# Energetic shifts predict the mortality of *Anopheles gambiae*

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## Abstract

Life history theory predicts that resource allocation adapts to ecological and evolutionary pressures. We investigated resource and energy dynamics in the malaria vector *Anopheles gambiae* after exposure to two stressors: blood meals and infection by the microsporidian *Vavraia culicis*. Our findings reveal the costs of blood feeding and parasitism on longevity, highlighting trade-offs in lifetime protein, carbohydrate, and lipid reserves. Notably, shifts in carbohydrate-to-lipid ratios predict survival likelihood, with survivors exhibiting higher resource reserves and uniquely transitioning from carbohydrate to lipid utilisation, a pattern absent in non-survivors. Through the integration of these results into ecological and epidemiological contexts, we discuss evolutionary constraints on reproduction and how *Plasmodium* adapts to host resource availability. This study emphasises the coevolutionary dynamics between hosts and parasites and encourages future research on host physiological changes influenced by intrinsic and extrinsic factors.

**Keywords:** *Anopheles gambiae*, resource allocation, infection, energetic shift, blood meal

## Highlights

- Having a blood meal did not affect mosquito longevity, resource content or *V. culicis* parasitaemia.
- Live mosquitoes harboured fewer spores than mosquitoes that just died, independently of the stage of infection, supporting the parasite load upon death hypothesis.
- Alive mosquitoes exhibited a shift in their usage of the energetic reserves (i.e., carbohydrates to lipids) late in life, which mosquitoes at death did not.
- Our findings support the hypothesis that *Plasmodium* might have coevolved with *Anopheles* lipid release dynamics, a nutrient which is essential for sporozoites development.

## Introduction

According to life history theory (Stearns 1992, 1989), organisms allocate resources to traits throughout their lives to maximise their reproductive success, which leads to trade-offs among the involved traits. Traditionally, the traits considered were mainly age-specific growth rate, fecundity and mortality rate. More recently, the approach has been expanded to study, for example, decisions about resource allocation to growth, reproduction and immune responses theoretically (Cressler et al. 2014) and experimentally (Budischak et al. 2018), and experimental work has confirmed the predicted trade-offs between fecundity and immune efficacy (Schwenke, Lazzaro, and Wolfner 2016).

While such work has made it clear that life-history theory can help to understand host-parasite interactions, it also shows that the approach needs more detailed data on how different resources are allocated to functions and how the allocation patterns affect the traits and underlie the trade-offs among them. One limitation in linking resource allocation and parasite-host interactions is that studies of resource sequestration by parasites often focus on specific time points rather than encompassing the host's entire adulthood, as illustrated by a review of malaria parasites in *Anopheles* mosquitoes (Shaw, Marcenac, and Catteruccia 2022).

Mosquitoes are well suited for such studies for, among other aspects, they obtain their primary resources from two food sources: protein and lipids from blood (A N Clements 1955; Alan Neville Clements 2023) and carbohydrates from the nectar of plants (Yee and Foster 1992). While carbohydrates and lipids are energy sources, proteins are used for embryogenesis and egg production (de Swart et al. 2023; Emami, Ranford-Cartwright, and Ferguson 2013). Blood meals, however, expose mosquitoes to several risks, including parasitism and unwanted blood components (Nouzova, Clifton, and Noriega 2019; Graça-Souza et al. 2006), and they trigger oxidative stress responses (Magalhaes et al. 2008; Jaramillo-Gutierrez et al. 2010), damage tissues because of the abdomen extension (Alan Neville Clements 2023; Dinglasan et al. 2009), and activate immune responses to fend off parasitic infections (Shen and Jacobs-Lorena 1997; Upton, Povelones, and Christophides 2014).

The long-term implications of blood meals on resource dynamics and their interaction with parasitism remain poorly understood. To move towards a description of the role of resource allocation on the interaction between a host's life history and parasitic infection, we investigated the impact of a blood meal and infection by the microsporidian *Vavraia culicis* on the longevity and resource dynamics of the mosquito *An. gambiae*. Although *Vavraia culicis* depletes larval resources (Rivero et al. 2007), it has few longevity and fecundity costs (Silva and Koella 2024; Zeferino and Koella 2024; Agnew and Koella 1997), enabling us to track long-term changes in resource allocation. In our experiment, we exposed some larvae to *V. culicis* and offered adults a blood meal or not, and then: a) monitored the dynamics of the protein, carbohydrate, and lipid content; b) measured parasite load at several time points throughout

the mosquitoes' lives; and c) evaluated a possible protective role of the concentrations of resource in mosquito survival. Through this comprehensive approach, we aimed to shed light on the influence of mosquito ecology and physiology on infection progression and outcome. Our findings show that the resource levels throughout the adult mosquito's life are influenced by blood meal and infection. Moreover, resources were tightly linked to adult survivorship, suggesting a predictive parameter for their mortality. This understanding is crucial for the understanding of the evolution of vector and non-vector-borne diseases and emphasises the need for closer integration of ecology and epidemiology in vector biology research.

## Results

*1. Effect of infection and blood meal on individuals that died naturally*

Mosquitoes that were not killed lived, on average, about 18 days. While neither exposure to *V. culicis* ($\chi^2$ = 0.02, df = 1, p = 0.900) nor blood-feeding ($\chi^2$ = 2.32, df = 1, p = 0.128) had a main effect on longevity, the exposure reduced the longevity of unfed mosquitoes by 3.3 days (interaction exposure * blood meal: $\chi^2$ = 9.42, df = 1, p = 0.002, **Fig. 1a**). Exposed mosquitoes harboured, on average, about $6.0 \times 10^5$ spores, independently of their blood-feeding status ($\chi^2$ = 3.57, df = 1, p = 0.059). However, spore load increased and then decreased as age at death increased ($\chi^2$ = 23.22, df = 1, p < 0.001), particularly in unfed individuals (interaction age at death * blood meal: $\chi^2$ = 4.65, df = 1, p = 0.031, **Fig. 1b**).

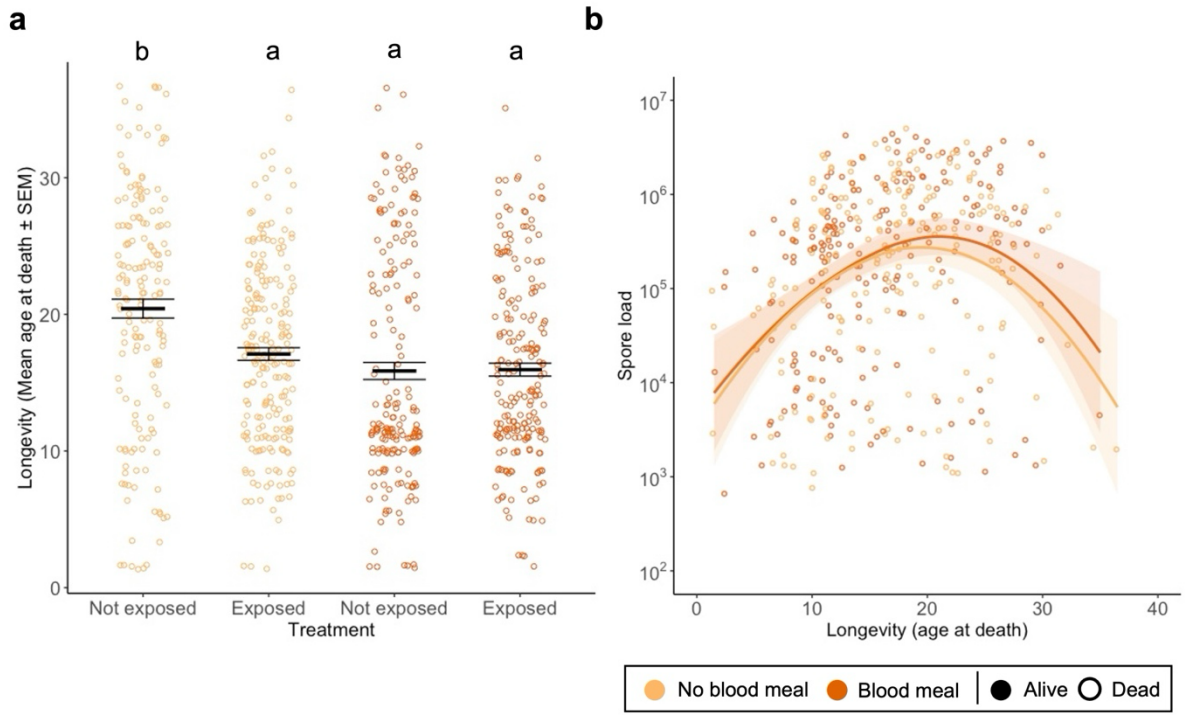


**Figure 1. Effect of infection and blood meal on longevity and spore load. (a)** Age at death for individuals exposed or not with *V. culicis*, that took or not a blood meal. Individuals who were collected alive were excluded from this analysis. The sample sizes were 165 and 210 for unexposed and exposed individuals who did not take a blood meal, and 190 and 209 for unexposed and exposed individuals who did take a blood meal. **(b)** Individual spore load at death for individuals that had a bloodmeal (orange) or not (yellow). A smooth line was drawn for ease of visualisation with the "loess" method, and the sample sizes were 209 for females who had a blood meal and 210 if they did not. The error bars show the standard error of the mean (SEM), and the letters indicate statistically significant differences from multiple comparisons.

