

ROYAL SOCIETY OPEN SCIENCE

Carcass size, not source or taxon, dictates breeding performance and carcass use in burying beetle

Journal:	<i>Royal Society Open Science</i>
Manuscript ID	Draft
Article Type:	Research
Date Submitted by the Author:	n/a
Complete List of Authors:	Hsu, Gen-Chang; Cornell University Department of Entomology Lin, Wei-Jiun; National Taiwan University Hsieh, Chi-Heng; National Taiwan University Institute of Ecology and Evolutionary Biology Lee, Yue-Jia; National Taiwan University Institute of Food Science and Technology Sun, Syuan-Jyun; National Taiwan University International Degree Program in Climate Change and Sustainable Development
Subject:	ecology < BIOLOGY
Keywords:	breeding performance, burying beetle, carcass, nutritional composition, offspring quality-quantity trade-off, resource use efficiency
Subject Category:	Organismal and Evolutionary Biology

SCHOLARONE™
Manuscripts

1

2

3

4

5

6

7

8

9

10

11

12

13

14

15

16

17

18

19

20

21

22

23

24

25

26

27

28

29

30

31

32

33

34

35

36

37

38

39

40

41

42

43

44

45

46

47

48

49

50

51

52

53

54

55

56

57

58

59

60

Author-supplied statements

Relevant information will appear here if provided.

8

9

10

11

12

13

14

15

16

17

18

19

20

21

22

23

24

25

26

27

28

29

30

31

32

33

34

35

36

37

38

39

40

41

42

43

44

45

46

47

48

49

50

51

52

53

54

55

56

57

58

59

60

Ethics

Does your article include research that required ethical approval or permits?:
This article does not present research with ethical considerations

Statement (if applicable):
CUST_IF_YES_ETHICS :No data available.

16

17

18

19

20

21

22

23

24

25

26

27

28

29

30

31

32

33

34

35

36

37

38

39

40

41

42

43

44

45

46

47

48

49

50

51

52

53

54

55

56

57

58

59

60

Data

It is a condition of publication that data, code and materials supporting your paper are made publicly available. Does your paper present new data?:
Yes

Statement (if applicable):
Data and code used in this manuscript are publicly available on Zenodo (DOI:
<https://doi.org/10.5281/zenodo.12747445>).

27

28

29

30

31

32

33

34

35

36

37

38

39

40

41

42

43

44

45

46

47

48

49

50

51

52

53

54

55

56

57

58

59

60

Conflict of interest

I/We declare we have no competing interests

Statement (if applicable):
CUST_STATE_CONFLICT :No data available.

1 *For submission to Royal Society Open Science*

2
3
4
5
6
7 **2 Carcass size, not source or taxon, dictates breeding performance and carcass**
8
9 **3 use in burying beetle**

10
11
12
13
14
15
16 Gen-Chang Hsu^{1,†}, Wei-Jiun Lin^{2,†}, Chi-Heng Hsieh², Yue-Jia Lee³, Syuan-Jyun Sun^{4,*}
17
18
19
20
21
22

23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

7 ¹Department of Entomology, Cornell University, Ithaca, New York, USA

8 ²Institute of Ecology and Evolutionary Biology, National Taiwan University, Taipei, Taiwan

9 ³Institute of Food Science and Technology, National Taiwan University, Taipei, Taiwan

10 ⁴International Degree Program in Climate Change and Sustainable Development, National
11 Taiwan University, Taipei, Taiwan

12
13 [†]These authors contributed equally to this study.

14 *Corresponding author: Syuan-Jyun Sun

15 Email: sjs243@ntu.edu.tw

16 Phone: +886-2-33664475

17 Address: International Degree Program in Climate Change and Sustainable Development,
18 National Taiwan University, Taipei, Taiwan

- 1
- 2
- 320 Email addresses
- 4
- 5
- 621 Gen-Chang Hsu: gh443@cornell.edu (ORCID: 0000-0002-6607-4382)
- 7
- 8
- 922 Wei-Jiun Lin: bnw16238@gmail.com
- 10
- 11
- 12
- 1323 Chi-Heng Hsieh: b06b01018@gmail.com
- 14
- 15
- 1624 Yue-Jia Lee: yuejiale7@ntu.edu.tw
- 17
- 18
- 1925 Syuan-Jyun Sun: sjs243@ntu.edu.tw (ORCID: 0000-0002-7859-9346)
- 20
- 21
- 2226
- 23
- 24
- 25
- 26
- 27
- 28
- 29
- 30
- 31
- 32
- 33
- 34
- 35
- 36
- 37
- 38
- 39
- 40
- 41
- 42
- 43
- 44
- 45
- 46
- 47
- 48
- 49
- 50
- 51
- 52
- 53
- 54
- 55
- 56
- 57
- 58
- 59
- 60

Abstract

Carcasses represent critical resources for many terrestrial organisms, including burying beetles, which rely on carcasses for survival and breeding. Carcass attributes can influence the reproduction of burying beetles, yet most studies on their breeding ecology have used laboratory-reared carcasses of limited sizes. We conducted breeding and feeding experiments using a wide size range of lab (laboratory mice) and wild carcasses (wild mammals, birds, and reptiles) to investigate how carcass size, source, and taxon affect various breeding outcomes (e.g., clutch size, brood size, and brood mass) of the burying beetle *Nicrophorus nepalensis*. Our results reveal a hump-shaped relationship between carcass size and breeding performance, with optimal breeding outcomes occurring on medium-sized carcasses. Furthermore, despite the variation in carcass tissue nutritional composition, breeding outcomes and larval growth did not differ between the two carcass sources or among the three wild carcass taxa. Finally, we found a larval quality-quantity trade-off across the range of carcasses examined, with carcass size shaping the larval life history traits. Overall, these results elucidate how carcass resources may influence the breeding performance of burying beetles. Importantly, our study provides solid evidence validating decades of research using lab carcasses to study the reproductive ecology of burying beetles.

Keywords

breeding performance, burying beetle, carcass, nutritional composition, offspring quality-quantity trade-off, resource use efficiency

1
2
3 48 **Introduction**
4

5
6 49 Carcasses represent a rich resource for a wide variety of terrestrial organisms, including
7
8 50 vertebrate scavengers, saprophagous invertebrates, and microbial decomposers [1-3]. These
9
10 51 carcass-feeding organisms facilitate the recycling of carcass nutrients and make the resource
11
12 52 available to other species [4]. For some species such as burying beetles (*Nicrophorus* spp.),
13
14 53 carcasses are particularly important because they serve as not only food resource but also
15
16 54 breeding sites where the offspring grow and develop under parental care [5]. Carcass attributes,
17
18 55 therefore, can strongly influence the reproduction of burying beetles.
19
20
21
22

23 56 Carcass size is a key factor for the reproductive success of burying beetles because it
24
25 57 determines the amount of resource available for breeding. Brood size and brood mass are
26
27 58 generally greater on larger (heavier) carcasses [5-9]. Moreover, parents can adjust their
28
29 59 reproductive investment based on carcass size [10]. For example, females lay more eggs on
30
31 60 larger carcasses within a certain carcass size range [11], and parents regulate the brood size via
32
33 61 filial cannibalism when carcass resource is limited [12]. However, despite the resource benefits,
34
35 62 large carcasses can be more difficult to utilize [9], and the energetic costs of processing carcass
36
37 63 tissue also increase with carcass size. Such cost-benefit trade-offs suggest that reproductive
38
39 64 performance might not necessarily be greater on larger carcasses, yet no study has empirically
40
41 65 examined whether there is an optimal carcass size for breeding.
42
43
44
45
46

47 66 Besides carcass size, the source of carcass can also influence the reproduction of
48
49 67 burying beetles. Carcasses in the wild come from animals feeding on diverse diets in various
50
51 68 environments. However, most breeding experiments use laboratory mice and chicks, which are
52
53 69 usually fed fixed diets and reared in a controlled environment. Consequently, lab and wild
54
55 70 carcasses may have considerably different body compositions as well as skin and gut
56
57 71 microbiomes [13], and these differences can alter larval survival and growth [1, 14]. Therefore,
58
59
60

experiments comparing the breeding outcomes of burying beetles on lab versus wild carcasses are essential for evaluating whether the results of past studies are representative of natural patterns. Furthermore, burying beetles have been documented to breed on carcasses from a variety of taxonomic groups [5, 15]. Different carcass taxa can vary in their tissue nutritional composition [16], which may influence larval growth and development [17]. However, it remains unknown how breeding outcomes and larval performance may vary among different groups of wild carcasses.

