Electronic Supplementary Materials:

High temperatures are associated with substantial reductions in breeding success and offspring quality in an arid-zone bird

Oecologia

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Provisioning rate versus provisioned biomass

Daily provisioning rate was linearly correlated with daily biomass delivered to the nest (LMM biomass provisioned as a function of provisioning rate, with male identity as a random factor; R^2 = 0.57; estimate: 0.37 ± 0.03, t = 11.53, p < 0.001; Fig. S1). Biomass per prey item was calculated following the methods presented in the Electronic Supplementary Materials of van de Ven et al *submitted*. The method requires input data for prey size and type, which we were not always able to obtain from our camera footage due to video quality or approach angle of the provisioning bird. Sample size available for provisioning rate was therefore larger than for biomass provisioned and data quality more reliable. We therefore use provisioning rate as a proxy for the quantity of energy and water supplied to the nest by breeding male hornbills in this study.

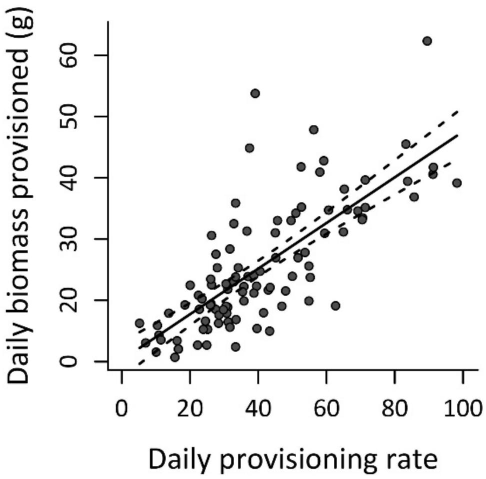

Figure S1: Daily biomass provisioned as a function of daily provisioning rate by male Southern Yellow-billed Hornbills (R^2 = 0.57), showing a strong but noisy relationship. Biomass estimation relies on correction identification of individual prey item size and type. We therefore use daily provisioning rate data in the main analyses in order to maximise sample size and the reliability of estimates of provisioning input to nests.

Daily provisioning rates as a function of air temperature

Table S1: Top three models explaining variation in daily provisioning rate while male Southern Yellow-billed Hornbills were sole provisioners. Global model: T_{max} + chick age + brood size + cumulative rainfall two months prior + ordinal date, with camera-trap recording hours as an offset term. Random term: individual ID. N = 45 days of observations on 5 males.

Model	df	logLik	AICc	ΔAICc	Model weight
T_{max}	4	-179.65	368.3	0.00	0.429
T_{max} + brood size	5	-179.06	369.7	1.36	0.217
T_{max} + chick age	5	-179.34	370.2	1.92	0.165

Table S2: Top five models explaining variation in daily provisioning rate while male and female Southern Yellow-billed Hornbills provisioned together. Global model: T_{max} + chick age + brood size + cumulative rainfall two months prior + ordinal date, with camera-trap recording hours as an offset term. Random term: individual ID. N = 49 days of observations on 7 pairs.

Model	df	logLik	AICc	ΔAICc	Model weight
T_{max} + chick age + rain	5	-217.89	447.0	0.00	0.242
T_{max} + chick age	4	-219.34	447.5	0.44	0.194
T_{max} + chick age + brood size	5	-218.32	447.9	0.84	0.159
T_{max} + chick age + brood size + rain	6	-217.32	448.4	1.38	0.121
T_{max} + chick age + ordinal date	5	-217.34	448.5	1.43	0.118

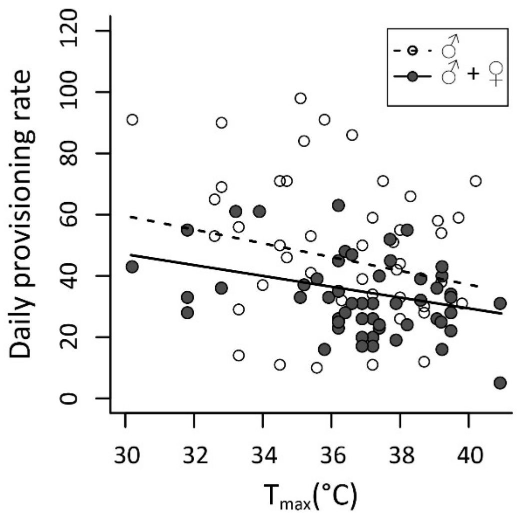

Figure S2: Daily provisioning rate as a function of daily T_{max} in Southern Yellow-billed Hornbills. The dashed line represents the model predictions while the males were single provisioners and includes the variable 'T_{max}' (raw data presented as open circles). The black line represents the model predictions of the male and female shared provisioning including the variables 'T_{max}' and 'chick age' (raw data presented as solid circles). Model predictions include individual ID nested in nest ID as a random factor. Data were derived from 99 days of camera recordings from seven nests.