*2. Spore load and resource dynamics in alive and dead mosquitoes across age classes*

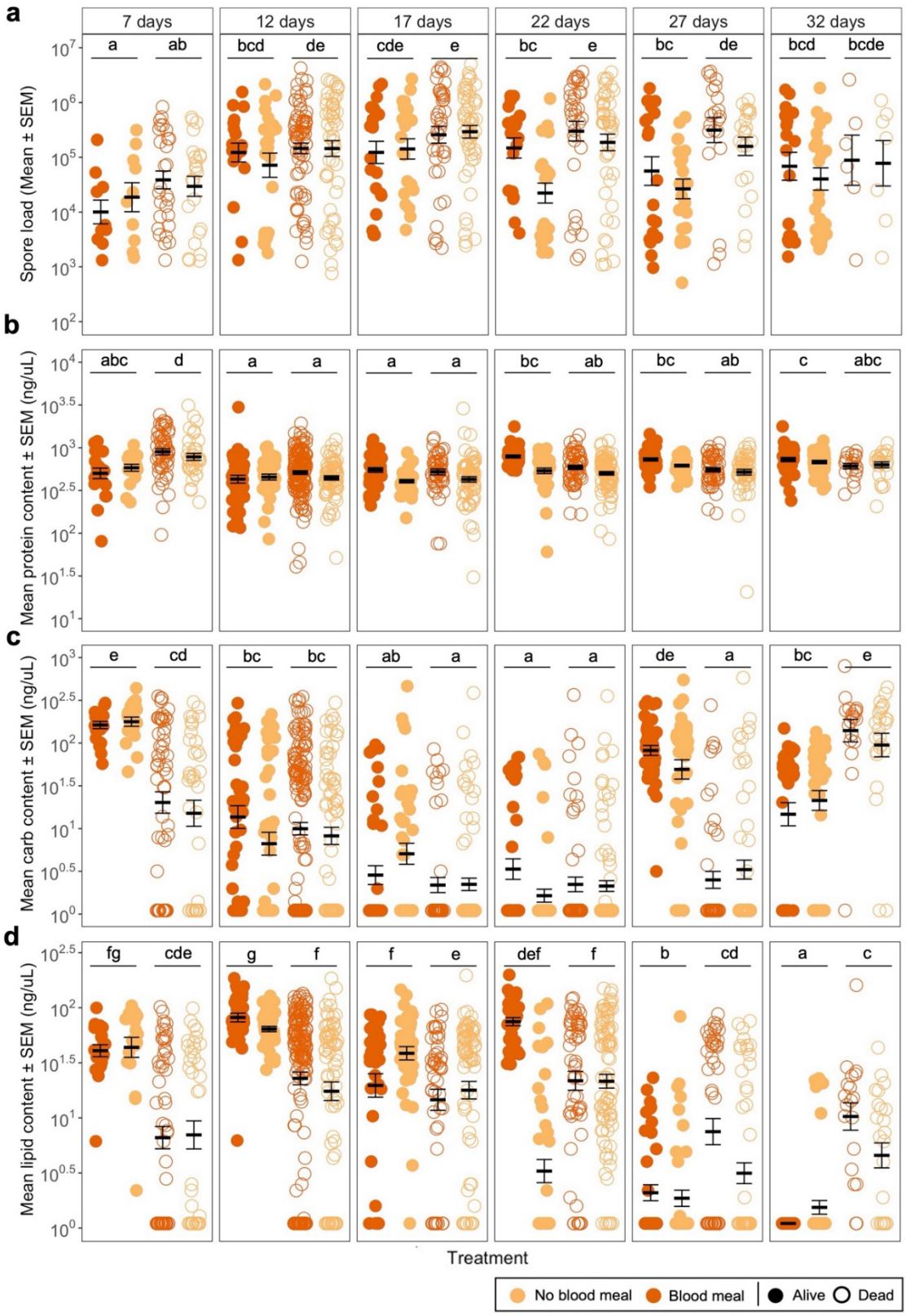
Spore load (**Fig. 2a**) increased with the age of mosquitoes ($\chi^2 = 27.59$, df = 5, $p < 0.001$) and was higher in dead than alive mosquitoes (dead: $5.0 \times 10^5$; alive: $2.1 \times 10^5$; $\chi^2 = 8.32$, df = 1, $p = 0.004$), independently of their age (interaction death status * age: $\chi^2 = 3.64$, df = 5, $p = 0.602$). On average, blood-fed mosquitoes harboured similar spore loads than unfed individuals ($\chi^2 = 1.25$, df = 1, $p = 0.263$) with the exception of day 22 and 27 (interaction blood * age: $\chi^2 = 14.18$, df = 5, $p = 0.014$). These effects were independent of any other combination of the treatments (for further details on the statistical analysis, see **Supplementary Table S2**).

Protein content (**Fig. 2b**) was highest at age 7, lowest at ages 12 and 17, and intermediate at ages 22, 27 and 32 ($\chi^2 = 17.31$, df = 5, $p = 0.004$), and was higher in dead than alive mosquitoes ($\chi^2 = 15.15$, df = 1, $p < 0.001$) although this effect was dependent of the age of the mosquitoes (interaction death status * age: $\chi^2 = 26.32$, df = 5, $p < 0.001$; **Fig. 2b**) . It was similar in blood-fed and unfed mosquitoes ($\chi^2 = 0.06$, df = 1, $p = 0.799$), and was independent of the infection status ($\chi^2 = 0.47$, df = 1, $p = 0.492$) or any other combination of the treatments (for further details on the statistical analysis see **Supplementary Table S2**).

Carbohydrate content (**Fig. 2c**) decreased from age 7 to age 22 and then increased as mosquitoes aged further ($\chi^2 = 50.57$, df = 5, $p < 0.001$). Individuals that died naturally had fewer carbohydrates than those that we killed ($\chi^2 = 7.02$, df = 1, $p = 0.008$), and this difference was stronger in the youngest and oldest mosquitoes than at other ages (interaction death status * age: $\chi^2 = 34.21$, df = 5, $p < 0.001$; **Fig. 3c**). It was similar in blood-fed and unfed mosquitoes ($\chi^2 = 0.05$, df = 1, $p = 0.820$), and was independent of the infection status ($\chi^2 = 0.01$, df = 1, $p = 0.910$) or any other combination of the treatments (for further details on the statistical analysis see **Supplementary Table S2**).

Lipid content (**Fig. 2d**) increased from age 7 to 12 and then decreased to the lowest value in the oldest individuals ($\chi^2 = 52.16$, df = 5, $p < 0.001$). On average, individuals that died naturally had similar levels of lipids than those that we killed ($\chi^2 = 0.52$, df = 1, $p = 0.472$), but their content was highly dependent

133 of their age and death status, as lipid content decreased with age in alive mosquitoes while it remained
134 constant in dead mosquitoes (interaction death status * age: $\chi^2 = 24.18$, df = 5, $p < 0.001$; **Fig. 2d**). It
135 was similar in blood-fed and unfed mosquitoes ($\chi^2 = 0.01$, df = 1, $p = 0.907$), and was independent of
136 the infection status ($\chi^2 = 0.73$, df = 1, $p = 0.391$) or any other combination of the treatments (for further
137 details on the statistical analysis see **Supplementary Table S2**).