Studies have shown that brood size and larval mass of burying beetles are often negatively correlated with each other [6, 12, 18]. Such a trade-off between larval quality and quantity may vary with carcass size [8, 19] because resource quantity can shape the life history traits of organisms [20-22]. However, most studies on the offspring trade-off in burying beetles were conducted under a limited range of carcass sizes, and the results have been mixed because of the differential responses of brood size and larval mass to carcass size [8]. Moreover, carcass sources with different quality can influence larval performance and thereby alter the trade-off patterns, yet few studies have examined this [but see 23]. Therefore, examining breeding outcomes across a wide range of carcass sizes from different carcass sources (e.g., lab and wild carcasses) will help better understand how resource variation affects the offspring life history trade-off in burying beetles.

In this study, we aimed to understand how various carcass attributes (size, source, and taxon) influence the breeding outcomes, larval performance, and offspring quality-quantity trade-off in burying beetles. We conducted breeding experiments on the species *Nicrophorus nepalensis*, which has been shown to provide extensive parental care for offspring. First, we examined how breeding outcomes (clutch size, brood size, brood mass, etc.) and carcass use efficiency varied across a broad range of carcass size (weight was used as a proxy for size in this study) on lab (laboratory mice) and wild carcasses (wild mammals, birds, and reptiles).

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

97 We further focused on the wild carcasses and compared the larval breeding outcomes and
98 carcass use efficiency of *N. nepalensis* on the three wild carcass taxa. We expected that there
99 would be an optimal carcass size for breeding, and the breeding outcomes may differ between
100 lab and wild carcasses as well as among different wild carcass taxa. We next quantified the
101 tissue nutritional composition of lab and wild carcasses and conducted a larval feeding
102 experiment using carcass tissues from different sources and taxa. We expected that the larvae
103 would perform better when feeding on diets with higher nutritional quality. Finally, we
104 examined the larval quality-quantity trade-off on lab and wild carcasses. We expected a trade-
105 off across a broad range of carcass sizes, and the trade-off pattern would differ between lab and
106 wild carcasses.
107

108 **Materials and Methods**

109 *Breeding experiments*

110 We conducted breeding experiments on *N. nepalensis* from the lab colony established in 2023.
111 Adult beetles were collected from Taipei and New Taipei City, Taiwan and reared in growth
112 chambers under a relative humidity of 70% and a 10:14 h light:dark cycle. The temperature
113 was set to mimic diurnal temperature fluctuation (mean: 17.8°C; range: 16–20°C). This
114 represents the natural temperature conditions during the breeding season (November–April) of
115 *N. nepalensis* in northern Taiwan. A male and a female were placed in a plastic breeding
116 container (14.2 cm in diameter and 6.3 cm in height) half-filled with moist commercial potting
117 mix (2 cm in depth, equivalent to 300 mL), and a defrosted carcass was then placed on the soil
118 surface. Frozen dead laboratory mice/rats were used as lab carcasses. Wild carcasses were
119 obtained from the Taiwan Roadkill Observation Network (<https://roadkill.tw/eng/home>) and
120 the Wild Bird Society of Taipei. These wild carcasses weighed from 1.6 to 99.5 grams and
121 consisted of small mammals, birds, and reptiles. The carcasses used for breeding experiments
122 were animals that had died within the past four months due to traffic collisions and other
123 accidental causes but not poisoning. Upon discovery, these carcasses were immediately
124 transferred to –20°C freezers for preservation. We paired each wild carcass with a lab carcass
125 of a similar weight (measured to the nearest 0.1 g using an electronic analytical balance
126 ATX224R, Shimadzu, Japan) and applied a sibship design where the two males and the two
127 females used in each lab-wild carcass were from the same family line, respectively, to control
128 for parental genotypes (the males and females came from genetically unrelated families). The
129 breeding containers were maintained under the same environmental conditions as those of the
130 lab colony. Five rounds of breeding experiments were conducted from May 2023 to March
131 2024 (each with a different beetle parent generation), consisting of a total of 121 lab-wild
132 carcass pairs (14, 76, and 31 wild mammal, bird, and reptile carcasses).

1
2
3 133 We recorded the clutch size of each breeding container at day 4 by counting the number
4
5 134 of eggs around the wall and at the bottom of the container from the outside. This minimized
6
7
8 135 the disturbance to the carcass and parents while providing an accurate estimate of the exact
9
10 136 clutch size ($r = 0.94$, $P < 0.001$, $n = 70$ broods) [24]. Eleven days after beetle pairing, we
11
12 137 inspected the carcass to record the brood size (number of larvae) and brood mass (total larval
13
14 138 weight; measured to the nearest 0.0001 g). We calculated hatching success as brood size
15
16 139 divided by clutch size, average larval mass as brood mass divided by brood size, and larval
17
18 140 density as brood size divided by carcass weight. We also measured the total weight of breeding
19
20 141 containers at the beginning and at the end of the experiments to estimate the amount of carcass
21
22 142 tissue used by parents and larvae during the breeding process (larvae were removed from the
23
24 143 carcasses). Carcass use efficiency was calculated as the amount of carcass tissue used divided
25
26 144 by the initial carcass weight.
27
28
29
30
31 145
32
33
34
35 146 *Nutritional analysis of carcass tissue*
36
37
38 147 To quantify the nutritional composition of lab and wild carcasses, which is essential for
39
40 148 understanding how burying beetles use different types of carcasses, we estimated the protein
41
42 149 and fat content of carcass tissue by adopting a proximate analysis approach as described by Al
43
44 150 Shareefi and Cotter [25]. We dissected the carcasses by first skinning the animals and retaining
45
46 151 the trunks. Trunk tissue was then separated from the bones with a pair of fine tweezers and a
47
48 152 scalpel and divided into viscera (all organs inside the peritoneum) and muscles (all visible
49
50 153 muscle parts). We next used a meat tenderizer to pound the viscera and muscles evenly and
51
52 154 sampled three pieces of visceral and muscle tissue for each carcass for the analysis of
53
54 155 nutritional composition. A total of seven lab mice, seven wild mammals, seven wild birds, and
55
56 156 seven wild reptiles were dissected and analyzed.
57
58
59
60

For each tissue sample, we dried approximately 100 mg (106 ± 18 mg) of wet tissue in a 40°C oven for 5 days until all water was removed. To determine the fat content, the dried tissue was thoroughly mixed with 100 µl of -20°C acetone and vortexed for one minute. The mixture was then placed in a -20°C fridge for a 30-minute reaction period [26]. After the extraction, the mixture was centrifuged to separate the components, and the acetone was carefully removed. If the acetone appeared turbid after centrifugation, the solvent was discarded and replaced with fresh acetone for further extraction. The process was repeated until the solvent became clear. The residual solvent was then allowed to evaporate at room temperature for 12 hours. After the fat removal process, the final product was weighed to determine the protein content, and the fat content was determined by subtracting the protein weight from the dry weight.

Larval feeding experiments

We conducted larval feeding experiments using the remaining dissected carcass tissue from the nutritional composition analysis. We placed *ca.* 400 mg (401 ± 21 mg) of carcass tissue into individual plastic containers filled with moist commercial potting mix (soil volume $3.2 \times 3.2 \times 2.7$ cm). Newly hatched larvae (five days after female oviposition) were obtained from pairs of breeding beetles (25 families) from the lab colony and one larva was introduced to each container ($n = 188$). After five days of feeding, the larval mass at dispersal was recorded and larval growth was measured as the larval weight gain during the experimental period.

