of females differing in average egg volume by fitting ‘first observed age’ and ‘last observed age’ as fixed effects – a method that accounts for between-individual age effects introduced by selective disappearance and appearance (van de Pol & Verhulst, 2006; Dingemanse et al., 2020). We modelled age effects on egg volume by fitting a univariate mixed-effect model, that included age, age squared, first observed age, last observed age, and average tarsus length as fixed covariates. Tarsus length was used to control for female structural size, and was averaged over an individual’s lifetime of measurements (i.e., our *a priori* expectation was that tarsus length is static over life and that variation in this trait is due to measurement error) – grand average 24.5 mm (±0.96 SD), grand average within-individual standard deviation 0.66 mm (±1.14 SD). In addition to these fixed covariates, we included a quadratic function of lay date to assess seasonal variation in egg volume as several shorebird studies report a seasonal increases ({Skrade:2013bu, Kwon:2018hl} and decreases (Dittmann & Hötker, 2001; Skrade & Dinsmore, 2013; Kwon et al., 2018; Kubelka et al., 2020; Verhoeven et al., 2020) in egg volume. We included random intercepts for nest, individual, and year, and assumed a Gaussian error distribution of egg volume. Following the recommendation of {Schielzeth:2009da} to allow individuals to differ in the slopes of their responses, we ran a preliminary submodel that attempted to incorporate the quadratic function of age as a random slope for individuals. If the random slope form of the model converged, we proceeded with interpretation; if not, we based our inference on the random intercept model.

We verified the relationship between egg volume and chick weight using the egg dataset described above but reduced observations to the nest level and filtered to only include nests that had chicks measured within one day of hatching, resulting in 456 nests from 276 females. As it was unclear which chick came from which egg, each datum represented the nest-level average of chick weights and egg volumes. We included random intercept for mother identity and year, and assumed a Gaussian error distribution of egg volume.

*Modelling individual variation in lay dat*e *(“Laydate Model”)*—Our sample for studying lay date dynamics made use of the same sample of 425 females used in the model of egg volume variation above, however, as we were interested in seasonal dynamics of female-female scramble competition, data were reduced to the nest level and limited to an individual’s first breeding attempt of a season, resulting in 664 nests. Modelling the age effects of lay date followed the same logic as the above senescence model, with a univariate mixed-effect structure that included age, age-squared, first observed age, last observed age, and average tarsus length as fixed covariates, and individual and year as random intercepts. Likewise, a preliminary submodel including the quadratic function of age as a random slope for individuals was also attempted and interpreted pending convergence. We visualized the distribution of lay dates to confirm normality and to assess the population-level variance in breeding schedule – an indication of inter-female breeding asynchrony and the intensity of scramble competition {Andersson:2004bz}.

*Evaluating effect sizes and uncertainty*—We employed the “lme4” (Bates et al., 2015), “rptR” {Stoffel:2017dp} and “partR2” {Stoffel:2020fn} packages in R (R Core Team, 2013) to conduct our statistical modelling and assessed homoscedasticity by visually examining the residuals (see Fig. S2). For each of the three mixed-effect models above, we evaluated uncertainty in our parameter estimates by simulating 1000 parametric bootstraps via the “partR2::partR2” function {Stoffel:2020fn}. Likewise we derived nest-, individual-, and year-level repeatabilities (i.e., intra-class correlation) by simulating 1000 parametric bootstraps of the three mixed-effect models using “rptR::rpt”. We report fixed effects as standardized regression coefficients (i.e., beta weights) and repeatability as the ‘adjusted repeatability’ – interpreted as the repeatability of a given hierarchical group after controlling for fixed effects {Nakagawa:2010ta}. For the “Egg Model” and “Date Model” we ran an additional simulation that acknowledged uncertainty in the BaSTA age estimate of a given individual: we bootstrapped each model 1000 times, with every iteration randomly drawing an age estimate for an individual from their posterior distribution provided by BaSTA. For both simulations, we made interpretations of effect size and relevance by examining the 95% confidence intervals of predictors in relation to zero. To ensure that intercepts of our age-dependent models represented the reproductive performance for the earliest age at reproduction (i.e., age 1 in snowy plovers, Page et al., 2009), we fitted age as ‘*age* – 1’ – otherwise it would represent reproduction as age 0, which is an empirically meaningless estimate.