138 **Figure 2. Spore and resource dynamics. (a)** Individual spore load, **(b)** protein, **(c)** carbohydrate and
139 **(d)** lipid content throughout their lifetime for individuals that took a blood meal, or not, and were
140 collected alive or dead. The error bars show the SEM and the letters indicate statistically significant
141 differences from multiple comparisons. The sample sizes were 10, 10, 28 and 23 for day 7; 20, 22, 74
142 and 52 for day 12; 21, 21, 40 and 54 for day 17; 19,22, 35 and 47 for day 22; 20, 21, 21 and 22 for day
143 27; and lastly 19, 22, 6 and 7 for day 32 in the treatment sequence of the caption for **(a)**. The sample
144 sizes were 21, 18, 55 and 35 for day 7; 38, 40, 152 and 72 for day 12; 39, 41, 49 and 74 for day 17; 37,
145 43, 56 and 87 for day 22; 39, 39, 48 and 55 for day 27; and lastly 38, 41, 19 and 24 for day 32 in the
146 treatment sequence of the caption for **(b)**. The sample sizes were 21, 19, 57 and 38 for day 7; 38, 42,
147 154 and 73 for day 12; 40, 41, 49 and 76 for day 17; 37, 43, 57 and 89 for day 22; 39, 41, 48 and 55 for
148 day 27; and lastly 38, 42, 19 and 24 for day 32 in the treatment sequence of the caption for **(cd)**.

149 *3. Resource ratios dynamics in alive and dead mosquitoes across age classes*

150 The ratio of proteins to carbohydrates increased until age 22 and then decreased ($\chi^2$ = 199.24, df = 5, p
151 < 0.001). Overall, the mosquitoes that we killed had lower P:C ratio than the ones that died naturally ($\chi^2$
152 = 96.36, df = 1, p < 0.001), but this difference was most apparent for the youngest mosquitoes and at
153 day 27 whereas at age 32 the mosquitoes that we killed had a slightly higher P:C ratio (interaction death
154 status * age: $\chi^2$ = 123.75, df = 5, p < 0.001; **Fig. 3a**). For further details on the statistical analysis see
155 **Supplementary Table S3**.

156 The ratio of proteins to lipids was highest at ages 7, 27 and 32, and lowest at ages 17 and 22 ($\chi^2$ = 191.11,
157 df = 5, p < 0.001). Up to age 17, mosquitoes that we killed had a lower P:L ratio those that died naturally,
158 but older mosquitoes showed the opposite pattern (interaction death status * age: $\chi^2$ = 104.19, df = 5, p
159 < 0.001; **Fig. 3b**) leading to alive mosquitoes having overall higher P:L ratios ($\chi^2$ = 40.96, df = 1, p <
160 0.001). For further details on the statistical analysis see **Supplementary Table S3**.

161 The ratio of carbohydrates to lipids was highest at ages 7, 27 and 32, and lowest at ages 17 and 22 ($\chi^2$ =
162 153.87, df = 5, p < 0.001). Overall, this ratio was lower in mosquitoes that we killed than in those that
163 died naturally ($\chi^2$ = 10.97, df = 1, p < 0.001), particularly if they were younger than 17 days old, but
164 higher, if they were older (interaction death status * age: $\chi^2$ = 58.72, df = 5, p < 0.001; **Fig. 3c**). For
165 further details on the statistical analysis see **Supplementary Table S3**.

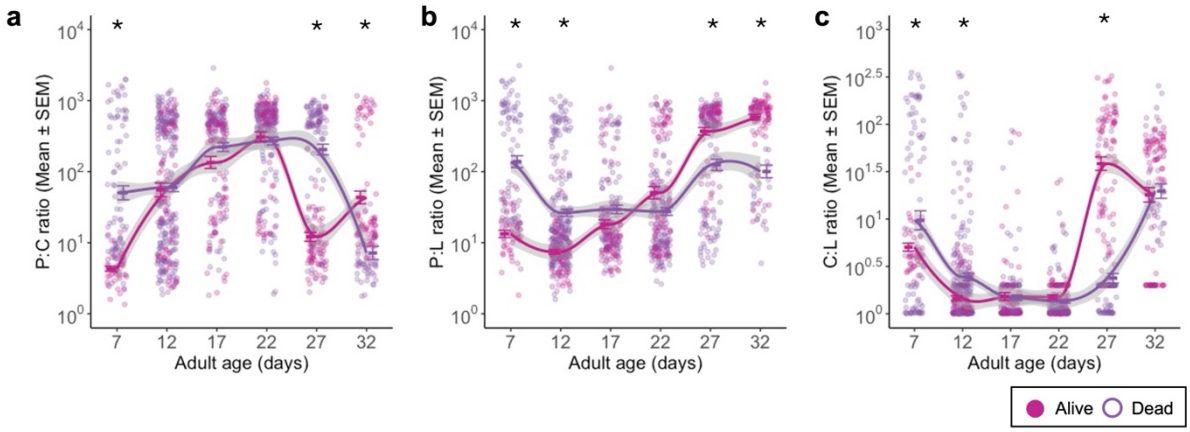



**Figure 3. Resource ratios.** Individual protein:carbohydrate (P:C) **(a)**, protein:lipid (P:L) **(b)** and carbohydrate:lipid (C:L) **(c)** ratios throughout their lifetime for individuals that were collected alive (pink) or dead (purple). As carbohydrates and lipids are energetic sources, their ratio is inherently energetic. The sample sizes for 7, 12, 17, 22, 27 and 32 days of adulthood were, respectively, 39, 78, 80, 80, 78 and 79 for alive and 90, 224, 123, 143, 103 and 43 for dead individuals in (**abc**). The error bars show the SEM and the asterisk indicates statistically significant differences between dead and alive individuals for that time point.

## Discussion

Our findings show complex relationships between some ecological factors that the main malaria vector, *An. gambiae*, is commonly exposed to (blood meal and parasitism) and longevity, which is a fundamental life-history trait determining the mosquito's fitness and vectorial capacity. They suggest the role of resource allocation underlying these relationships. In particular, the resource levels throughout the adult mosquito's life were influenced by blood meal and by the infection by a microsporidian. And they were closely linked to survivorship.

Taking a blood meal strongly shortened the mosquitoes' lives (**Fig. 1a**), most likely due to increased oxidative stress and gut tissue damage in mosquitoes (Nouzova, Clifton, and Noriega 2019; Graça-Souza et al. 2006; Devenport et al. 2006; Oliveira et al. 2011). In our design, individuals had *ad libitum* access to blood, potentially exacerbating these costs, particularly concerning tissue damage. Infection by *V. culicis* also shortened the lifespan, corroborating other studies (Lorenz and Koella 2011; Silva and Koella 2024; Zeferino and Koella 2024). The infection cost appeared to be linked to the spore load, for mosquitoes that died naturally harboured more spores than those of the same age we killed. More surprisingly, there was a cost of infection only in mosquitoes that had not blood-fed, although blood-feeding increased the spore load. A possible explanation is that both the production of spores and the host's survival are limited by resources replenished by blood-feeding. Indeed, at many ages, the resource content was lower in the mosquitoes that died naturally than in those we killed (**Fig. 2**).

192 Our findings highlight that there are clear shifts in the ratios of resources during the life of the
193 mosquitoes. As protein content remained relatively stable over the lifespan (**Fig. 2b**), the shifts of P:C
194 and P:L predominantly stem from differences in carbohydrate and lipid levels, respectively (**Fig. 3ab**).
195 In particular, individuals at death consistently exhibited elevated P:C and P:L ratios over time (**Fig.**
196 **3ab**), indicative of reduced carbohydrate and lipid reserves. Conversely, alive individuals show dynamic
197 energy use, primarily relying on carbohydrates until day 22, after which lipid reserves became the
198 predominant fuel source (**Fig. 3c**). Below, we propose a few complementary explanations for these
199 findings.