Table S3: Analysis of variation in daily provisioning rate at the individual level while male Southern Yellow-billed Hornbills were sole provisioners. Global model: T_{max} + individual ID + chick age + brood size + T_{max} * individual ID, with camera-trap recording hours as an offset term and no random terms. Outputs are presented from the single best-supported model (T_{max} + individual ID). N = 45 days of observations on 5 males.

Variable	Estimate	Std. Error	z value	p value
T_{max}	-0.04	0.01	-3.40	0.0006
maleGA21	-1.65	0.17	-9.59	< 0.001
maleGA25	-0.76	0.21	-3.71	< 0.001
maleGA33	-0.56	0.09	-6.48	< 0.001
maleLEA05	-0.45	0.08	-5.52	< 0.001

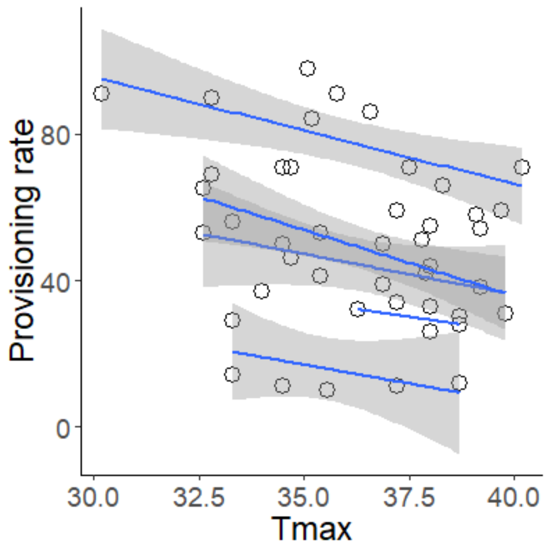

Fig S3: Daily provisioning rates of five individual male Southern Yellow-billed Hornbills during the period in which they were provisioning alone (females incarcerated within nest boxes / cavities), across a range of T_{max}. N = 45 days of observations, 5 males.

Table S4: Top three models explaining variation in daily provisioning rate at the level of individual pairs of Southern Yellow-billed Hornbills, while pairs were provisioning together. Global model: T_{max} + pair ID + chick age + brood size + T_{max} * pair ID, with camera-trap recording hours as an offset term and no random terms. N = 48 days of observations on 6 pairs (one pair was removed from the dataset as there was only one observation-day for this pair).

Model	df	logLik	AICc	ΔAICc	Model weight
T_{max} + chick age + pair ID	9	-173.35	369.4	0.00	0.477
T_{max} + brood size + chick age + pair ID	10	-172.37	370.7	1.25	0.255
chick age + pair ID	8	-175.82	371.3	1.89	0.186

Table S5: Analysis of variation in daily provisioning rate at the individual level while pairs of Southern Yellow-billed Hornbills provisioned together. Estimates are model-averaged outputs from the models in Table S4. Global model: T_{max} + individual ID + chick age + brood size + T_{max} * individual ID, with camera-trap recording hours as an offset term and no random terms. N = 48 days of observations on 6 pairs (one pair was removed from the dataset as there was only one observation-day for this pair).

Variable	Estimate	Std. Error	Adjusted SE	z value	p value
T_{max}	-0.04	0.03	0.03	1.44	0.150
Chick age	-0.03	0.01	0.01	3.11	0.002
Brood size	-0.08	0.16	0.16	0.47	0.064
PairGA24	1.20	0.30	0.30	3.95	< 0.001
PairGA25	0.39	0.15	0.16	2.48	0.013
PairGA32	0.77	0.16	0.16	4.74	< 0.001
PairGA33	0.54	0.16	0.17	3.29	0.001
PairLEA05	0.30	0.16	0.16	1.82	0.069

Relationship between nest temperature and air temperature

Nest temperature, as measured by iButtons within boxes and natural cavities, was positively correlated with T_{max}. The slope of the relationship between nest temperature and T_{max} was steeper for nest boxes (LMM estimate: 0.77 ± 0.01, t = 66.71, p < 0.001) than for natural cavities (LMM estimate: 0.35 ± 0.03, t = 11.92, p < 0.001; Figure S3S3).