RESULTS(XX words)

We collected measurements from 2391 eggs, originating from 840 clutches of 425 females over a 14-year period. Modal clutch size was 3 eggs (724 nests, 86%; 2-eggs: 103 nests, 12.3%, 1-egg: 13 nests, 1.5%). Average egg length was 3.09 cm (±0.10 cm SD, Fig. 1a) and width was 2.24 cm (±0.05 cm SD, Fig. 1b), which translated into an average egg volume of 7.58 cm3 (± 0.46 cm3 SD). The average egg volume of a clutch strongly predicted the average hatch weight of the subsequent brood (*β* with 95% CIs: 0.604, 0.558–0.664; R2*marginal* = 0.370, 0.301–0.436; Fig. 1c, Table SX). Based on BaSTA’s estimated birth year, 184 of the 382 unknown-age females in our sample were first observed nesting at age 1 (48.1%), 120 at age two (31.4%), 72 at age three (18.8%; Fig. 2), five at age 4 (1.3%), and one at age 5 (0.3%). Of the 42 locally hatched females in our sample, 29 first nested at age one (67.4%), six were first observed nesting at age two (14.0%), two at age 3 (4.7%), three at age 4 (7.0%), three at age 5, 7, and 8, respectively (6.9%; Fig. 2). The average tenure of all females in the sample was 1.57 years (± 2.16 SD) with an average age span of 3.12 years (±2.03 SD, median: 3, range: 1 to 14 years) and an average of 1.56 years of observed ages per female (±1.04 SD, median: 1, range: 1 to 8 age-specific observations; Fig. 2). Females in our sample were typically observed nesting every consecutive year since their first observation, however, some individuals skipped years (average yearly interval between nesting attempts = 1.07 ±0.29 SD).

*Seasonal variation in polyandry potential*

A female’s likelihood of being polyandrous was strongly dependent on the lay date of their first nest (*β* [95% CIs]: -2.24 [-3.09, -1.77]; R2*marginal* = 0.367 [0.244, 0.493]; Fig. 1c, Table SX). On average, females made 1.43 (±0.56 SD) nesting attempts per season (median = 1, range 1 to 3) and, as expected, polyandrous females laid more nests per year than their monogamous conspecifics (Fig. S5). The lay date distribution of polyandrous females was bimodal, with peaks in the first and second nests occurring 11.7 days before and 29.2 days after the unimodal seasonal peak for monogamous females (Fig. 3b). Females had low repeatability in polyandry among years (adjusted individual cross-year repeatability (*r*) [95% CIs] = 0.011 [0, 127]; Fig. XX). In at least one breeding season, 76 (17.9%) females were polyandrous and 127 (30.0%) females laid multiple clutches throughout the observation period.

*Individual variation in egg volume*

Overall, mixed effects accounted for 71.4% of variation in egg volume, with fixed effects explaining 6% of this variation (Table 1). Females were highly repeatable in their egg volumes between clutches: *r* = 0.50 ([0.44, 0.56] 95%CI; Fig. 3, Table S3). Furthermore, eggs within the same clutch were moderately repeatable in volume (*r* = 0.16 [0.12, 0.20; Fig. 3, Table S3). We detected no evidence for senescence in egg volume (*βage* [95% CIs]: 0.08 [-0.05, 0.21], *βage2*: -0.11 [-0.21, 0.00]; semi-partial R2 of quadratic senescence function = 0.005 [0, 0.05]; Fig. 1c, Table SX). Furthermore, we found no support for selective (dis)appearance of individuals according to egg volume, as the effects of first and last observed ages of reproduction were not strongly supported (Fig. 3, Table S3). These results remained consistent when we ran a bootstrap that incorporated the individual birth-year posteriors estimated from BaSTA (STATS, Fig. X). The strongest fixed effect explaining egg volume variation was the quadratic season function (Table SX): eggs were smallest at the start of the season (model prediction: 6.95 *cm*3 [6.78, 7.13] 95%CI, Fig. 1c) and largest shortly after the middle of the season (model prediction: 7.65 *cm*3 [7.58, 7.72] 95%CI, Fig. 1c). Females with larger tarsi laid larger eggs (*βtarsus* [95% CI]: 0.14 [0.07, 0.21]; semi-partial R2 of female tarsus = 0.02 [0, 0.06]; Fig. 1c, Table SX).