200 Lipid reserves are a last resort energy source, less accessible to the host than carbohydrates, prompting
201 individuals to primarily rely on carbohydrates. Hence, as they had constant access to sucrose (a
202 carbohydrate), we expected individuals to use carbohydrates as their main source of energy until they
203 depleted their reserves, likely due to the inability to reach their sucrose source, therefore shifting towards
204 lipids. Indeed, this energetic shift interestingly coincides with an expected production of a new cluster
205 of eggs. It has been discussed that several mosquito species do not need the energetic resources to
206 produce the new cluster of eggs, but instead solely the iron signalling (Alan Neville Clements 2023;
207 Zhou et al. 2007; Whiten and Adelman 2018; Briegel and Hörler 1993). If such is the case for *An.*
208 *gambiae*, following egg laying around day 10, by day 12, individuals will begin to spend carbohydrates
209 to prepare a future egg cluster. We show support for this hypothesis with a consistent decrease in
210 carbohydrate content from day 12 onwards in alive individuals, reaching their lowest point on day 22
211 (**Fig. 3ac**). Simultaneously, lipids are initially used to compensate for energetic demands for mosquito
212 homeostasis and later become the primary energy source. Once the egg cluster is produced, live
213 mosquitoes can replenish their carbohydrate reserves, likely through the sucrose cottons that are
214 constantly available throughout the experiment (**Fig. 3bc**, day 27-32).

215 Moreover, when comparing the overall energetic use between individuals collected alive *versus* those
216 collected at death over the same period, distinct energetic trajectories emerge. In particular, individuals
217 who die not only exhibit lower energetic profiles but also consistently begin adulthood with fewer
218 energetic reserves compared to their surviving counterparts. This suggests that the initial reserve content
219 at adult emergence may hold predictive value not only for resource acquisition but also for longevity.
220 Constantly lower energetic reserves likely correspond to reduced physical condition and overall fitness,
221 increasing susceptibility to mortality. Furthermore, personal observations indicate that mosquitoes
222 nearing death exhibit reduced activity and tend to remain at the bottom of the cup. In such compromised
223 conditions, accessing sucrose at the cup's surface becomes challenging, hindering resource
224 replenishment and increasing both the usage of lipids reserves and the mortality risk. Conversely,
225 individuals with higher baseline energetic reserves may retain the energy to fly and access available
226 sucrose, as evidenced by carbohydrate replenishment observed on day 27 in surviving mosquitoes (**Fig.**

227 **3c**). Thus, we postulate that the quantity of energetic resources individuals possess at the onset of
228 adulthood may significantly influence and potentially predict their longevity. Building on the findings
229 of Bedhomme *et al.* (2004), which demonstrated that *V. culicis*-infected mosquito larvae have
230 significantly reduced levels of lipids, sugars, and glycogen compared to uninfected larvae (Bedhomme
231 et al. 2004), our results extend this understanding into adult mosquitoes. While the reduction in energy
232 resources during the larval stage may seem modest, our data highlight the cumulative impact of infection
233 across the mosquito's lifespan. By adulthood, infected mosquitoes exhibit resource depletion of 2-3
234 times higher than their uninfected counterparts (e.g., carbohydrates: 64 vs. 187 ng/µL; lipids: 20 vs. 48
235 ng/µL by day 7). This underscores the long-term energetic cost of microsporidian infections.

236 Through a vector biology perspective, our findings reveal a noteworthy pattern with significant
237 implications for epidemiology. As mentioned above, *An. gambiae* is known as the main *Plasmodium*
238 vector. A study by Costa and colleagues (2018) demonstrated that the within-mosquito resource
239 environment affects *Plasmodium* infection success and virulence, in particular regarding lipid
240 exploitation. For instance, only 20% of the mice bitten by mosquitoes with lipid depletion were infected
241 with *Plasmodium* compared to the ones bitten by control mosquitoes, which had a 90% infection success
242 (Costa et al. 2018). This result was shown to be due to the need for lipids by sporozoites but not oocysts.
243 Lipids are harder to access by the *Plasmodium* during the early stages, as they are mostly stored in the
244 ovaries. However, once the reproductive cycle is complete, lipids become much more accessible. The
245 authors proposed that the duration of *Plasmodium* sporogony, typically occurring 13 to 16 days after a
246 blood meal, is an evolutionary adaptation to the temporal dynamics of mosquito reproduction. Our
247 results seem to lend support to this hypothesis as we observe that the major shifts in lipid reserve
248 mobility align with the expected timing of sporogony in *Plasmodium*-infected mosquitoes, suggesting
249 an evolutionary adaptation of this parasite to timely exploit mosquito resource dynamics.

250 Altogether, our study highlights the significance of accounting for resource availability and usage in
251 mosquito life studies. Our findings indicate that resource reserves are affected by the individual life
252 history traits and environmental stressors, such as parasites. We demonstrated that blood meals impact
253 mosquito longevity and resource dynamics, which might contribute to changes in energetic shifts within
254 the mosquito. Furthermore, our evidence also suggests that the quantity and dynamics of energetic
255 reserves may serve as predictive factors for mosquito survival. We believe that these results will
256 contribute to a better understanding and prediction of the evolution of *Plasmodium* infections and hope
257 to inspire similar studies in other vector and non-vector infection models.

258 **Limitations of the study**

259 In this study, we demonstrated the predictive and deterministic role of energy reserves throughout the
260 life history of *Anopheles gambiae*. However, one major limitation of our work is the lack of experimental

testing on resource dynamics during *Plasmodium* infection and co-infection with *V. culicis*, which is crucial to evaluate our hypothesis regarding resource competition during co-infection.

Another limitation is that our initial measurements were taken on day 7. While this timing ensured that all mosquitoes harboured spores, allowing us to quantify spore load, it also gave them time to replenish their resources through feeding on the sucrose source, potentially hindering the true impact of infection on some measured reserves. Measuring energy reserves immediately after adult emergence would provide a clearer baseline of resources before feeding begins. Furthermore, assessing resource dynamics at critical life stages—such as immediately before pupation, at the pupal stage, and just after emergence—would offer valuable insights into the energetic costs of metamorphosis. This approach would help quantify how these transformative stages deplete resources and how infection amplifies these costs, shedding light on the trade-offs imposed by infection during key developmental transitions.

## Author contributions

LMS, JCK and TGZ conceived and designed the experiments. LMS and TGZ collected, analysed and wrote the first draft of the manuscript. All authors contributed critically to the drafts.

## Acknowledgements

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## Competing Interests

The authors declare that they have no competing interests.

## Materials and Methods

*Experimental system*

The host of our experiment was the Kisumu strain of *Anopheles gambiae s.s.* (Vulule et al. 1994), which we had maintained at a density of about 600 individuals per cage and standard lab conditions (26 ± 1ºC, 70 ± 5% relative humidity and 12 h light/dark) for several years before the experiments. During this time, cohorts were initiated weekly and kept in separate cages throughout their lives, and eggs were obtained from several cages. Our parasite was the microsporidian *Vavraia culicis floridensis* (provided by James Becnel, USDA, Gainesville, FL), which is a generalist, obligatory, intracellular parasite that infects mosquito epithelial gut cells (Zeferino and Koella 2024). Before beginning the study, we maintained *V. culicis* in large numbers by alternatingly infecting *Aedes aegypti* and *An. gambiae* populations to ensure that it remains a generalist parasite.

291 *Experimental design*

292 Each experiment was started with eggs from three cages (which held mosquitoes of different ages). We
293 used a cross-factorial design, where one factor was exposure or not to *V. culicis,* and the other was
294 blood-fed or not. Freshly hatched *An. gambiae* larvae were moved individually into the wells of 12-well
295 culture plates, each containing 3 ml of distilled water. They were fed daily with Tetramin Baby ® fish
296 food according to their age: 0.04, 0.06, 0.08, 0.16, 0.32 and 0.6 mg/larva at ages 0, 1, 2, 3, 4 and 5 days
297 or older, respectively (Kulma, Saddler, and Koella 2013). Two-day-old larvae were exposed to 0 or
298 10,000 spores of *V. culicis*. Pupae were moved to sets of three cages (21 x 21 x 21 cm) based on their
299 treatment, where they emerged and then had constant access to a 6% sucrose solution. The males were
300 removed upon emergence, and untreated males from the colony were added to the cages at a number
301 equal to the number of females, who were left to mate for seven days. The males were then removed,
302 and the females were allowed, or not, to take a blood meal on TGZ's arm for five minutes. Two days
303 later, they were moved individually to 150 ml cups (5 cm Ø x 10 cm) that were covered with a net and
304 contained a 50 mm Ø petri dish (to keep the mosquitoes from drowning) on the surface of 50 ml
305 deionised water, a 10 x 7 cm rectangular filter paper (to keep the air humid) and a 110 mm Ø Whatman
306 filter paper. They were fed with cotton balls soaked with 6% sucrose solution, which were replaced
307 daily. The mosquitoes were kept in these cups for 48 hours to let them lay eggs, and then moved to other
308 150 ml cups and fed with 6% sucrose solution. Living individuals were collected on day 7 (before the
309 bloodmeal), 12, 17, 22, 27 and 32; dead individuals were collected every 12 hours. The 12-hour period
310 was based on preliminary results (further details in **Fig. S1**) that showed no significant degradation of
311 any of the resources for at least 18 hours after death. The collected mosquitoes were frozen at – 80ºC
312 until we assayed spores, proteins, carbohydrates and lipids.