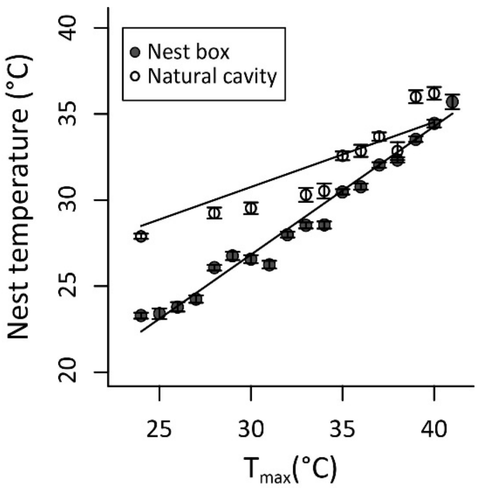

Figure S4: Nest temperature as a function of T_{max}. Nest temperature data were collected from 14 occupied nest boxes (black circles) and 2 occupied natural cavities (white circles) over 219 days during three summer seasons. Symbols represent mean values, lines represent the best-fit of the LMM and error bars represent 1 SE.

Nestling growth curves

Mean daily M_b (growth) of the chicks was assessed as a function of chick age separately for successfully fledged chicks and chicks that died, because the latter chicks had a lower growth asymptote. Non-linear models with graphical representation: exponential, Gompertz, logistic, log-logistic and Weibull were fitted to the data and goodness of model fits were assessed by AIC value (Szabelska et al., 2010; Tjørve & Tjørve, 2010) and computed in the drc package in R (Ritz and Streibig, 2005). The growth in mass of hornbill chicks was best explained by a log-logistic relationship of chick growth *y* with chick age *x*:

$$y = f(x) = \alpha + \frac{\beta - \alpha}{(1 + exp(\gamma(lnx - ln\delta)))^{\epsilon}}$$

where α is the lower limit, β is the upper limit, γ is the slope of the curve around δ. δ is the number of days where growth is 50 % of fledgling mass. If the parameter ε differs from 1 then the function is asymmetric, otherwise it is symmetric (on a log scale). The data used for this analysis were collected across three breeding seasons from 276 observations on 19 chicks that successfully fledged, and 310 observations on 56 chicks that failed to fledge.This latter group (failed-to-fledge chicks) included three chicks that did leave the nest but were depredated on the day of fledge. AIC comparison of fitted models showed that the 30 observations on these three chicks fitted the log-logistic growth of failed-to-fledge chicks, hence their inclusion in this group.

Hornbill chick growth rates (grams per day; $g.d^{-1}$) were best described by a log-logistic model. Chicks that fledged successfully gained 4.98 ± 0.16 $g.d^{-1}$, reached 50 % growth after 36.5 ± 1.1 days and reached a growth asymptote of 210.2 ± 4.3 g. Chicks that died in the nest or were depredated on the day of fledging gained on average 2.79 ± 0.17 $g.d^{-1}$, reached 50 % of final mass after 39.6 ± 1.8 days and reached a growth asymptote at 146.9 ± 4.4 g (Table S2; Figure S5).

Table S6: Parameters describing growth rates of Southern Yellow-billed Hornbill chicks that fledged successfully (n = 19) and those that failed to fledge (n = 56); estimates of effect sizes, standard error, t values and p values. N = 276 observations on 19 successfully fledged chicks and 310 observations on 56 failed-to-fledge chicks.