*Individual variation in lay date*

Females had low repeatability in the lay date of their first nest among years (*r* = 0.07 [0, 0.18] 95%CI; Fig. 3, Table S3). We found moderate support for the linear term of the age function predicting the lay date of a female’s first nest in the season: young individuals laid later nests compared to their older conspecifics with lay date advancing by 2.98 days per year of age (95% CI: [0.62, 5.24]), however our uncertainty in this trend became unwieldly in the oldest age classes of our sample (Fig. 3b). The strongest effects explaining first nest lay date were the age at first reproduction (i.e., ‘first age’) and female structural size (i.e., ‘tarsus’ length): individuals that first bred in the population at older age classes tended to start nesting later in the season and smaller-bodied females initiated the earliest nests.

DISCUSSION(1555 words)

Identifying trade-offs between reproductive effort and survival in wild organisms is central for understanding of the evolutionary mechanisms of senescence (Lemaître et al., 2015). Here we show that egg size variation in snowy plovers is not a senescent trait – but is rather a seasonally dynamic trait driven by female-female scramble competition to breed early and increase polyandry potential. Consistent with previous work (Christians, 2002), we found that egg size was highly repeatable for individual females, even after controlling for their structural size. The distribution of laydates in the population extended over a *ca*. 110-day period, indicating high phenological asynchrony within the breeding population, a pre-cursor for intra-sexual competition. Early nesting females had a much higher likelihood of being sequentially polyandrous than late nesters, likely due to the generous time budget early breeders have for engaging in multiple breeding attempts. Despite being long-lived and investing substantially in reproduction year after year, we found no evidence of age-dependent trade-offs in egg size. However, younger females tended to lay their first nest of the season later than their older conspecifics – indicating age-dependent competitive abilities that likely reflect experience and local knowledge. Yet, an individual’s likelihood of polyandry in a given year was unpredictable egg size dynamics exhibited age-dependent changes that were consistent with reproductive senescence: the within-female relationship between age and egg size had a negative quadratic shape. Egg size peaked in individuals between three and four years of age with a moderate increase in egg size before peak performance and a strong decrease in egg volume thereafter.

Several studies of oviparous organisms have observed age-dependent variation in egg size, with some studies finding a positive relationship (Cooch et al., 1992; Flint & Sedinger, 1992; Robertson et al., 1994; Warner et al., 2016; Verhoeven et al., 2020) and others observing a negative relationship (Reid, 1988; Potti, 1993; Ito, 1997). However, several of these studies failed to account for selective disappearance (e.g., Cooch et al., 1992; Flint & Sedinger, 1992; Potti, 1993) and thus complicate the interpretation of individual- vs. population-level effects. Recent longitudinal studies document an increase in egg size in early life, followed by peak and then a late-life decline (Bouwhuis et al., 2009; Jankowiak et al., 2018) – the early-life increase in egg size may indicate individual improvement through more efficient foraging abilities, better mate choice, or improved predator avoidance (Forslund & Pärt, 1995). Although we did not find statistical support for a relationship between age and egg volume, we did find evidence that females tended to nest earlier as they aged. We suspect that this early-life delay in lay date is related to the inferior competitive abilities and lack of experience that young females have when faced with the seasonal scramble for early breeding opportunities.

Furthermore, under the polyandrous breeding system of the species, females may be engaging in reproduction before their physiological development is completed . We recorded females first breeding as early as 10 months after hatching (Eberhart-Phillips et al., 2020b) – an age at which females might not be fully mature and consequently unable to invest heavily into reproduction.

The observed post-peak decline (average 36 *cm*3 per year, Fig. 4) appears moderate at first sight (0.5% of egg volume) although it was statistically well supported. Importantly, the observed senescence effect was robust to the removal of the outlier nests of two females that were still reproducing after an age of nine (Fig. S3). In fact, when we excluded the outlier clutches of these two females, we observed that both the post-peak senescence effect and the quadratic relationship became stronger (Figs. S3 and S4). This could be indicative that these two longer-lived “outlier” females might be of higher quality, as the senescence effect seems to appear earlier for the majority of the female population. Another possibility is that immigrant females are actually older than what was estimated through our survival trajectory analysis – making the early appearance of senescence an artefact of methodological limitations to accurately age unknown birds. Regardless, the quadratic effect of age on egg volume was robust in both scenarios.