313 *Spore load*

314 Since spore load and resource content are directly related to body size, all individuals were weighed and
315 transferred to a 1.5 ml microcentrifuge tube. Then, 100 µl of extraction buffer (100 mM $KH_2PO_4$; 1 mM
316 dithiothreitol; 1 mM EDTA) per mg of the mosquito was added to each tube, and the mosquitoes were
317 homogenised at 30 Hz for three minutes with a stainless-steel bead (Ø 5 mm) and a Qiagen TissueLyser
318 LT. From the homogenate, 20 µl were used to measure the spore load in a haemocytometer with a phase-
319 contrast microscope (400x magnification). Spore load per individual mosquito was normalised based on
320 their body size. All of the mosquitoes exposed to the parasite were infected.

321 *Resources*

322 The remaining homogenate solution was used to quantify protein, carbohydrate and lipid content
323 through colourimetry with a SpectraMax i3x plate reader (Foray et al. 2012). For each plate (and
324 therefore resource), an eight-multipoint standard curve was prepared with 10 to 400 µg/mL of albumin

325 (for proteins), 1 to 40 µg/mL of glucose (for carbohydrates) or 5 to 200 µg/mL of triolein (for lipids).
326 All samples and points of the standard curve were measured in duplicate to account for experimental
327 variation.

328 Proteins were measured with the Bradford method (Kruger 2009), which consists of centrifuging the
329 samples at 12,000 rpm at 4 ºC for four minutes, transferring 5 µl of the supernatant into a 96-well plate,
330 adding 200 µl of Bradford reagent (Sigma-Aldrich) to the samples and standards, and incubating them
331 at room temperature with soft agitation for 15 minutes. Optical density (OD) was then read at 595 nm.

332 For carbohydrates quantification, we added 20 µl of 20% sodium sulphate, 5 µl of extraction buffer and
333 1500 µL of chloroform-methanol solution (1:2) to the remaining homogenate solution, briefly mixed
334 the sample, and centrifuged it at 12,000 rpm at 4 ºC for 15 minutes. 300 µl of the supernatant were
335 placed into a quartz 96-well plate (Hellma) and left to evaporate for 40 minutes under the hood. 240 µl
336 of 1.42 g/l anthrone reagent were added to each sample and each standard. The solutions were incubated
337 for 15 minutes at room temperature and a further 15 minutes in a water bath at 90 ºC. The optical density
338 was then read at 625 nm.

339 Lipids were estimated by pipetting 200 µl of the remaining solution into a quartz microplate and
340 incubating the plate in a preheated oven at 90 ºC for about 30 minutes. When all the solvent had
341 evaporated, 10 µl of 98% sulfuric acid was added to each well and incubated in a water bath at 90 ºC
342 for two minutes. After ice-cooling the plate for a few minutes, 190 µl of vanillin reagent was added to
343 each well, and the plate was sealed and incubated for 15 minutes with gentle agitation. Optical density
344 was read at 525 nm. All the resources were quantified according to the standard curves with the software
345 SoftMax Pro version 7.1 in the SpectraMax i3x plate reader.

346 *Statistical analysis*

347 All analyses were conducted with R version 4.4.2, using the packages "DHARMa" (Hartig and Hartig
348 2017), "car" (Fox et al. 2012), "glmmTMB" (Brooks et al. 2017), "emmeans" (Lenth et al. 2019) and
349 "multcomp" (Hothorn et al. 2016). Significance was assessed with the Anova function of the "car"
350 package (Fox et al. 2012) We used a type III ANOVA in the case of a significant interaction and a type
351 II ANOVA otherwise. When relevant, we performed post-hoc multiple comparisons with the package
352 emmeans, using the default Tukey adjustment.

353 Age at death of the mosquitoes that died naturally was analysed with a linear model with a Gaussian
354 distribution of errors, where the response variable was age at death in days and the explanatory variables
355 were infection status, blood meal and their interactions.

356 Mosquitoes with detectable spores were then used to assess the spore load. Because we counted the
357 number of spores in a haemocytometer containing 0.1 µl of the sample (i.e. 1/1000 of the total volume),

358 the detection threshold was estimated to be 1000 spores. Spore load at death (from mosquitoes that died
359 naturally) was analysed using a generalised linear model with a negative binomial distribution of errors
360 (Venables and Ripley 2013) where the response variable was spore load and the explanatory variables
361 were age at death, blood meal and their interactions.

362 We then tested whether the spore load differed between blood-fed and unfed mosquitoes and between
363 those that died naturally or that we killed. We first pooled the mosquitoes that died within 2.5 days of
364 an age at collection (i.e., 7, 12, 17, 22, 27 and 32 days) so that the time points for the mosquitoes that
365 died naturally or that we killed were the same. Since spores do not appear before about four days after
366 emergence and since very few mosquitoes lived beyond 34 days, we omitted the youngest and oldest
367 individuals. We analysed the spore load of the mosquitoes that were infected with a generalised linear
368 model with a negative binomial distribution of errors, where the explanatory variables were blood meal,
369 death status, age at collection and their interactions.

370 To analyse the mosquitoes' protein, carbohydrate and lipid content, we again pooled the mosquitoes that
371 died naturally into groups corresponding to the ages at collection of the living mosquitoes. Because of
372 the distribution of the resource contents, protein content was analysed with a generalised linear model
373 with a Gamma distribution of errors whereas carbohydrates and lipids were analysed with a generalised
374 linear model with a tweedie distribution of errors. The explanatory variables were blood meal, death
375 status, infection by *V. culicis*, age at collection and their interactions.

376 Finally, we assessed differences in the ratios between resources, i.e., protein:carbohydrate (P:C), protein:
377 lipid (P:L), and carbohydrate:lipid (C:L) ratio, as a proxy for energetic shifts in the host. Since some of
378 the resource levels were 0, we added 1 to each value before calculating the ratio. The ratios were
379 analysed with a generalised linear model with a Gamma distribution of errors, where the explanatory
380 variables were blood meal, death status, infection by *V. culicis*, age at collection and their interactions.

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491
492
493 **Figure legends**
494 **Figure 1. Effect of infection and blood meal on longevity and spore load. (a)** Age at death for
495 individuals exposed or not with *V. culicis*, that took or not a blood meal. Individuals who were collected
496 alive were excluded from this analysis. The sample sizes were 165 and 210 for unexposed and exposed
497 individuals who did not take a blood meal, and 190 and 209 for unexposed and exposed individuals who
498 did take a blood meal. **(b)** Individual spore load at death for individuals that had a bloodmeal (orange)
499 or not (yellow). A smooth line was drawn for ease of visualisation with the "loess" method, and the
500 sample sizes were 209 for females who had a blood meal and 210 if they did not. The error bars show
501 the standard error of the mean (SEM), and the letters indicate statistically significant differences from
502 multiple comparisons.