Data analyses

1. Breeding outcomes and carcass use efficiency

1
2
3 180 To examine how clutch size, hatching success, brood size, brood mass, and carcass use
4
5 181 efficiency varied with carcass size on lab and wild carcasses, we fit generalized linear mixed
6
7 182 effects models (GLMMs) with each of the aforementioned breeding outcomes as the response,
8
9
10 183 carcass weight and carcass source as well as their interaction as the fixed effects, and lab-wild
11
12 184 carcass pair as the random effect. The pronotum widths of the parents and parent generation
13
14
15 185 were included as the covariates in the models. For clutch size and brood size, we used a
16
17 186 negative binomial error distribution with a log link function for model fitting to account for
18
19 187 data overdispersion; for hatching success, we used a binomial error distribution with a logit
20
21 188 link function; for brood mass, we used a Gaussian error distribution; for carcass use efficiency,
22
23
24 189 we used a beta error distribution with a logit link function. Because clutch size and brood size
25
26 190 contained many zero values, we additionally included a zero inflation structure in the models.
27
28 191 We determined whether a quadratic curve better described the relationship between each
29
30 192 response and carcass weight by comparing the GLMMs fitted with and without a quadratic
31
32 193 term for carcass weight via the likelihood ratio test. Results from the quadratic model were
33
34 194 reported if the test was significant ($\alpha = 0.05$).
35
36
37

38
39 195 To compare the brood size, brood mass, average larval mass, and carcass use efficiency
40
41 196 on wild mammal, bird, and reptile carcasses, we fit generalized linear models (GLMs) with
42
43 197 each of the aforementioned breeding outcomes as the response and wild carcass taxon as the
44
45 198 fixed effect. Carcass weight, pronotum widths of the parents, and parent generation were
46
47 199 included as the covariates in the models. The error distribution and link function for each of
48
49
50 200 the responses were the same as the GLMMs. Because the carcass range was considerably
51
52 201 smaller for reptiles (1.6–64.4 g) than for mammals (3.8–94.8 g) and birds (3.2–99.5 g), we
53
54 202 restricted the carcass weight range to that of reptiles (≤ 64.4 g) so that the results were more
55
56 203 comparable among the three wild taxa.
57
58
59
60

2. Nutritional composition and larval growth

To compare the nutritional composition between the two carcass sources and the three wild carcass taxa, we fit GLMMs with the proportion of protein/fat as the responses, carcass source/taxon and tissue type (viscera vs. muscles) as the fix effects, and carcass ID as the random effect (a total of four GLMMs). We used a beta error distribution with a logit link function for model fitting in the GLMMs.

To compare the larval growth between the two carcass sources and the three wild carcass taxa, we fit GLMMs with larval weight gain as the response, carcass source/taxon and tissue type as the fix effects, and carcass ID and larval family as the random effects (a total of two GLMMs). Larval mass at hatching was included in the models as a covariate. We used a Gaussian error distribution for model fitting in the GLMMs. To further investigate the effect of nutrient content on larval growth on both carcass sources and on wild carcasses only, we fit GLMMs with larval weight gain as the response, proportion of protein, proportion of fat, and tissue type as the fixed effects, and larval family as the random effects (a total of two GLMMs). Larval mass at hatching was included as a covariate. Dead larvae were excluded from the analysis.

3. Larval quality-quantity trade-off

To evaluate the trade-off between offspring quality and quantity on lab and wild carcasses, we fit a linear model with average larval mass as the response and larval density, carcass source, and their interaction as the predictors. A significant negative slope indicates a larval quality-quantity trade-off.

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

228 We fit all aforementioned models using the glmmTMB() function in the R “glmmTMB”
229 package [27]. Model assumptions were checked via the quantile residuals generated from the
230 simulateResiduals() function in the R “DHARMa” package [28]. Predictor significance was
231 assessed with the Wald chi-square test via the Anova() function (type II sums of squares) in
232 the R “car” package [29]. Post-hoc pairwise comparisons among carcass taxa with the Tukey
233 multiplicity adjustment were conducted via the emmeans() function in the R “emmeans”
234 package [30]. All analyses were performed in R version 4.3.3 [31].

Results

Breeding outcomes and carcass use efficiency

Clutch size, hatching success, brood size, and brood mass all showed a quadratic relationship with carcass weight (clutch size: $\chi^2_2 = 44.6$, $P < 0.001$; hatching success: $\chi^2_2 = 32.1$, $P < 0.001$; brood size: $\chi^2_2 = 63.3$, $P < 0.001$; brood mass: $\chi^2_2 = 91.9$, $P < 0.001$; Table 1) and peaked on medium-sized carcasses (Fig. 1). Moreover, these breeding outcomes did not differ between lab and wild carcasses (clutch size: $\chi^2_1 = 1.4$, $P = 0.39$; hatching success: $\chi^2_1 = 0.8$, $P = 0.37$; brood size: $\chi^2_1 = 0.009$, $P = 0.93$; brood mass: $\chi^2_1 = 0.001$, $P = 0.99$; Table 1; Fig. 1). Carcass use efficiency decreased with carcass weight ($\chi^2_2 = 64.5$, $P < 0.001$) but did not differ between lab and wild carcasses ($\chi^2_1 = 0.003$, $P = 0.96$; Table 1; Fig. 2).

Brood size, brood mass, average larval mass, and carcass use efficiency did not differ among wild mammal, bird, and reptile carcasses (brood size: $\chi^2_2 = 0.6$, $P = 0.75$; brood mass: $\chi^2_2 = 3.6$, $P = 0.17$; average larval mass: $\chi^2_2 = 3.3$, $P = 0.19$; carcass use efficiency: $\chi^2_2 = 0.4$, $P = 0.81$; Fig. 3).

249

Nutritional composition of carcasses

Protein content was similar between lab and wild carcasses (mean proportion: lab = 25.5%, wild = 27.9%; $\chi^2_1 = 3.5$, $P = 0.06$; Fig. 4a) but differed among wild carcass taxa (mean proportion: mammal = 28.7%, bird = 30.6%, reptile = 24.3%; $\chi^2_2 = 26.6$, $P < 0.001$; Fig. 4b). Specifically, reptile carcasses had significantly lower protein content than mammal and bird carcasses (Fig. 4b). Fat content was similar between lab and wild carcasses (mean proportion: lab = 4.0%, wild = 3.7%; $\chi^2_1 = 1.1$, $P = 0.29$; Fig. 4c) and among wild carcass taxa (mean proportion: mammal = 4.4%, bird = 4.4%, reptile = 2.1%; $\chi^2_2 = 3.5$, $P = 0.18$; Fig. 4d).

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

258

259

260
261
262
263
264
265
266
267

268

269

270
271
272
273

274

Larval growth

Growth was similar for larvae feeding on tissue from lab and wild carcasses ($\chi^2_1 = 0.1$, $P = 0.74$; Fig. 4e). Similarly, larval growth did not differ significantly among the three wild carcass taxa ($\chi^2_2 = 5.2$, $P = 0.07$; Fig. 4f), although larvae feeding on wild bird carcasses tended to gain more weight compared to those feeding on wild mammals and reptiles (Fig. 4f). When lab and wild carcasses were combined, larval growth was not associated with either tissue protein content ($\chi^2_1 = 0.9$, $P = 0.34$) or fat content ($\chi^2_1 = 0.05$, $P = 0.83$) (Fig. S2a and b). On the other hand, larvae feeding on wild carcass tissue with higher fat content ($\chi^2_1 = 5.2$, $P = 0.02$), but not protein content ($\chi^2_1 = 0.01$, $P = 0.92$), did grow better (Fig. S2c and d).

Larval quality-quantity trade-off

Average larval mass decreased with larval density on both lab and wild carcasses ($\beta = -0.096$, $\chi^2_1 = 74.7$, $P < 0.001$; Fig. 5). The interaction between larval density and carcass source was not significant ($\chi^2_1 = 1.2$, $P = 0.28$), indicating that the trade-off did not differ between lab and wild carcasses (Fig. 5).

Discussion

We examined how breeding outcomes and carcass use efficiency of the burying beetle *N. nepalensis* varied with carcass size on lab and wild carcasses. Clutch size, hatching success, brood size, and brood mass all exhibited a quadratic relationship with carcass size, whereas carcass use efficiency decreased with carcass size. Furthermore, these breeding outcomes and carcass use efficiency did not differ between lab and wild carcasses. Despite the variation in tissue nutritional composition (protein content) among wild mammal, bird, and reptile carcasses, larval traits (brood size, brood mass, and average larval mass), carcass use efficiency, and larval growth did not differ among the three wild carcass taxa. Finally, a negative relationship existed between larval density and average larval mass on both lab and wild carcasses, suggesting a trade-off between offspring quality and quantity. Taken together, our results indicate that carcass size, but not carcass source or carcass taxon, is the main determinant for the breeding performance and carcass resource use of burying beetles.