Given that we have observed females still breeding at an age of 14 years (i.e., ten years after the peak; Fig. 2), the cumulative decline would tally up to a 5% reduction of peak egg volume. Such a decrease becomes relevant when considering the developmental mode of snowy plovers. For plovers with their nidifugous chicks, small egg volume differences can have significant ramifications for chick survival (Starck & Ricklefs, 1998), as chicks are not fed by the parents but rather must forage for themselves immediately after hatching. Moreover, chicks of polyandrous females are typically cared for solely by their father, forcing them to rely more on their intrinsic reserves than the added benefits of biparental care. Consequently, comparatively small differences in egg size could have large knock-on effects for chick survival (Williams, 1994; Starck & Ricklefs, 1998). Yet, females need to trade-off the survival benefits of increased egg size for their offspring with their own resources required for maintenance and future reproductive investments, particularly when they attempt to maximize their reproductive output through polyandry. In snowy plovers, a completed clutch equals approximately 60% of a female’s body mass (Page et al., 2009): representing a substantial investment. Furthermore, snowy plover females incubate the clutch jointly with their male partner but desert soon after hatching to seek a sequential breeding attempt with a different male (Warriner et al., 1986; Eberhart-Phillips, 2019). Consistent with theoretical assumptions and previous empirical findings, we found that in years when females were polyandrous, they laid smaller eggs than in years when they were monogamous, suggesting a trade-off with between gamete size and number (Andersson, 2004). Contrary to our prediction, we found no effect of female age on polyandry.

Most studies conducted on temperate or high latitude breeding shorebirds have found a negative association between time of the season and egg size (Byrkjedal & Kalas, 1985; Sandercock et al., 1999; Kubelka et al., 2020) although in polyandrous red-necked phalaropes (*Phalaropus lobatus*)egg size increased across the breeding season (Kwon et al., 2018). However, most investigations of seasonal egg size dynamics did not disentangle whether the observed changes were due to within- or among-individual effects. For example, laying schedules associated with female quality and/or age could be responsible for much of the observed seasonal variation in egg size. A study including 15 arctic shorebirds suggested that indeed among-individual variation may account for more of the seasonal variation in egg size than within-individual variation (Weiser et al., 2018). We observed a quadratic effect of time of season on egg size: early and late season clutches had smaller eggs than those nesting at the middle of the season. Our observed seasonal variation in egg size might be explained by a combination of mating strategy and environmental constraints. Polyandrous females generally produced early- and late-season clutches (Fig. 5) while also laying smaller eggs. This indicates that polyandrous females trade-off egg quantity with size. The seasonal variation could represent a trade-off between a female’s capacity to build up adequate energy reserves for egg volume investment while also attempting to breed early enough in order to allow time for sequential mating opportunities later in the season. At the end of the season, late nesting females are under a tight schedule for producing sequential clutches rapidly before impending high tides and precipitation flood the breeding grounds (Plaschke et al., 2019). Notably, chick survival is especially high at the beginning of the season when resources are plentiful (Cruz-López et al., 2017; Kupán et al., 2019), which would support the notion that monogamous females breeding in the middle of the season may account for resource constraints by producing larger eggs to enhance chick survival. Past studies have linked polyandry and sex-role reversal to reduced female gamete size (Slotow, 1996; Andersson, 2004). Smaller eggs would permit females to lay several clutches rapidly (Liker et al., 2001). Since Snowy Plover females are sequentially polyandrous (Warriner et al. 1986), early breeding females are more likely to have a second breeding attempt with a different male. Indeed, brood desertion by females early in the breeding season is very often followed by re-mating locally (Kupán et al. 2019). Chick survival also decreases with the season because environmental conditions deteriorate (Cruz-López et al. 2017). As there is little variation in the number of eggs per clutch, early laying polyandrous females may adjust their reproductive investment into the first clutch and produce small eggs to enable them to quickly produce a second clutch. Therefore, polyandry is related to both early breeding and small eggs.