**Figure 2. Spore and resource dynamics. (a)** Individual spore load, **(b)** protein, **(c)** carbohydrate and **(d)** lipid content throughout their lifetime for individuals that took a blood meal, or not, and were collected alive or dead. The error bars show the SEM and the letters indicate statistically significant differences from multiple comparisons. The sample sizes were 10, 10, 28 and 23 for day 7; 20, 22, 74 and 52 for day 12; 21, 21, 40 and 54 for day 17; 19,22, 35 and 47 for day 22; 20, 21, 21 and 22 for day 27; and lastly 19, 22, 6 and 7 for day 32 in the treatment sequence of the caption for **(a)**. The sample sizes were 21, 18, 55 and 35 for day 7; 38, 40, 152 and 72 for day 12; 39, 41, 49 and 74 for day 17; 37, 43, 56 and 87 for day 22; 39, 39, 48 and 55 for day 27; and lastly 38, 41, 19 and 24 for day 32 in the treatment sequence of the caption for **(b)**. The sample sizes were 21, 19, 57 and 38 for day 7; 38, 42, 154 and 73 for day 12; 40, 41, 49 and 76 for day 17; 37, 43, 57 and 89 for day 22; 39, 41, 48 and 55 for day 27; and lastly 38, 42, 19 and 24 for day 32 in the treatment sequence of the caption for **(cd)**.

**Figure 3. Resource ratios.** Individual protein: carbohydrate (P:C) **(a)**, protein: lipid (P:L) **(b)** and carbohydrate: lipid (C:L) **(c)** ratios throughout their lifetime for individuals that were collected alive (pink) or dead (purple). As carbohydrates and lipids are energetic sources, their ratio is inherently energetic. The sample sizes for 7, 12, 17, 22, 27 and 32 days of adulthood were, respectively, 39, 78, 80, 80, 78 and 79 for alive and 90, 224, 123, 143, 103 and 43 for dead individuals in (**abc**). The error bars show the SEM and the asterisk indicates statistically significant differences between dead and alive individuals for that time point.

522 **Supplementary information**

523 for " Energetic shifts predict the mortality of *Anopheles gambiae* " by Tiago G. Zeferino, Luís M. Silva
524 and Jacob C. Koella.

525

526 **Table S1.** Effect of infection and blood meal on individuals that died naturally.

527 **Table S2.** Spore load and resource dynamics in alive and dead mosquitoes across age classes.

528 **Table S3.** Resource ratios dynamics in alive and dead mosquitoes across age classes.

529 **Figure S1.** Resource degradation after different times post-death.

530 **Table S1.** Effect of infection and blood meal on individuals that died naturally.

531

| **Tested effect** | | | |
|---|---|---|---|
| **Model 1a** – Longevity | ***df*** | $\chi^2$ | ***p*** |
| Infection | 1 | 0.02 | 0.900 |
| Blood meal | 1 | 2.32 | 0.128 |
| Infection : Blood meal | 1 | 9.42 | **0.002** |
| **Model 1b** – Spore load | ***df*** | $\chi^2$ | ***p*** |
| Age at death | 1 | 23.22 | **<0.001** |
| Blood meal | 1 | 3.57 | 0.059 |
| Age at death : Blood meal | 1 | 4.65 | **0.031** |

532

533 **Table S2.** Spore load and resource dynamics in alive and dead mosquitoes across age classes.

534

| **Tested effect** | | | |
|---|---|---|---|
| **Model 2a** – Spore load | ***df*** | $\chi^2$ | ***p*** |
| Death status | 1 | 8.32 | **0.004** |
| Blood meal | 1 | 1.25 | 0.263 |
| Age class | 5 | 27.59 | **<0.001** |
| Death status : Blood meal | 1 | 1.87 | 0.172 |
| Death status : Age class | 5 | 3.64 | 0.602 |
| Blood meal : Age class | 5 | 14.18 | **0.014** |
| Death status : Blood meal : Age class | 5 | 4.47 | 0.483 |
| **Model 2b** – Proteins | ***df*** | $\chi^2$ | ***p*** |
| Death status | 1 | 15.15 | **<0.001** |
| Infection | 1 | 0.47 | 0.492 |
| Blood meal | 1 | 0.06 | 0.799 |
| Age class | 5 | 17.31 | **0.004** |
| Death status : Infection | 1 | 0.53 | 0.466 |
| Death status : Blood meal | 1 | 1.84 | 0.175 |
| Infection : Blood meal | 1 | 0.51 | 0.476 |
| Death status : Age class | 5 | 26.32 | **<0.001** |
| Infection : Age class | 5 | 2.32 | 0.803 |
| Blood meal : Age class | 5 | 5.54 | 0.354 |
| Death status : Infection : Blood meal | 1 | 1.00 | 0.318 |
| Death status : Infection : Age class | 5 | 2.03 | 0.844 |
| Death status : Blood meal : Age class | 5 | 7.04 | 0.217 |
| Infection : Blood meal : Age class | 5 | 1.89 | 0.864 |
| Death status : Infection : Blood meal : Age class | 5 | 2.93 | 0.710 |
| **Model 2c** – Carbohydrates | ***df*** | $\chi^2$ | ***p*** |
| Death status | 1 | 7.02 | **0.008** |
| Infection | 1 | 0.01 | 0.910 |
| Blood meal | 1 | 0.05 | 0.820 |
| Age class | 5 | 50.57 | **<0.001** |
| Death status : Infection | 1 | 0.89 | 0.344 |

| | | | |
|---|---|---|---|
| Death status : Blood meal | 1 | 0.12 | 0.728 |
| Infection : Blood meal | 1 | 0.01 | 0.915 |
| Death status : Age class | 5 | 34.21 | **<0.001** |
| Infection : Age class | 5 | 16.54 | **0.005** |
| Blood meal : Age class | 5 | 9.06 | 0.106 |
| Death status : Infection : Blood meal | 1 | 3.44 | 0.063 |
| Death status : Infection : Age class | 5 | 11.86 | **0.037** |
| Death status : Blood meal : Age class | 5 | 7.45 | 0.189 |
| Infection : Blood meal : Age class | 5 | 21.04 | **<0.001** |
| Death status : Infection : Blood meal : Age class | 5 | 22.42 | **<0.001** |
| **Model 2d** – Lipids | ***df*** | $\chi^2$ | ***p*** |
| Death status | 1 | 0.52 | 0.472 |
| Infection | 1 | 0.73 | 0.391 |
| Blood meal | 1 | 0.01 | 0.907 |
| Age class | 5 | 52.16 | **<0.001** |
| Death status : Infection | 1 | 5.17 | **0.023** |
| Death status : Blood meal | 1 | 2.23 | 0.135 |
| Infection : Blood meal | 1 | 0.25 | 0.619 |
| Death status : Age class | 5 | 24.18 | **<0.001** |
| Infection : Age class | 5 | 3.69 | 0.594 |
| Blood meal : Age class | 5 | 14.36 | **0.013** |
| Death status : Infection : Blood meal | 1 | 3.93 | **0.047** |
| Death status : Infection : Age class | 5 | 6.41 | 0.268 |
| Death status : Blood meal : Age class | 5 | 17.00 | **0.004** |
| Infection : Blood meal : Age class | 5 | 13.08 | **0.022** |
| Death status : Infection : Blood meal : Age class | 5 | 14.95 | **0.010** |

537 **Table S3.** Resource ratios dynamics in alive and dead mosquitoes across age classes.

538

| **Tested effect** | | | |
|---|---|---|---|
| **Model 3a** – P:C | ***df*** | $\chi^2$ | ***p*** |
| Death status | 1 | 96.36 | **<0.001** |
| Infection | 1 | 0.10 | 0.751 |
| Blood meal | 1 | 0.21 | 0.644 |
| Age class | 5 | 199.24 | **<0.001** |
| Death status : Infection | 1 | 1.47 | 0.224 |
| Death status : Blood meal | 1 | 0.61 | 0.433 |
| Infection : Blood meal | 1 | 0.02 | 0.887 |
| Death status : Age class | 5 | 123.75 | **<0.001** |
| Infection : Age class | 5 | 81.18 | **<0.001** |
| Blood meal : Age class | 5 | 61.65 | **<0.001** |
| Death status : Infection : Blood meal | 1 | 0.95 | 0.330 |
| Death status : Infection : Age class | 5 | 7.85 | 0.165 |
| Death status : Blood meal : Age class | 5 | 6.21 | 0.286 |
| Infection : Blood meal : Age class | 5 | 128.88 | **<0.001** |
| Death status : Infection : Blood meal : Age class | 5 | 31.31 | **<0.001** |
| **Model 3b** – P:L | ***df*** | $\chi^2$ | ***p*** |
| Death status | 1 | 40.96 | **<0.001** |
| Infection | 1 | 0.04 | 0.838 |
| Blood meal | 1 | 0.01 | 0.909 |
| Age class | 5 | 191.11 | **<0.001** |
| Death status : Infection | 1 | 0.36 | 0.548 |
| Death status : Blood meal | 1 | 0.10 | 0.748 |
| Infection : Blood meal | 1 | 0.23 | 0.629 |
| Death status : Age class | 5 | 104.19 | **<0.001** |
| Infection : Age class | 5 | 3.75 | 0.586 |
| Blood meal : Age class | 5 | 84.52 | **<0.001** |
| Death status : Infection : Blood meal | 1 | 0.01 | 0.920 |
| Death status : Infection : Age class | 5 | 0.69 | 0.984 |
| Death status : Blood meal : Age class | 5 | 79.01 | **<0.001** |