As expected, clutch size, hatching success, brood size, and brood mass all showed a quadratic relationship with carcass size, with optimal breeding outcomes occurring on medium-sized carcasses. The increase in breeding performance from small to medium carcasses is consistent with previous studies on other burying beetle species [6, 10, 32]. Interestingly, when the parents bred on large carcasses, their breeding performance decreased, along with a reduction in carcass use efficiency. This may be because large carcasses are more energetically costly to process and females may lay fewer eggs as a result of lower energy storage. In fact, Müller, Eggert [11] found that clutch size levels off beyond a certain carcass weight threshold, suggesting an energetic or physiological constraint on beetles breeding on larger carcasses. Parents breeding on large carcasses also face stronger competition with microbes, which can reduce the usable resource for breeding [5] or produce compounds harmful to eggs and larvae [1].

1
2
3 300 Contrary to our prediction, we found no major difference in the breeding outcomes and
4
5 301 carcass use efficiency of *N. nepalensis* on lab versus wild carcasses. A potential explanation is
6
7
8 302 that the parents manipulated the carcasses (e.g., by secreting antimicrobial compounds) such
9
10 303 that the eggs and larvae experienced similar growing environments regardless of carcass source.
11
12 304 Studies have shown that parental care is crucial for larval performance in burying beetles [1,
13
14 305 33], and we speculate that parental food preparation and regurgitation may offset the difference
15
16
17 306 between the two carcass sources. Further experiments comparing breeding outcomes on lab
18
19 307 and wild carcasses with versus without parents will help verify our speculation. The analyses
20
21 308 did reveal an interaction between carcass size and carcass source for brood mass. In fact, the
22
23 309 patterns were mostly similar between lab and wild carcasses on small and medium carcasses,
24
25
26 310 whereas the difference on large carcasses was mainly driven by two observations on large wild
27
28 311 carcasses (the interaction became non-significant when these two observations were removed;
29
30 312 $P = 0.38$, Fig. S3). Overall, our results support the validity of research using lab-reared
31
32
33 313 organisms as breeding carcasses to study the reproductive biology of burying beetles.

34
35
36 314 Our tissue nutritional analysis showed that protein content was higher in wild mammal
37
38 315 and bird carcasses than in wild reptile carcasses, whereas fat content was similar among these
39
40
41 316 taxa. Yet, despite the variation in tissue protein content, larval growth in the feeding
42
43 317 experiments did not vary significantly among the wild carcass taxa. In fact, we found that it
44
45 318 was fat content, not protein content, that affected larval growth on wild carcasses. Since fat
46
47 319 content did not vary among the three wild carcass taxa, we did not observe major difference in
48
49
50 320 larval growth. This may also partially explain why larval traits and carcass use efficiency were
51
52 321 similar among the three wild carcass taxa in our breeding experiments. Interestingly, larvae did
53
54 322 tend to grow better on bird carcasses in the feeding experiments without parents. This suggests
55
56
57 323 that parental care in burying beetles (e.g., carcass preparation and food provisioning) may help
58
59
60

324 maintain breeding performance on a variety of carcasses in the wild. But without parental care,
325 carcass taxon may potentially influence individual larval performance.

326 The negative relationship between average larval mass and larval density on both lab
327 and wild carcasses indicates a trade-off between offspring quality and quantity regardless of
328 carcass source. Similar trade-off patterns have been shown in previous studies [19, 34] and can
329 arise from both larval competition and brood regulation by parents [34]. Stronger interspecific
330 competition under a higher larval density may reduce individual larval growth, leading to lower
331 average larval mass. On the other hand, parents may regulate brood size by culling excess
332 larvae to reduce larval competition [35], thereby leading to greater larval growth and higher
333 average biomass. Furthermore, the slope of the negative relationship between average larval
334 mass and larval density did not depend on carcass source, agreeing with our findings that brood
335 size and brood mass did not differ between lab and wild carcasses. Interestingly, we found that
336 the average larval mass increased with carcass size for small and medium carcasses, whereas
337 larval density decreased (Fig. S1). This suggests that the larval life history traits of burying
338 beetles can shift depending on breeding resource availability, with smaller carcasses favoring
339 larval quantity (per capita carcass resource) and larger carcasses favoring larval quality.

340 Our results illustrate the role of carcass size in the breeding outcomes of a single parent
341 pair. This is the most common breeding system in burying beetles on small- and medium-sized
342 carcasses [5]. However, multiple males and females may engage in cooperative breeding to
343 better utilize large carcasses in the wild [36], although past results for the reproductive benefits
344 of cooperation are mixed [37-39]. Additionally, burying beetles in nature may face carcass
345 competition not only from microbes but also from various vertebrate scavengers and
346 invertebrate carcass feeders [40, 41], and such interspecific competition can interact with
347 carcass size to influence breeding success [42]. Field experiments using a wide range of carcass
348 sizes will help elucidate how intraspecific and interspecific interactions as well as the interplay

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

349 between biotic interactions and carcass size jointly shape the breeding performance of burying
350 beetles.

351 Using a broad range of carcass sizes from both lab and wild sources, our study revealed
352 for the first time the quadratic relationship between breeding performance and carcass size in
353 burying beetle, with optimal breeding outcomes occurring on medium-sized carcasses.
354 Breeding outcomes did not differ between lab and wild carcasses. Furthermore, despite the
355 variation in tissue nutritional composition (particularly protein content) among wild mammal,
356 bird, and reptile carcasses, larval traits, carcass use efficiency, and larval growth were generally
357 similar among these wild carcass taxa. Finally, the larval quality-quantity trade-off existed
358 across the range of lab and wild carcass sizes, and larval life history traits may shift depending
359 on carcass size, with smaller carcasses favoring larval quantity and larger carcasses favoring
360 larval quality. Taken together, our study confirms that previous results from lab carcasses are
361 fairly representative of natural patterns and provides a more complete picture of how carcass
362 resources shape the breeding performance of burying beetles.

363
Acknowledgements

365 We thank Mu-Tzu Tsai and Yi-Ta Wu for assisting with field sampling and laboratory
366 experimental setup. We thank Te-En Lin and Yu-Kai Chen from the Taiwan Roadkill
367 Observation Network, the Wild Bird Society of Taipei, and Yun Ho for providing wild
368 carcasses. Last but not least, we extend our gratitude to the beetles as well as the lab and wild
369 animals used in this study. This work was supported by National Taiwan University New
370 Faculty Founding Research Grant, National Science and Technology Council 2030 Cross-
371 Generation Young Scholars Program (111-2628-B-002-050-; 112-2628-B-002-013-), and

372 Yushan Fellow Program (112V1024-2) provided by the Ministry of Education, Taiwan
373 (R.O.C.).

374

375 **Conflict of interest**

376 The authors declare no conflict of interest regarding this manuscript.

377

378 **Author contributions**

379 Gen-Chang Hsu and Syuan-Jyun Sun conceived the ideas; Gen-Chang Hsu, Wei-Jiun Lin, Yue-
380 Jia Lee, and Syuan-Jyun Sun designed the experiments; Gen-Chang Hsu, Wei-Jiun Lin, Chi-
381 Heng Hsieh, Yue-Jia Lee, and Syuan-Jyun Sun collected the data; Gen-Chang Hsu and Syuan-
382 Jyun Sun analyzed the data; Gen-Chang Hsu and Syuan-Jyun Sun wrote the first draft of the
383 manuscript; all authors revised the manuscript and approved the final version for publication.

384

385 **Data accessibility**

386 Data and code used in this manuscript are publicly available on Zenodo (DOI:
387 <https://doi.org/10.5281/zenodo.12747445>).

388

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

References

[1] Rozen, D., Engelmoer, D. & Smiseth, P.T. 2008 Antimicrobial strategies in burying beetles breeding on carrion. *Proceedings of the National Academy of Sciences* **105**, 17890-17895.

[2] Stiegler, J., Von Hoermann, C., Müller, J., Benbow, M.E. & Heurich, M. 2020 Carcass provisioning for scavenger conservation in a temperate forest ecosystem. *Ecosphere* **11**, e03063.

[3] Barton, P.S., Cunningham, S.A., Lindenmayer, D.B. & Manning, A.D. 2013 The role of carrion in maintaining biodiversity and ecological processes in terrestrial ecosystems. *Oecologia* **171**, 761-772.

[4] Tomberlin, J.K., Barton, B.T., Lashley, M.A. & Jordan, H.R. 2017 Mass mortality events and the role of necrophagous invertebrates. *Current Opinion in Insect Science* **23**, 7-12.

[5] Scott, M.P. 1998 The ecology and behavior of burying beetles. *Annual Review of Entomology* **43**, 595-618.

[6] Creighton, J.C. 2005 Population density, body size, and phenotypic plasticity of brood size in a burying beetle. *Behavioral Ecology* **16**, 1031-1036.