One limitation of our study is that some snowy plover females show high breeding dispersal and can produce sequential nests hundreds of kilometres apart (Stenzel et al., 1994; D’Urban Jackson et al., 2020). As our population is open to immigration and emigration, we have likely missed documenting polyandrous breeding attempts at unmonitored neighbouring nesting sites – meaning that we underestimate the true extent of polyandry. Yet, our observed clutch laying distribution (Fig. 5) suggests that this unavoidable limitation is not a major concern because we would have otherwise expected a larger share of seemingly monogamous females breeding at the beginning and end of the breeding season – instead we see that monogamous breeders tend to nest in the middle of the season. Furthermore, we acknowledge that our relatively small sample of known-age individuals presents a limitation to our study, however this simply reflects the challenge of studying an open population in the wild that exhibits high natal dispersal (jackdaw *Corvus monedula*, *N* = 30, Boonekamp et al., 2014; white-throated sparrow *Zonotrichia albicollis*, *N* = 59, Grunst et al., 2018). Nonetheless, we believe our study provides important insights that are robust to our sample size.

In conclusion, we show that individual variation in egg size of snowy plovers is modulated by age, mating strategy, and time of season. Our results suggest that senescence is a major driver of age-dependent dynamics of egg size – consistent with the disposable soma theory. Yet, we also show that the mating strategy, which is not related to age in this system, has an impact on egg size, a reproductive trait that is commonly used to detect senescence. We suggest that future research should explore whether and how polygamy and senescence interact to affect the reproductive output and what consequences these factors have on offspring survival. Studying patterns of senescence in wild populations with flexible mating systems may help shed light on how variation in mating strategies shape individual life history trajectories and lifetime reproductive success.

Egg Size variation paper

Intro:

* Scramble competition in a polyandrous breeding system:
  + Females face trade-offs between
    - Current metabolic demands (i.e., seasonal variation in food availability)
    - Time for multiple sequential breeding attempts (i.e., season length)
  + Egg size
    - A pure intrinsic measure of a female’s current investment
    - *Assumption*: A female should always lay the largest egg possible given her
      * structural size (constant over season and lifetime)
      * her current condition (variable over season and lifetime)

Rational:

Female scramble competition in a polyandrous breeding system:

The timing of breeding is dependent upon multiple traits Breeding phenology are often seasonally variable, with environmental conditions creating the space needed for breeding and the

Limited habitat available at start of season (quadratic seasonal trend: increase at start of seasons as winter flooding recedes, but decreases at end of season when flooding moves in. Competition among males to secure early territories, and competition among females to aquire early breeding attempts. These elements translate into variation in lay dates among females, which creates asynchrony in the breeding schedules of individuals in the population.

In Ceuta, the breeding season is long enough for sequential breeding attempts:

The "time-out" for a nesting male is ~2 months (i.e., a period that includes courtship, incubation, and brood care) versus ~1 to 2 months for a nesting female (i.e., a period that includes courtship and incubation, BUT variable amount of brood care). Thus, there is intra-female variation in "time-out", but constant intra-male variation in "time-out". Females tend to desert broods to pursue sequential mates after successful nesting attempts, but this varies depending on the amount of time left in the season: females desert if there is enough time for a second attempt, but stay if there is not enough time.

Relationship between lay date and polyandry:

Taken together, the seasonally dependent "time out" period of females and the scramble competition described above means that the liklihood of a female being polyandrous is dependent on the lay date of her first breeding attempt.

Trade-offs with laying early:

Assumption: if given the chance, all females should lay as early as possible in order to be polyandrous.

Assumption: females that lay early are making a trade-off between the quality of the current breeding attempt and the future prospect for multiple breeding attempts. The rational is that by laying early, the quality of the attempt will be poor (given the post-winter physiological state of the female, and current resource availability) but it will give her time to have a second attempt.

Measure of "quality of the current breeding attempt":

Egg volume - a pure intrinsic measure of a female's current investment.

Assumption: A female should always lay the largest egg possible given her 1) structural size, and 2) her current condition.

Assumption: egg size is positively associated with chick survival

Age-specific variation:

disposable soma theory suggests an age-dependent compromise between survival and reproduction. Reproductive performance should decline at older ages.

How does egg size vary with age? Expectiation: there is a peak age

of egg volume and it declines later in life.

Potential confounding effects:

- Does lay date of first nest vary wih age?