| | | | |
|---|---|---|---|
| Infection : Blood meal : Age class | 5 | 7.82 | 0.166 |
| Death status : Infection : Blood meal : Age class | 5 | 5.42 | 0.366 |
| **Model 3c** – C:L | ***df*** | $\chi^2$ | ***p*** |
| Death status | 1 | 10.97 | **<0.001** |
| Infection | 1 | 0.02 | 0.890 |
| Blood meal | 1 | 0.12 | 0.726 |
| Age class | 5 | 153.87 | **<0.001** |
| Death status : Infection | 1 | 0.50 | 0.478 |
| Death status : Blood meal | 1 | 0.00 | 0.968 |
| Infection : Blood meal | 1 | 0.62 | 0.430 |
| Death status : Age class | 5 | 58.72 | **<0.001** |
| Infection : Age class | 5 | 13.46 | **0.019** |
| Blood meal : Age class | 5 | 24.36 | **<0.001** |
| Death status : Infection : Blood meal | 1 | 0.83 | 0.361 |
| Death status : Infection : Age class | 5 | 11.35 | **0.045** |
| Death status : Blood meal : Age class | 5 | 2.33 | 0.801 |
| Infection : Blood meal : Age class | 5 | 14.38 | **0.013** |
| Death status : Infection : Blood meal : Age class | 5 | 22.13 | **<0.001** |

539

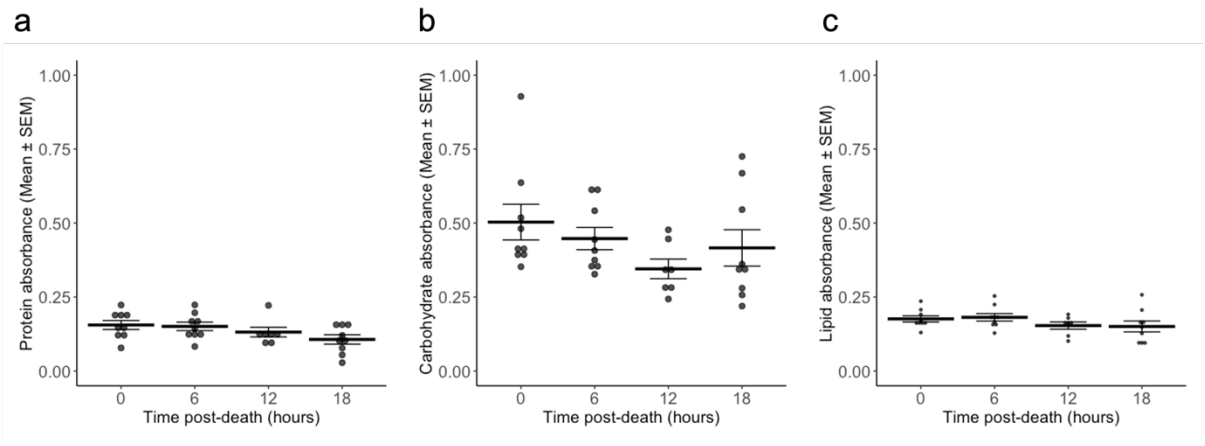
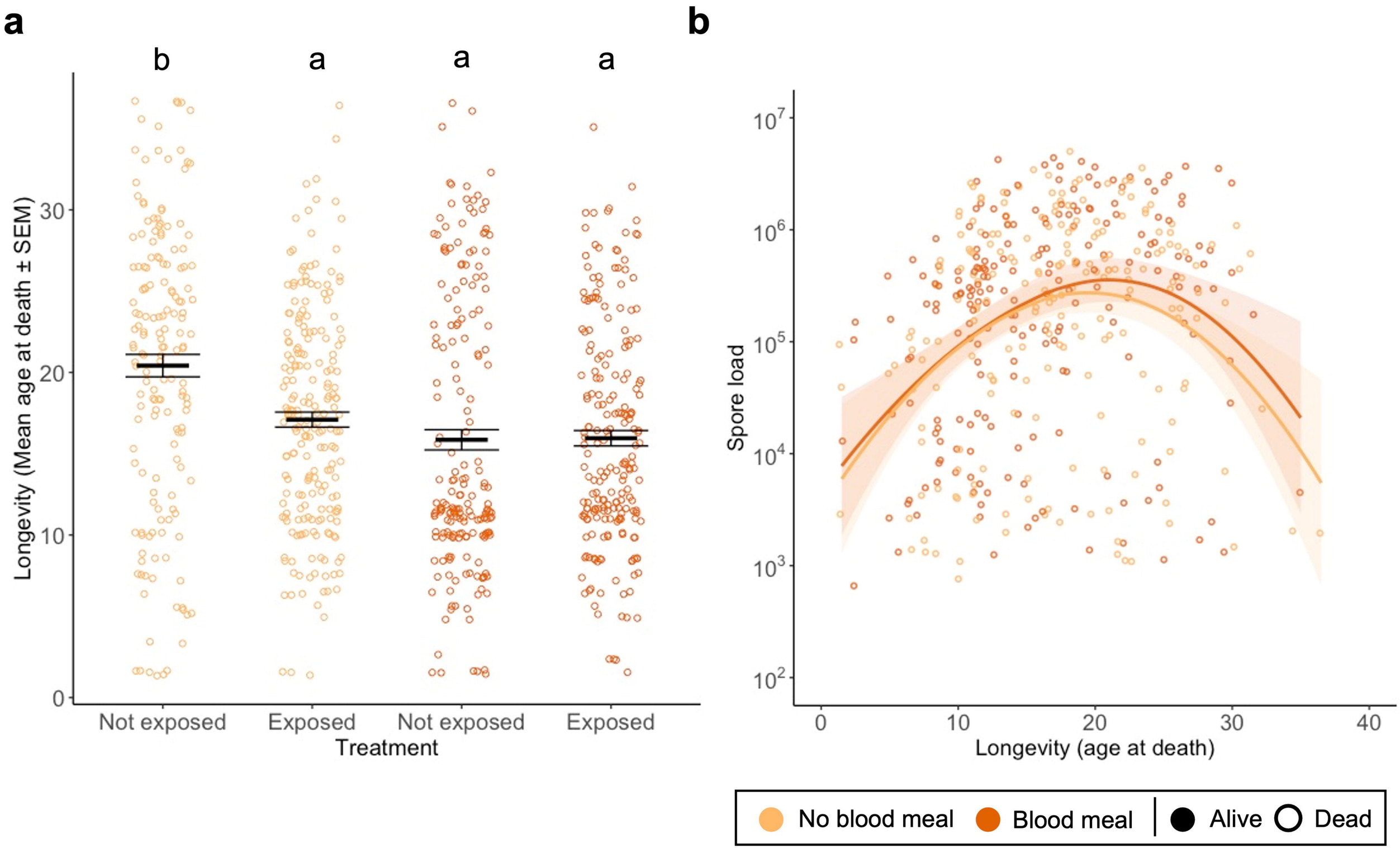
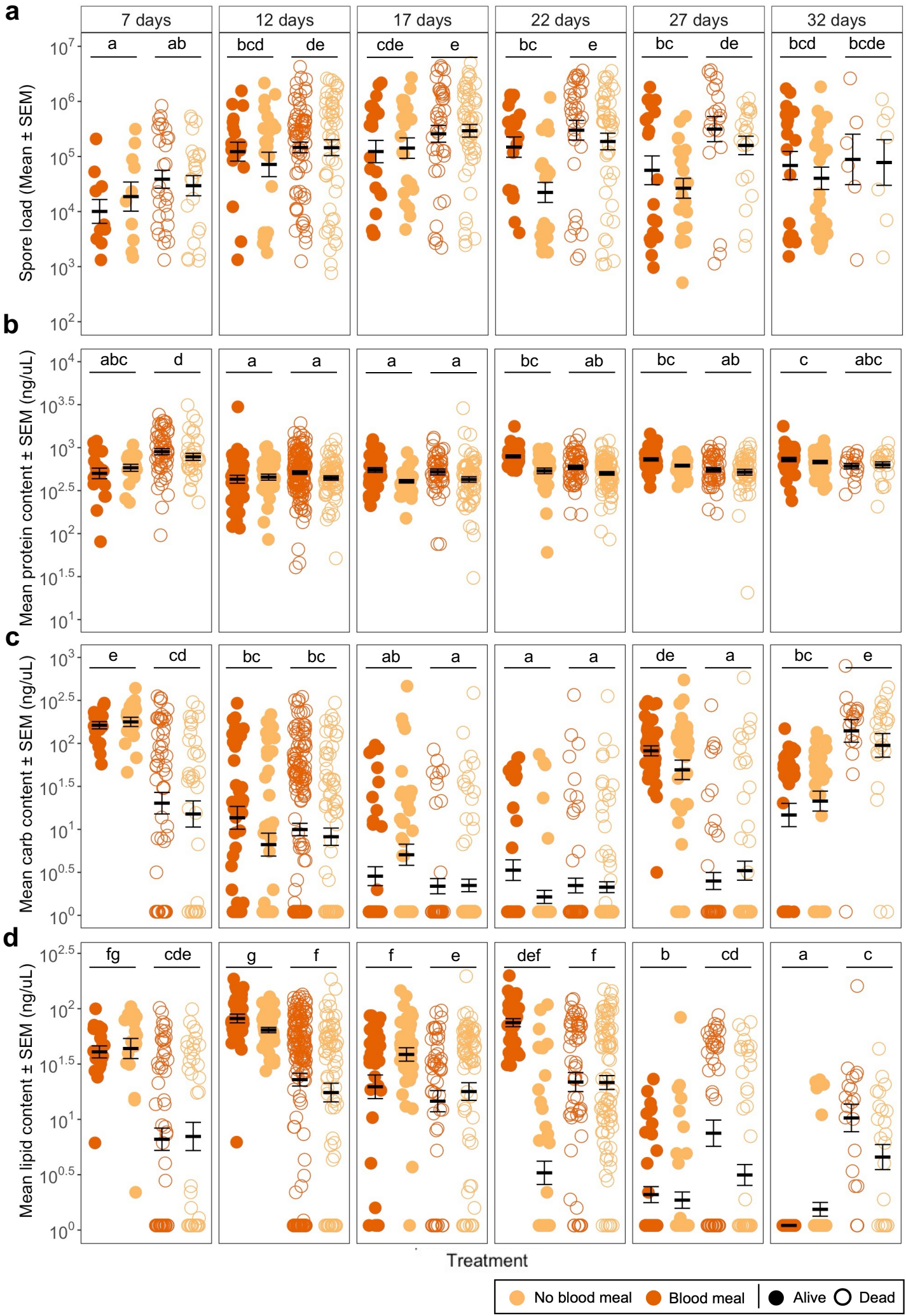
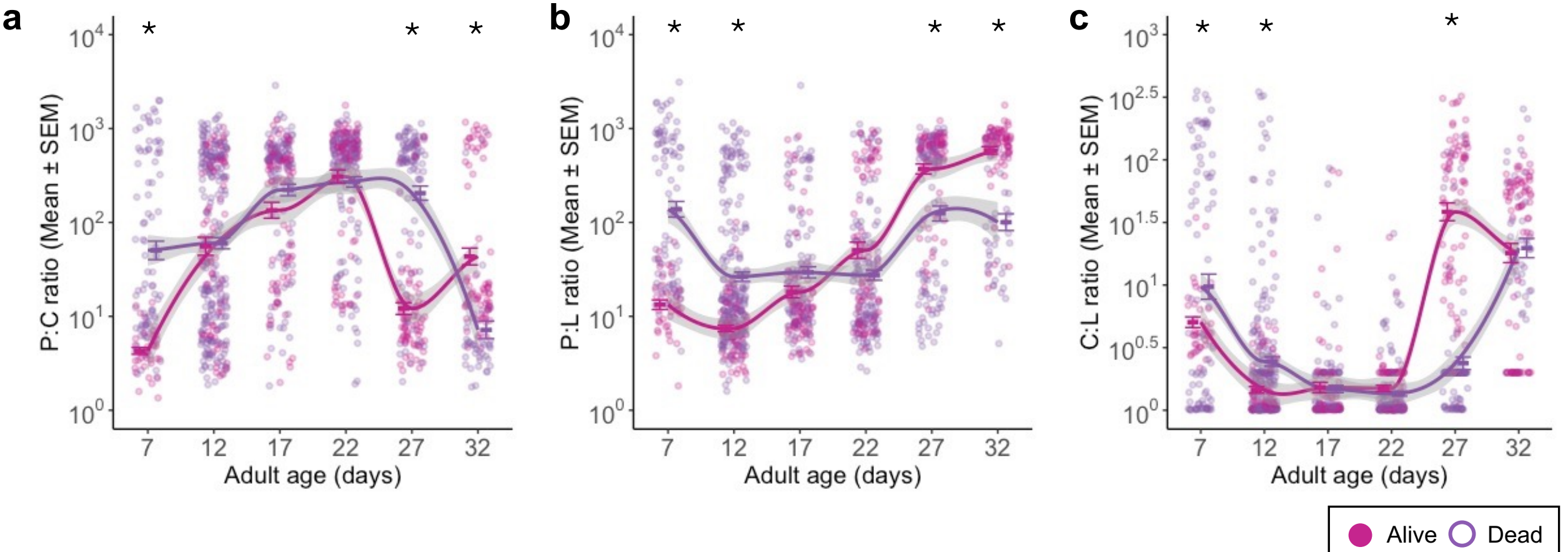