[7] Scott, M.P. & Traniello, J.F. 1990 Behavioural and ecological correlates of male and female parental care and reproductive success in burying beetles (*Nicrophorus* spp.). *Animal Behaviour* **39**, 274-283.

[8] Smiseth, P.T., Andrews, C.P., Matthey, S.N. & Mooney, R. 2014 Phenotypic variation in resource acquisition influences trade-off between number and mass of offspring in a burying beetle. *Journal of Zoology* **293**, 80-83.

[9] Trumbo, S.T. 1992 Monogamy to communal breeding: exploitation of a broad resource base by burying beetles (*Nicrophorus*). *Ecological Entomology* **17**, 289-298.

[10] Hopwood, P.E., Moore, A.J., Tregenza, T. & Royle, N.J. 2016 Niche variation and the maintenance of variation in body size in a burying beetle. *Ecological Entomology* **41**, 96-104.

- 414 [11] Müller, J.K., Eggert, A.-K. & Furlkröger, E. 1990 Clutch size regulation in the burying
415 beetle *Necrophorus vespilloides* Herbst (Coleoptera: Silphidae). *Journal of Insect Behavior* **3**,
416 265–270.
- 417 [12] Bartlett, J. 1987 Filial cannibalism in burying beetles. *Behavioral Ecology and*
418 *Sociobiology* **21**, 179-183.
- 419 [13] Weldon, L., Abolins, S., Lenzi, L., Bourne, C., Riley, E.M. & Viney, M. 2015 The gut
420 microbiota of wild mice. *PLoS One* **10**, e0134643.
- 421 [14] Shukla, S.P., Plata, C., Reichelt, M., Steiger, S., Heckel, D.G., Kaltenpoth, M., Vilcinskas,
422 A. & Vogel, H. 2018 Microbiome-assisted carrion preservation aids larval development in a
423 burying beetle. *Proceedings of the National Academy of Sciences* **115**, 11274-11279.
- 424 [15] Hocking, M., Ring, R. & Reimchen, T. 2006 Burying beetle *Nicrophorus investigator*
425 reproduction on Pacific salmon carcasses. *Ecological Entomology* **31**, 5-12.
- 426 [16] May, E.M. & El-Sabaawi, R.W. 2022 Life stage and taxonomy the most important factors
427 determining vertebrate stoichiometry: A meta-analysis. *Ecology and Evolution* **12**, e9354.
- 428 [17] Scriber, J. & Slansky Jr, F. 1981 The nutritional ecology of immature insects. *Annual*
429 *Review of Entomology* **26**, 183-211.
- 430 [18] Monteith, K.M., Andrews, C. & Smiseth, P.T. 2012 Post-hatching parental care masks the
431 effects of egg size on offspring fitness: a removal experiment on burying beetles. *Journal of*
432 *Evolutionary Biology* **25**, 1815-1822.
- 433 [19] Bartlett, J. & Ashworth, C. 1988 Brood size and fitness in *Nicrophorus vespilloides*
434 (Coleoptera: Silphidae). *Behavioral Ecology and Sociobiology* **22**, 429-434.
- 435 [20] Richardson, J. & Smiseth, P.T. 2020 Effects of variation in resource acquisition during
436 different stages of the life cycle on life-history traits and trade-offs in a burying beetle. *Journal*
437 *of Evolutionary Biology* **32**, 19-30.

1
2
3 438 [21] Tessier, A.J. & Consolatti, N.L. 1991 Resource quantity and offspring quality in *Daphnia*.
4
5 439 *Ecology* **72**, 468-478.
6
7
8 440 [22] Boggs, C.L. 2009 Understanding insect life histories and senescence through a resource
9
10 441 allocation lens. *Functional Ecology* **23**, 27-37.
11
12 442 [23] Woelber, B.K., Hall, C.L. & Howard, D.R. 2018 Environmental cues influence parental
13
14 443 brood structure decisions in the burying beetle *Nicrophorus marginatus*. *Journal of Ethology*
15
16 444 **36**, 55-64.
17
18
19 445 [24] Sun, S.-J., Catherall, A.M., Pascoal, S., Jarrett, B.J., Miller, S.E., Sheehan, M.J. & Kilner,
20
21 446 R.M. 2020 Rapid local adaptation linked with phenotypic plasticity. *Evolution Letters* **4**, 345-
22
23 447 359.
24
25
26 448 [25] Al Shareefi, E. & Cotter, S.C. 2018 The nutritional ecology of maturation in a carnivorous
27
28 449 insect. *Behavioral Ecology* **30**, 256-266. (doi:10.1093/beheco/ary142).
29
30
31 450 [26] Saini, R.K., Prasad, P., Shang, X. & Keum, Y.-S. 2021 Advances in lipid extraction
32
33 451 methods—a review. *International Journal of Molecular Sciences* **22**, 13643.
34
35
36 452 [27] Brooks, M.E., Kristensen, K., van Benthem, K.J., Magnusson, A., Berg, C.W., Nielsen,
37
38 453 A., Skaug, H.J., Maechler, M. & Bolker, B.M. 2017 glmmTMB Balances Speed and Flexibility
39
40 454 Among Packages for Zero-inflated Generalized Linear Mixed Modeling. *The R Journal* **9**, 378-
41
42 455 400. (doi:10.32614/RJ-2017-066).
43
44
45 456 [28] Hartig, F. 2022 DHARMa: Residual Diagnostics for Hierarchical (Multi-Level / Mixed)
46
47 457 Regression Models.
48
49 458 [29] Fox, J. & Weisberg, S. 2019 *An R Companion to Applied Regression*. Third ed. Thousand
50
51 459 Oaks CA, Sage.
52
53
54 460 [30] Lenth, R.V. 2024 emmeans: Estimated Marginal Means, aka Least-Squares Means. (
55
56 461 [31] R Core Team. 2024 R: A Language and Environment for Statistical Computing. (Vienna,
57
58 462 Austria.
59
60