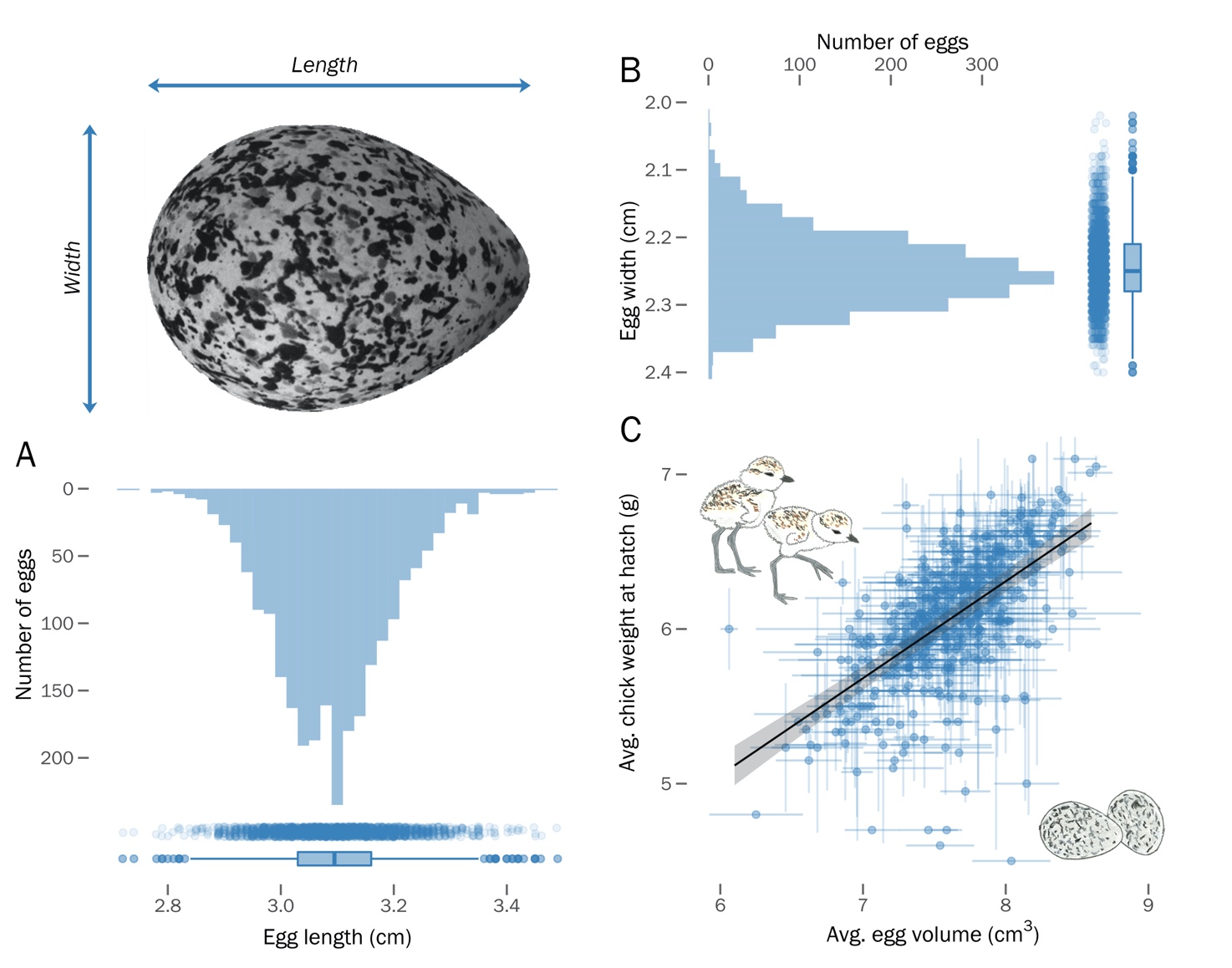
- Does liklihood of polyandry vary with age?