**Figure S1. Resource degradation after different times post-death.** A preliminary experiment was carried out to estimate if there is resource degradation at different time points post mosquito death: 0, 6, 12, and 18 hours post-death. For this, eight three-day-old mosquitoes (four exposed to *V. culicis* and four unexposed) per time-point were snap-frozen at -80 ºC for 24 hours and then left at room temperature for the duration of their time treatment. At the respective time-point, each individual was frozen at -80 ºC and their resources were quantified the next morning (see section 2.4 of the Materials and Methods). The average protein (a), carbohydrate (b) and lipid (c) content for each of the time post-death treatments is plotted above using absorbance as a proxy. A linear model was run for each resource category, with resource content as the response variable and time as an explanatory variable. There was no significant effect of time on the average content for any of the resource classes (Proteins: $F_{3,30} = 2.197$, $p = 0.109$; Carbohydrates: $F_{3,30} = 1.508$, $p = 0.233$; Lipids: $F_{3,30} = 1.260$, $p = 0.306$).


a
b
a
a
a
Longevity (Mean age at death ± SEM)
0
10
20
30
Not exposed
Exposed
Not exposed
Exposed
Treatment
b
Spore load
$10^2$
$10^3$
$10^4$
$10^5$
$10^6$
$10^7$
0
10
20
30
40
Longevity (age at death)
No blood meal
Blood meal
Alive
Dead


a
7 days
12 days
17 days
22 days
27 days
32 days
a
ab
bcd
de
cde
e
bc
e
bc
de
bcd
bcde
Spore load (Mean ± SEM)
b
abc
d
a
a
a
a
bc
ab
bc
ab
c
abc
Mean protein content ± SEM (ng/uL)
c
e
cd
bc
bc
ab
a
a
a
de
a
bc
e
Mean carb content ± SEM (ng/uL)
d
fg
cde
g
f
f
e
def
f
b
cd
a
c
Mean lipid content ± SEM (ng/uL)
Treatment
No blood meal
Blood meal
Alive
Dead


a
b
c
P:C ratio (Mean ± SEM)
P:L ratio (Mean ± SEM)
C:L ratio (Mean ± SEM)
Adult age (days)
7
12
17
22
27
32
Alive
Dead