Nesting outcome	Parameters	Estimate	Std. Error	t value	p value
Successful fledge	γ: slope	4.98	0.16	31.80	< 0.001
	α: lower limit	6.85	4.63	1.48	0.140
	β: upper limit	210.18	4.34	48.43	<0.001
	δ: 50% growth	36.47	1.09	33.56	<0.001
	ε: assymetry	0.05	0.02	2.49	0.014
Failed to fledge	γ: slope	2.79	0.17	16.82	<0.001
	α: lower limit	6.36	2.49	2.55	0.011
	β: upper limit	146.86	4.44	33.10	<0.001
	δ: 50% growth	39.62	1.76	22.57	<0.001
	ε: assymetry	0.04	0.02	2.36	0.019

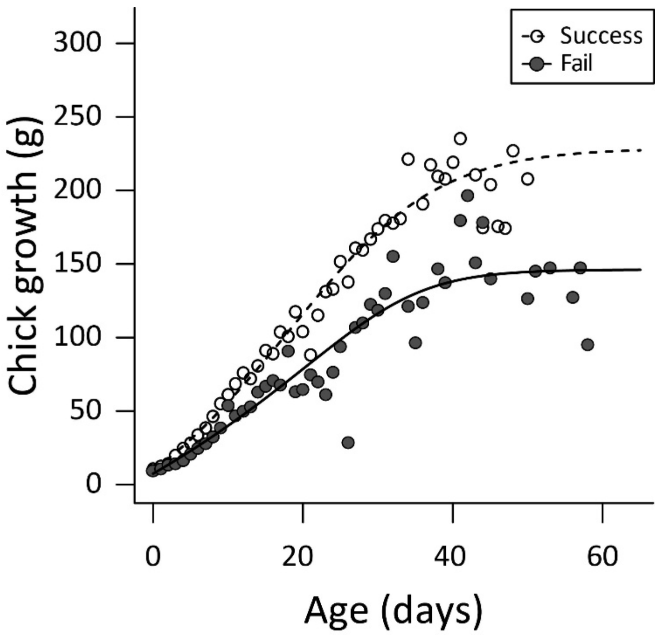

Figure S5: Daily mean M_b (g) as a function of chick age (days) of Southern Yellow-billed Hornbill chicks for successfully fledged chicks ('success': white circles, n = 276 of 19 chicks) and for chicks that died before fledging or on the day of fledge ('fail': black circles, n = 310 of 56 chicks). Data points represent the least squares estimation of the five-parameter log-logistic model. Lines represent the best-fit log-logistic model ('success': dashed line and 'fail': solid line).

Daily mean body mass during nesting attempts

Females

We analysed female daily mean M_b (taken as the mean of M_b records of one day) separately for the period during which females were incubating, and the period during which they had chicks in the nest. These models were fitted as LMMs with a Gaussian error structure and individual identity nested within season included as a random term. In the global model for female daily mean M_b during incubation we included predictor variables T_{max} of the previous day, days spent in the nest and female M_b at nest entry. Data were derived from 17 females during 27 nesting attempts (n = 103 observations). In the global model predicting female daily mean M_b from chicks hatching to female departure we included the variables T_{max} of the previous day, chick age, brood size and female M_b at nest entry. Data were derived from 20 females during 30 nesting attempts (n = 323 observations).

During the incubation period: M_b data collected during the incubation period consisted of 103 samples from 17 females during 27 nesting attempts. The best-fit model explaining variation in female M_b during the incubation period had a model weight of 0.430 and included only M_b at entry as the predictor variable. A competing model within two ΔAICc points also included the variable T_{max} of the day before (Table S6).

Table S7: Top two models explaining daily mean M_b of female Southern Yellow-billed Hornbills during incubation. Global model: T_{max} day prior + days spent in the nest + M_b at nest entry (M_b entry). Random term: Indiviual ID nested within season. N = 103 observations on 27 nesting attempts by 17 females.

Model	df	logLik	AICc	ΔAICc	Model weight
M_b entry	5	-444.43	899.5	0.00	0.430
M_b entry + T_{max} day prior	6	-443.40	899.7	0.19	0.392

The averaged parameter estimates of these two best-fit models indicated that female M_b at nest entry had a significant positive impact on female M_b during incubation; while the effect of T_{max} the day before was negative but non-significant (Table S7).

Table S8: Factors affecting daily mean M_b of female Southern Yellow-billed Hornbills during incubation; estimates of effect sizes, standard error, adjusted standard error, z values and p values. N = 103 observations on 27 nesting attempts by 17 females.