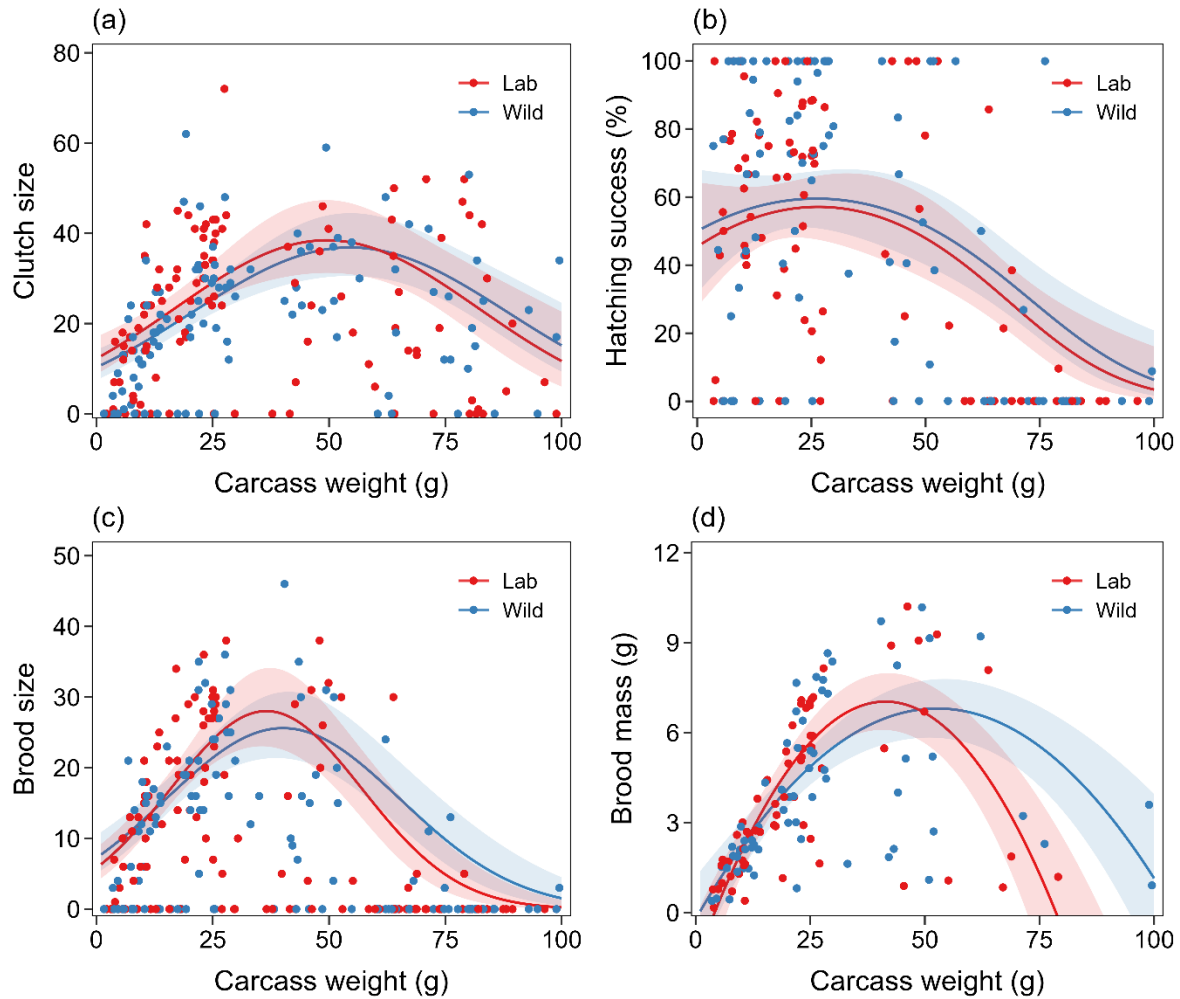
- [32] Eggert, A.-K. & Müller, J.K. 1992 Joint breeding in female burying beetles. *Behavioral Ecology and Sociobiology* **31**, 237-242.
- [33] Eggert, A.-K., Reinking, M. & Müller, J.K. 1998 Parental care improves offspring survival and growth in burying beetles. *Animal Behaviour* **55**, 97-107.
- [34] Trumbo, S.T. 1990 Regulation of brood size in a burying beetle, *Nicrophorus tomentosus* (Silphidae). *Journal of Insect Behavior* **3**, 491-500.
- [35] Trumbo, S.T. 2006 Infanticide, sexual selection and task specialization in a biparental burying beetle. *Animal Behaviour* **72**, 1159-1167.
- [36] Scott, M.P., LEE, W.J. & Van Der Reijden, E. 2007 The frequency and fitness consequences of communal breeding in a natural population of burying beetles: a test of reproductive skew. *Ecological Entomology* **32**, 651-661.
- [37] Müller, J.K., Braunisch, V., Hwang, W. & Eggert, A.-K. 2007 Alternative tactics and individual reproductive success in natural associations of the burying beetle, *Nicrophorus vespilloides*. *Behavioral Ecology* **18**, 196-203.
- [38] Eggert, A.K. & Sakaluk, S.K. 2000 Benefits of communal breeding in burying beetles: a field experiment. *Ecological Entomology* **25**, 262-266.
- [39] Komdeur, J., Schrama, M.J., Meijer, K., Moore, A.J. & Beukeboom, L.W. 2013 Cobreeding in the burying beetle, *Nicrophorus vespilloides*: tolerance rather than cooperation. *Ethology* **119**, 1138-1148.
- [40] DeVault, T.L., Rhodes, J., Olin E & Shivik, J.A. 2003 Scavenging by vertebrates: behavioral, ecological, and evolutionary perspectives on an important energy transfer pathway in terrestrial ecosystems. *Oikos* **102**, 225-234.
- [41] Chen, B.F., Liu, M., Rubenstein, D.R., Sun, S.J., Liu, J.N., Lin, Y.H. & Shen, S.F. 2020 A chemically triggered transition from conflict to cooperation in burying beetles. *Ecology Letters* **23**, 467-475.

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

488 [42] Scott, M.P. 1994 Competition with flies promotes communal breeding in the burying
489 beetle, *Nicrophorus tomentosus*. *Behavioral Ecology and Sociobiology* **34**, 367-373.
490