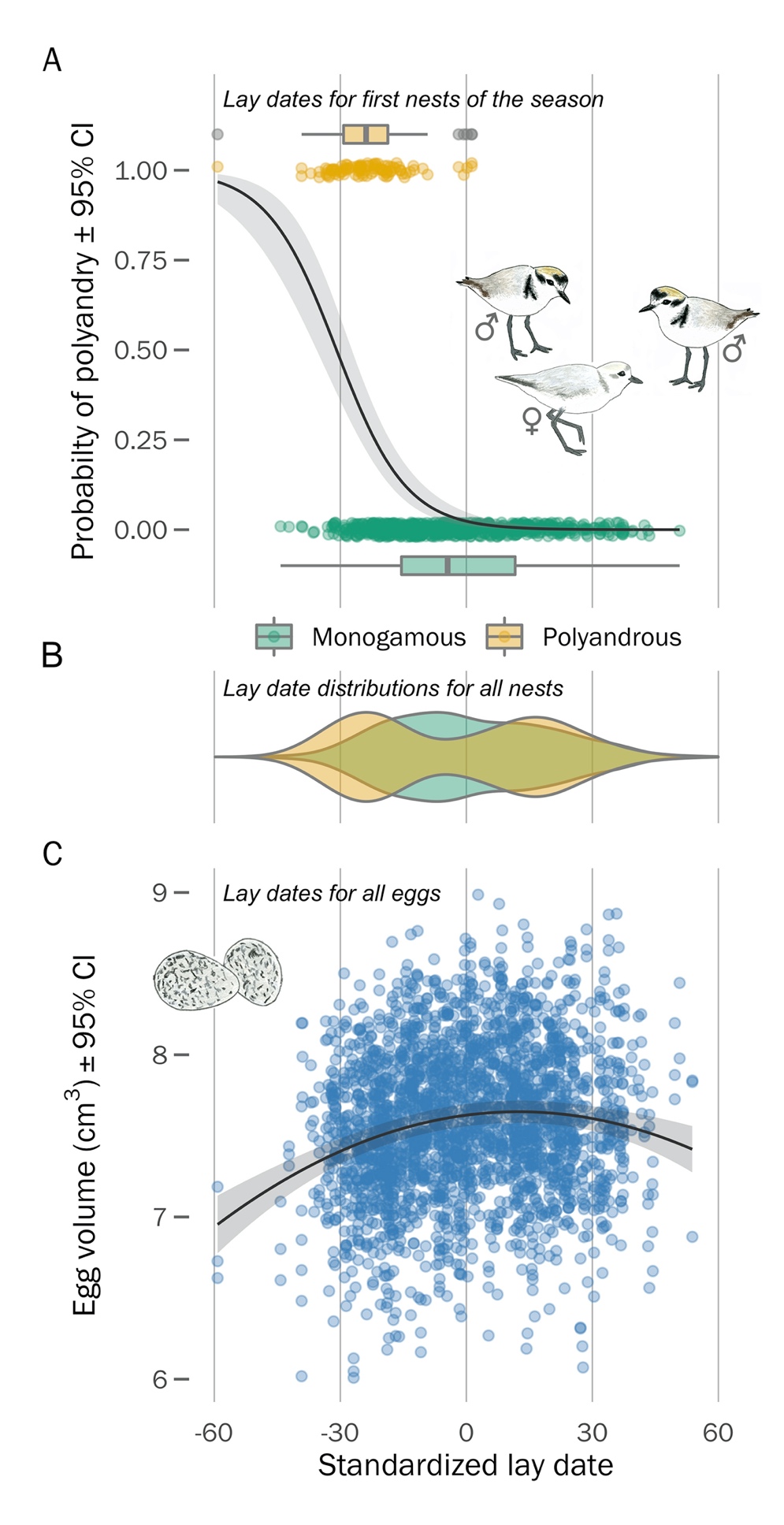
Figures:

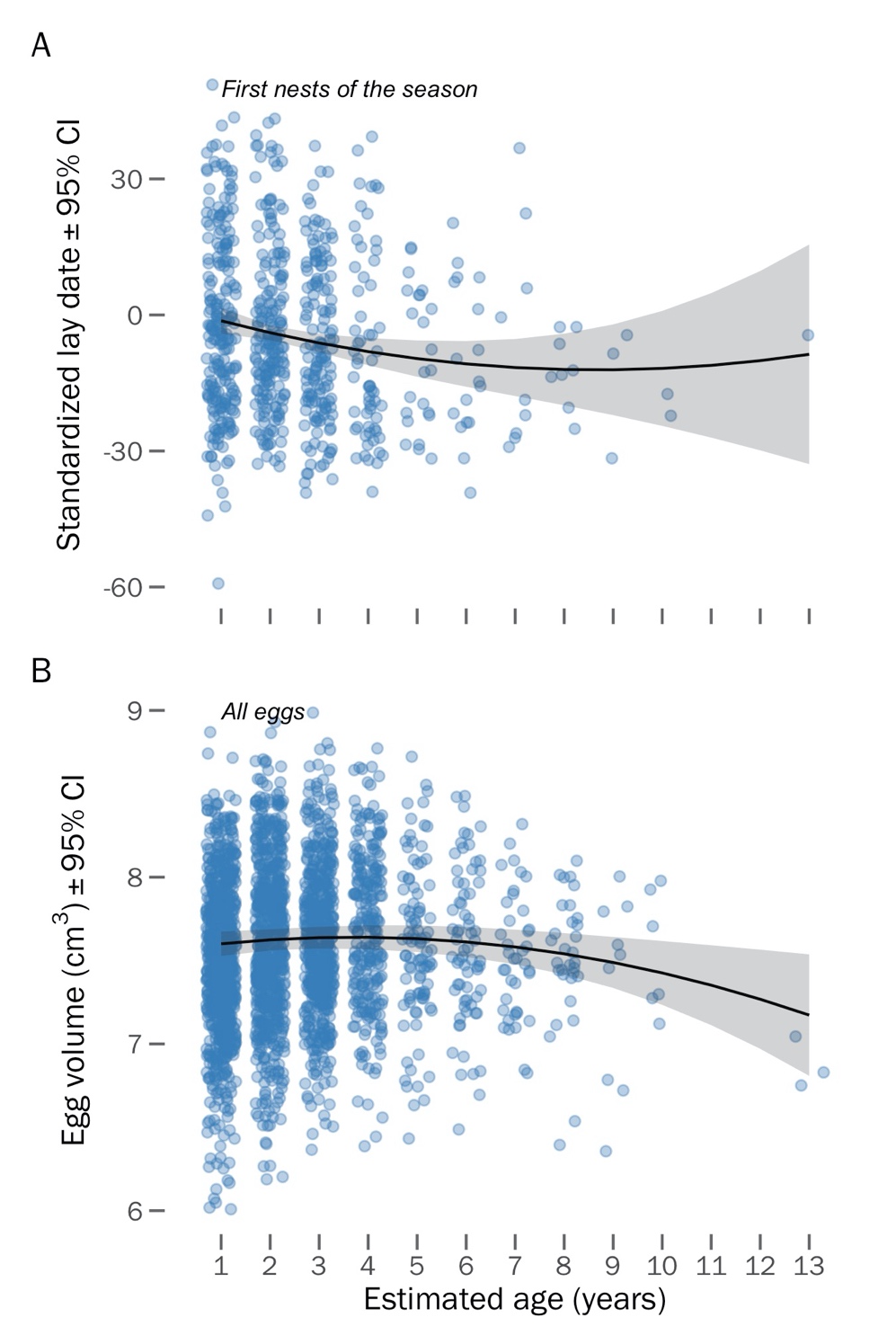
1. Egg morphometric distributions and the “chick weight ~ egg volume trend”
2. Sample size distribution of ages and polyandry (i.e., same as in the original manuscript, but with the extra data added). For visual purposes I will show only females that have two or more years of observations (i.e., including the singletons will make the figure unwieldly).
3. Season dynamics: top panel is the “P(polyandry) ~ lay date trend”, middle panel is the mating behaviour distributions according to laydate, and the lower panel is the “egg volume ~ lay date trend”.
4. Age dynamics: top panel is the “egg volume ~ age trend”, bottom panel is the “lay date ~ age trend”
5. A four panel forest plot of the effect sizes for the four models:
   1. Chick weight ~ egg volume
   2. P(polyandry) ~ lay date
   3. Egg volume ~ lay date + age
   4. Lay date ~ age
6. Heat map showing spatiotemporal variation in first lay date across the study site (i.e., overlay a gradient colored surface over the satellite imagery showing how the nests start on the edge of the salina and move north west with the retreating waterline – this would show how space is limited at the start of the season and emphasize the female-female competition over resources).

Tables:

1. BaSTA model selection (same as what was presented in the original ms)







Chart, scatter chart

Description automatically generated

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