Variable	Estimate	Std. Error	Adjusted SE	z value	p value
M_b entry	0.818	0.10	0.10	8.16	<0.001
T_{max} day prior	-0.326	0.55	0.55	0.59	0.555

During the nestling period: During the period that females were caring for their chicks inside the nest (post-hatch to female departure) a total of 323 records of M_b were collected from 20 females across 30 nesting attempts in three seasons. For the period after the chicks hatched, the best-fit model explaining the variation in female M_b included the predictor variables T_{max} of the preceding day, chick age, brood size and M_b at nest entry and had a model weight of 0.485. A second competing model (model weight 0.433) excluded the variable 'brood size' (Table S8).

Table S9: Top two models explaining variation in daily mean M_b of female Southern Yellow-billed Hornbills post-hatch to female departure. Global model: T_{max} day prior + chick age + brood size + M_b entry. Random term: Individual ID nested within season. N = 323 observations on 30 nesting attempts by 20 females.

Model	df	logLik	AICc	ΔAICc	Model weight
T_{max} day prior + chick age + brood size + M_b entry	8	-1296.32	2609.1	0.00	0.485
T_{max} day prior + chick age + M_b entry	7	-1297.48	2609.3	0.23	0.433

The averaged parameter estimates of these two best-fit models indicated that the variables T_{max} of the preceding day and chick age had a significant negative impact on daily mean M_b and M_b at nest entry had a significant positive impact on daily mean M_b of the females after the chicks had hatched, while the effects of brood size were non-significant (Table S9, Figure S5).

Table S10: Factors affecting the daily mean M_b of female Southern Yellow-billed Hornbills from hatching to female departure; estimates of effect sizes, standard error, z values and p values. N = 323 observations on 30 nesting attempts by 20 females.

Variable	Estimate	Std. Error	Adjusted SE	z value	p value
T_{max} day prior	-0.774	0.24	0.24	3.23	0.001
Chick age	-2.096	0.15	0.15	14.25	<0.001
Brood size	-0.178	0.91	0.92	0.19	0.846
M_b entry	0.390	0.11	0.11	3.45	<0.001

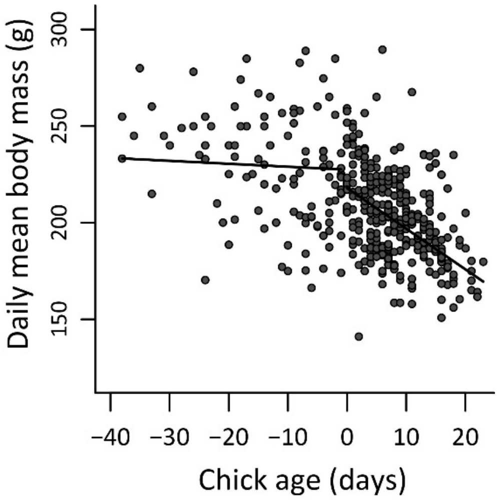

Figure S6: Daily mean M_b of female Southern Yellow-billed Hornbills as a function of chick age (zero being the hatching date); individual ID nested within season was used as a random term. The lines represent predictions of the best-fit models for the pre-hatch and post-hatch period (n = 426 observations of 40 nesting attempts of 23 females).

Males

During the nestling period: The single best-fit model for male daily mean M_b during the period from chick hatch until chick fledge was explained by the predictor variables chick age, initial M_b when chicks hatched and T_{max} the day prior to M_b measurement (AICc = 810.5, df = 7, model weight of 0.897). Although mean daily M_b of the males in this study outside the breeding season is unknown, the males lost mass at an average rate of 0.69 g.day^{-1} during the nestling period (indicated by the variable chick age, which was measured in days from hatch = day 0; Figure S6). In addition, M_b was on average > 0.8 g lower for each 1°C increase in T_{max} the day prior to M_b measurement. Finally, daily M_b was positively correlated with initial M_b throughout this period (i.e. males that were heavier at chick hatch maintained higher M_b throughout the nestling period; Table S10).

Table S11: Factors affecting daily mean M_b of male Southern Yellow-billed Hornbills during the period from chick hatch to chick fledge; estimates of effect sizes, standard error, t values and p values. N = 122 observations on 14 nesting attempts by 10 males.