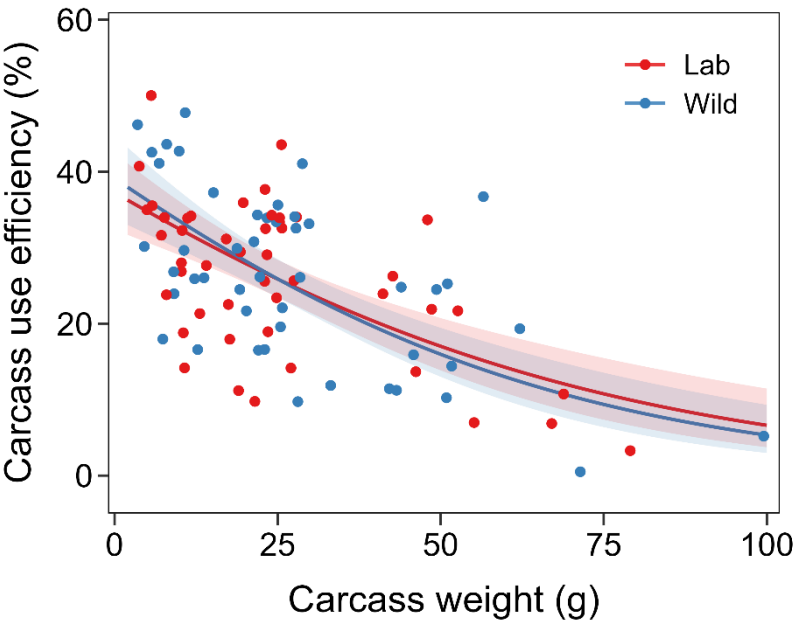
Figures

Figure 1



1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

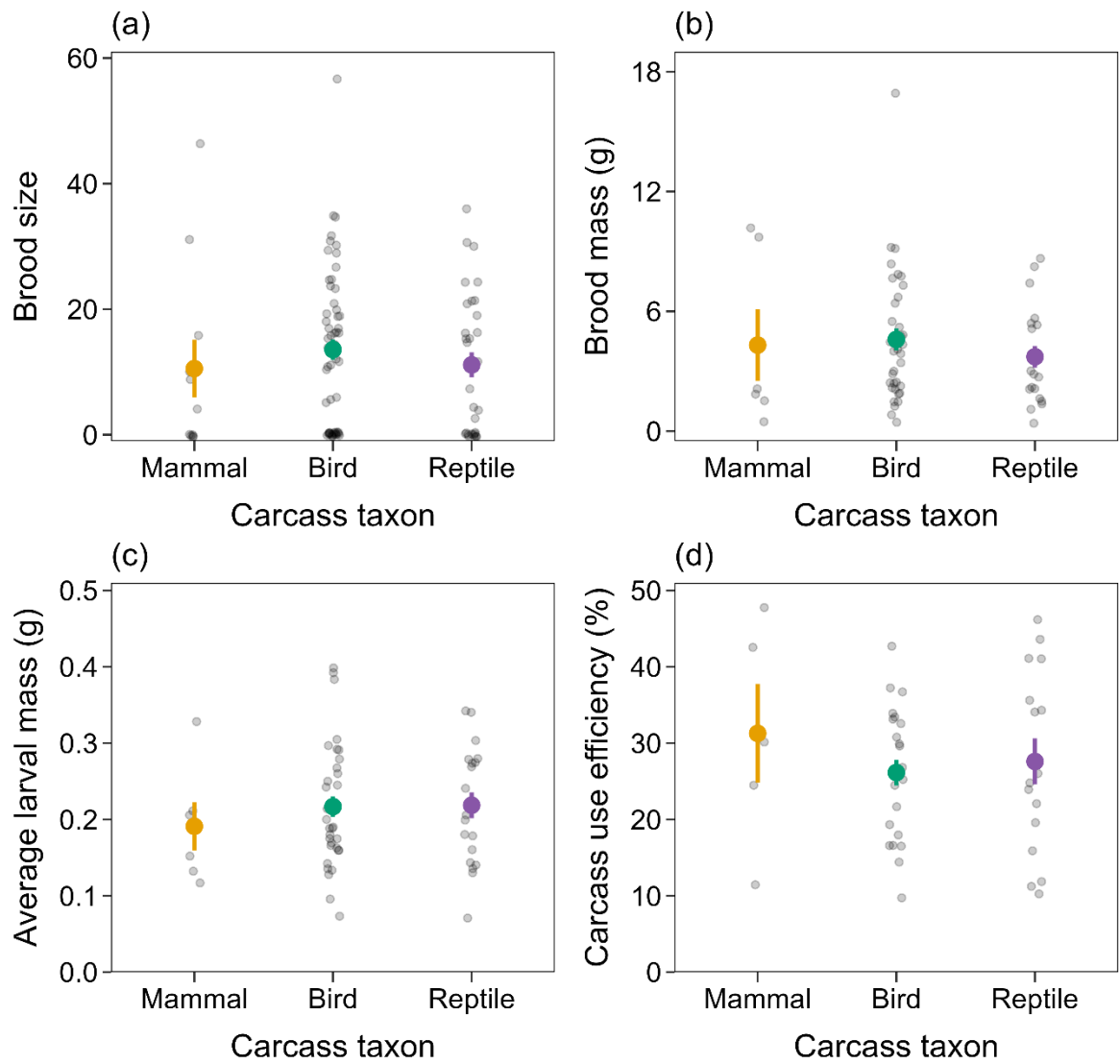
495 Figure 2



496

497

Figure 3



1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

Figure 4

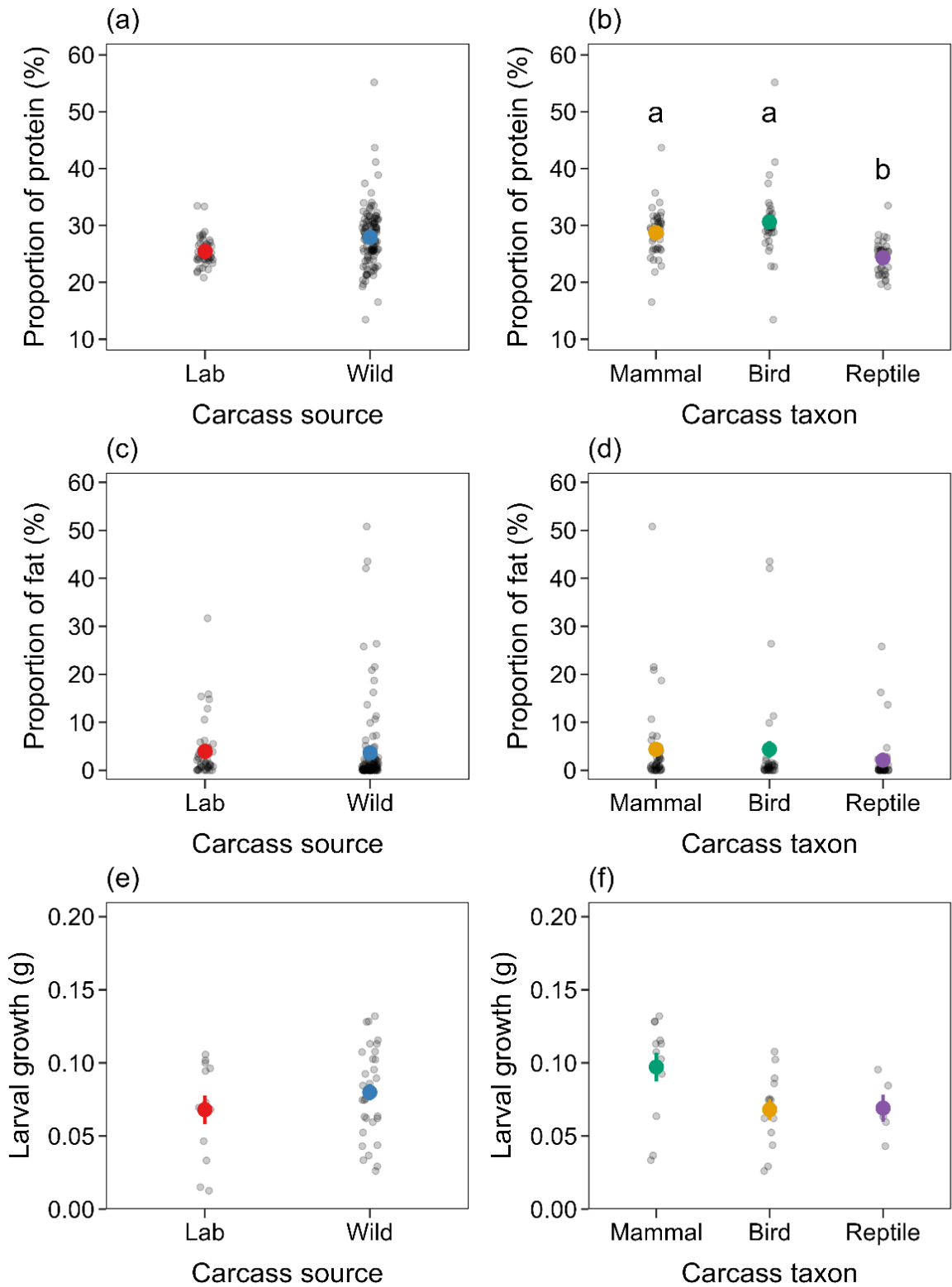
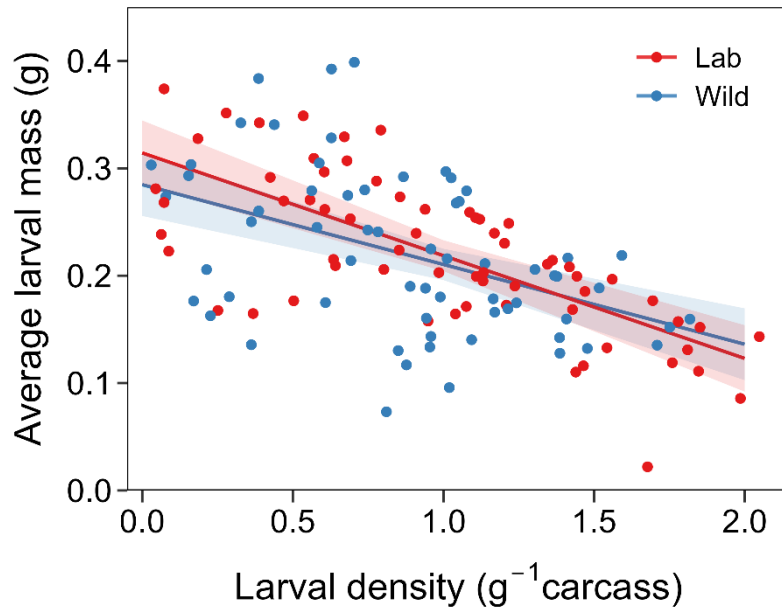


Figure 5



1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

Figure legends

Figure 1. The relationship between carcass weight and clutch size (a), hatching success (b), brood size (c), and brood mass (d) on lab and wild carcasses. Note that the observations without any larva were excluded from the brood mass analysis. Lines represent the statistically significant relationships predicted from GLMMs ($\alpha = 0.05$); shaded areas represent the 95% confidence intervals.

Figure 2. The relationship between carcass weight and carcass use efficiency on lab and wild carcasses. Note that the observations without any larva were excluded from the analysis. Lines represent the statistically significant relationships predicted from GLMMs ($\alpha = 0.05$); shaded areas represent the 95% confidence intervals.

Figure 3. Brood size (a), brood mass (b), average larval mass (c), and carcass use efficiency (d) on wild mammal, bird, and reptile carcasses. Points represent the means and error bars represent the standard errors. Note that the observations without any larva were excluded from the brood mass analysis.

Figure 4. Tissue protein and fat content (a–d) and larval growth (e and f) on lab and wild carcasses as well as on wild mammal, bird, and reptile carcasses. Points represent the means and error bars represent the standard errors. Letters denote significant difference with Tukey multiplicity adjustment ($\alpha = 0.05$).

Figure 5. The relationship between larval density and average larval mass on lab and wild carcasses. Lines represent the statistically significant relationships predicted from GLMMs ($\alpha = 0.05$); shaded areas represent the 95% confidence intervals.

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

Tables

Table 1. A summary of the GLMM results for the breeding outcomes and carcass use efficiency of *Nicrophorus nepalensis*. The pronotum widths of the parents and parent generation were included as the covariates in all models.