Variable	Estimate	Std. Error	t value	p value
Chick age	-0.694	0.09	-7.37	<0.001
Initial M_b	0.572	0.15	3.92	0.003
T_{max} day prior	-0.848	0.29	-2.93	0.011

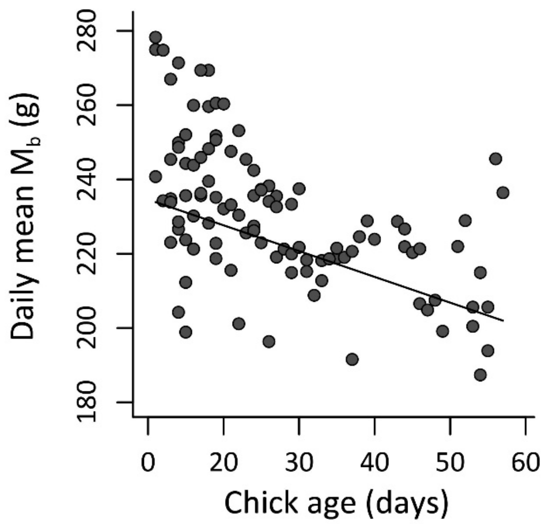

Figure S7: Daily mean male M_b (g) during the period from chick hatch to chick fledge decreased with chick age. The line represents the prediction from the model that includes the variables chick age, initial M_b and T_{max} the day prior to M_b measurement and individual ID nested within season as a random term. Data were derived from 122 M_b measurements during 14 nesting attempts of 10 individuals across three summer seasons.

Top model set for nestling diurnal mass change (dawn – dusk)

Table S12: Top two models explaining variation in diurnal mass change (ΔM_b) of Southern Yellow-billed Hornbill chicks from the period hatching to fledging. Global model: T_{max} + chick age + brood size. Random term: Individual ID nested within brood ID and season. N = 306 observations on 44 chicks.

Model	df	logLik	AICc	ΔAICc	Model weight
T_{max} + chick age + brood size	7	-1123.77	2261.9	0.00	0.596
T_{max} + chick age	6	-1125.53	2263.3	1.42	0.293

Duration of successful versus failed nesting attempts

The average incubation period was 23.8 ± SD 3.5 days (18 – 27, n = 37) and was not significantly different between successful (n = 15) and failed (n = 22) breeding attempts (t = 0.95, p = 0.18). Of the 15 nests that successfully fledged chicks, the females stayed with the chicks in the nest for an average period of 26.6 ± SD 4.0 (23 – 37) days post-hatch, and left the nest 58.4 ± SD 7.8 (49 – 76) days after they entered the nest. Of the 22 nests that failed to fledge any chicks the females stayed with the chicks in the nest for 16.6 ± SD 8.5 days post-hatch (3 – 32; success vs fail; t = 3.76, p < 0.001) and left the nest 44.8 ± SD 13.1 days (26 – 75; success vs fail; t = 3.51, p < 0.001) after they entered the nest, both significantly shorter than females with successful nests. The 11 nests that failed had chicks surviving for 14.7 ± SD 10.4 days (3 – 23) after the females departed. Chicks that fledged remained in the nest on their own for an average of 19.7 ± SD 7.4 (9 – 32; success vs fail; t = 6.65, p < 0.001) days while being fed by both parents. Successful chicks fledged the nest 78.3 ± SD 6.8 (69 – 90) days after the females first entered the nest and the first-hatched chicks per brood had an average age of 46.0 ± SD 6.5 days (35 – 57) when fledging (Figure S).

The earliest nest abandonment date by females post entry was after only one day spent in the box/cavity (n = 2, not included in the analysis). Nests in which eggs were laid, but which subsequently failed to fledge any chicks did so for several reasons: the eggs were infertile or embryos died during incubation (n = 1), the females left the nest early and abandoned the eggs (n = 3), the females ate the eggs (n = 2) or chicks (n = 5), or the females left the nest early while the chicks were still dependent on their care in the nest and they eventually died (n = 8) or were depredated (n = 3).