Model response	<i>n</i>	Predictor		
		Carcass weight	Carcass source	Weight × Source
Clutch size	210*	$\chi^2_2 = 44.6$, $P < 0.001$	$\chi^2_1 = 1.4$, $P = 0.39$	$\chi^2_2 = 1.9$, $P = 0.24$
Hatching success	176 [†]	$\chi^2_2 = 32.1$, $P < 0.001$	$\chi^2_1 = 0.8$, $P = 0.37$	$\chi^2_2 = 0.3$, $P = 0.88$
Brood size	238	$\chi^2_2 = 63.3$, $P < 0.001$	$\chi^2_1 = 0.009$, $P = 0.93$	$\chi^2_2 = 3.5$, $P = 0.17$
Brood mass	129 [‡]	$\chi^2_2 = 91.9$, $P < 0.001$	$\chi^2_1 = 0.001$, $P = 0.99$	$\chi^2_2 = 11.0$, $P = 0.004$
Carcass use efficiency	95 [§]	$\chi^2_1 = 64.5$, $P < 0.001$	$\chi^2_1 = 0.003$, $P = 0.96$	$\chi^2_1 = 0.3$, $P = 0.57$

*Clutch size was not recorded in the first round of breeding experiments.

[†]Observations with a zero clutch size were excluded from the analysis.

[‡]Observations with a zero brood size were excluded from the analysis.

[§]Carcass use was not measured in the first and second round of the breeding experiments; observations with a zero brood size were excluded from the analysis.

Supplementary Materials

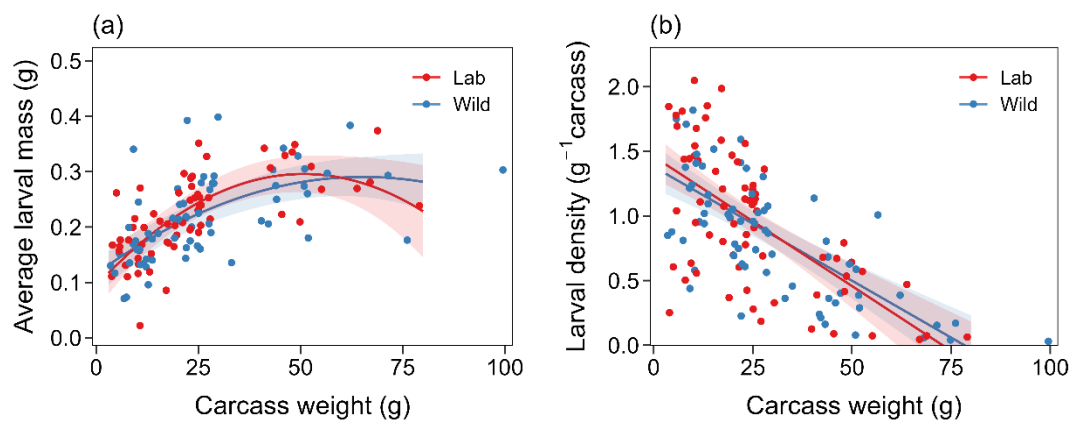


Figure S1. The relationship between carcass weight and average larval mass (a) and larval density (b) on lab and wild carcasses. Lines represent the statistically significant relationships predicted from GLMMs ($\alpha = 0.05$); shaded areas represent the 95% confidence intervals.

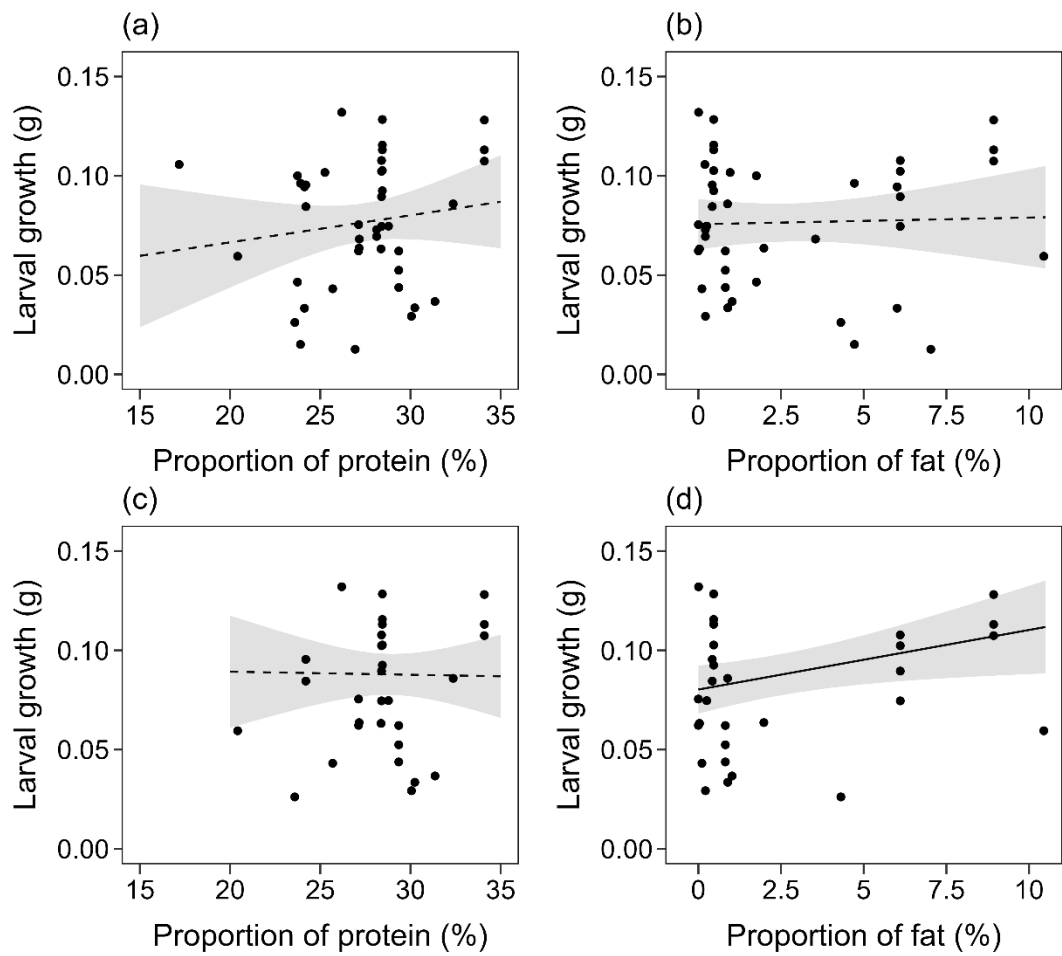


Figure S2. The relationship between tissue nutrient content and larval growth. Panel (a) and (b) include observations from both lab and wild carcasses; panel (c) and (d) include only observations from wild carcasses. Solid and dashed lines represent the significant and non-significant relationships predicted from GLMMs, respectively ($\alpha = 0.05$); shaded areas represent the 95% confidence intervals.

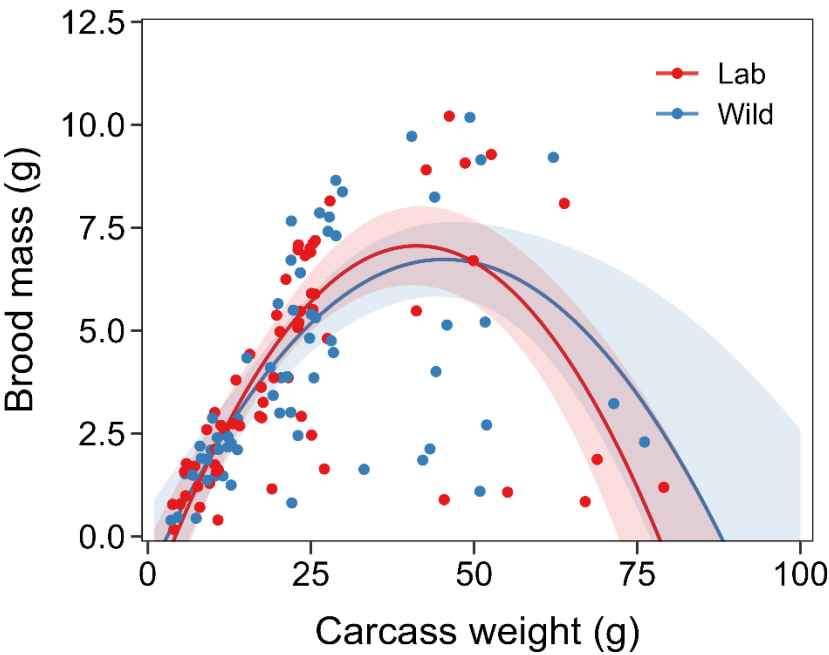


Figure S3. The relationship between carcass weight and brood mass on lab and wild carcasses with two observations on large wild carcasses removed. Lines represent the statistically significant relationships predicted from GLMMs ($\alpha = 0.05$); shaded areas represent the 95% confidence intervals.