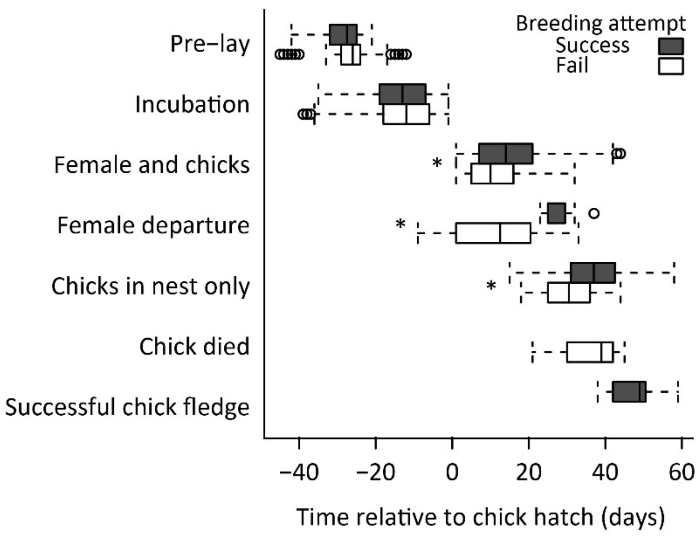

Figure S8: The interquartile range and median of the duration of nest stages as a function of hatching date of the first chick: pre-lay, incubation, female with chicks, female departure, chicks in the nest only, chicks died and chick fledge. Data were collected across three breeding seasons from 15 nests that successfully fledged one or more chicks and 22 nests that failed to fledge chicks. Asterisks indicate significant differences between the nest stages of successful and failed breeding attempts (* = α < 0.001).

Some observations in the field are worth noting: in one nest the female died during incubation of three eggs. Fresh invertebrates in the nest confirmed that the male had been attempting to feed her. In three failed nests the chicks were unable to re-seal the nest opening and were depredated on day 3, 9 and 23 after the females had left. In one nest the female ate her two chicks that were then two and four days of age and remained in the nest together with the remaining two eggs for another 17 days, presumably to complete her moult, after which she came out leaving the eggs unhatched.

Additional factors affecting probability of successful fledge

Mean T_{max} and female M_b at nest entry indirectly as well as directly affecting nesting success, by affecting the age and mass of nestlings when females departed the nest. Mean T_{max} during the nestling period was negatively correlated with the M_b chicks were able to obtain by the time females departed the nest (Est. -31.6 ± 9.20, p = 0.003; Fig. 4 main text); whereas female M_b at nest entry was positively correlated with both chick M_b (Est. 1.15 ± 0.45, p = 0.02) and chick age (Est. 0.30 ± 0.10, p = 0.006) on the day that females left the nest. Relationships between female M_b at nest entry, chick M_b and chick age at the time the females left the nest, and probability of nest success are summarised in Fig. S8.

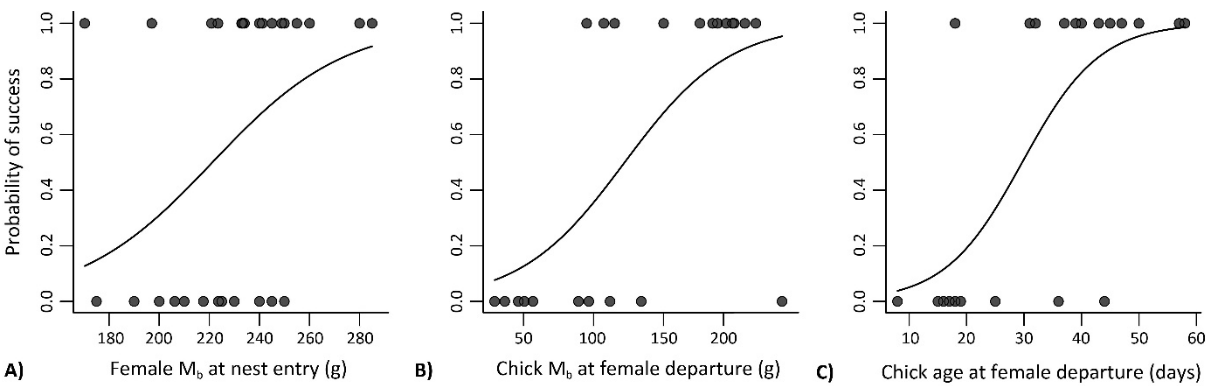

Figure S9: Probability of successfully fledging of a chick from the nest in Southern Yellow-billed Hornbills as a function of A) female M_b at nest entry, B) chick M_b and C) chick age at the time the females left the nest. The solid line represents the prediction from a model with a binomial distribution; chick identity nested within season was used as a random term.

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