Understanding glycaemia and glycation levels in birds: diet and life history traits associations

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ABSTRACT

The pace of life hypothesis (POL) suggests that organisms' life history, physiological and behavioural traits should co-evolve. In this context, glycaemia (i.e., blood glucose levels) and its consequences to ageing through its reaction with proteins and other compounds (i.e. glycation) constitute physiological traits which remain under-investigated in an evolutionary comparative framework, notably in relation to life history traits and ecological factors. Although their blood glucose levels are twice as high as in mammals, birds live longer when accounting for their body mass. We thus performed a comparative analysis on glucose and albumin glycation rates on 87 bird species from 22 orders, in relation to life history traits (body mass, clutch mass, maximum lifespan and developmental time) and diet. Glucose levels correlated positively with albumin glycation rates in a non-linear fashion, suggesting resistance to glycation in species with higher glucose levels. Plasma glucose levels decreased with increasing body mass and increased with maximum lifespan before reaching a plateau. Finally, terrestrial carnivores showed higher albumin glycation compared to omnivores. Our results open an important new avenue of research to help us to better understand the striking condition of hyperglycaemic yet long-lived birds.

INTRODUCTION

The pace of life (POL) hypothesis [1][2][3] postulates that organisms behavioural/physiological characteristics and life histories have co-evolved in answer to specific ecological conditions along a continuum. According to these characteristics, the pace of life can be either slow (e.g. large body mass, late maturation, slow growth rate, small number of large offspring and high longevity) or fast (e.g. small body mass, early maturation, high growth rate, a large number of small offspring and a short lifespan (see [4][5][6][7]). Studies have often tested predictions of POLS by focusing on metabolic rate (e.g. [8][9][10][11]). However, key energy substrates related to metabolic performance, such as glucose concentrations in tissues, have been largely overlooked (but see [12][13]). Notably, glucose, a central energy source for many organisms, plays a pivotal role in metabolism and its circulating blood or plasma levels correlate positively with metabolic rate (e.g. [14] for interspecific comparison; [15] for healthy humans).

Research focusing on plasma glucose becomes highly relevant as high glycaemia can entail costs that accelerate ageing. Along with other reducing sugars, glucose can react non-enzymatically with free amino groups of proteins, lipids or nucleic acids, a reaction known as glycation [16][17].

This reaction, after several molecular reorganizations, can lead to the formation of a plethora of molecules called Advanced Glycation End-products (AGEs) [18]. AGEs can form aggregates in tissues that contribute to several diseases related to ageing like diabetes (e.g., reviews by [19][20][21][22]). Also, AGEs are known to promote a proinflammatory state through their action on specific receptors called RAGEs [23][24].

Remarkably, birds show circulating glucose levels much higher than other vertebrate groups, on average twice as high as mammals [25]. Such relatively high glucose levels might support the higher metabolic rates [26][10] and body temperatures observed in birds compared to mammals [27][28]. In addition, elevated glycaemia is thought to be an adaptation to flight, providing birds with rapid access to an easily oxidizable fuel during intense bursts of aerobic exercise (see [29][30]), such as during take-off and short-term flapping flights [31][32]). However, the presence of high glycaemia in birds is also paradoxical, given their remarkable longevity compared to their mammalian counterparts — living up to three times longer than mammals of equivalent body mass [33][10].

Several non-excluding hypotheses have been proposed to explain how birds apparently resist the pernicious effects of a high glycaemic state. One possibility is that birds might resist protein glycation through a lower exposure of lysine residues at the surface of their proteins [34]. Another hypothesis suggests that increased protein turnover may play a role [35][36]. Additionally, birds might benefit from more effective antioxidant defences [37][38][39] or even the presence of "glycation scavengers" such as polyamines which circulate at high concentration [32]. Moreover, it is generally considered that RAGEs are not present in avian tissues, suggesting possible adaptive mechanisms that would allow birds to avoid the inflammatory consequences associated with RAGE activation [40][41]. However, Wein et al. [42] identified a putative candidate for RAGE and a case of AGE-induced inflammation, warranting further investigation.

To date, several studies have measured protein glycation levels in birds, but these have included a reduced number of species and are merely descriptive [43][44][45][46][47][48][49][50][51]. Additionally, many of these studies employ commercial kits that were not specifically designed for avian species, making it challenging to interpret the results [50]. These factors limit the ability to draw general conclusions from these studies. Here, we performed a comparative analysis on 87 species belonging to 22 orders and assessed whether and how bird glycaemia and glycation rates are linked to ecological and life-history traits. While doing this, we checked whether glycation levels are influenced by circulating plasma glucose concentrations. In addition, diet is

88 a key factor likely to influence glycaemia (see e.g. [52] but [13] found no significant effects), and
89 glycation. We hypothesized that carnivorous birds would exhibit higher glycaemia and glycation
90 levels than omnivorous or herbivorous species. This hypothesis is based on the evidence that a
91 low-carbohydrate, high-protein, high-fat diet is associated with hyperglycaemia and reduced
92 insulin sensitivity in some vertebrates (e.g.; [53][54][55]). This may be attributed to high levels
93 of constitutive gluconeogenesis, which has been confirmed in certain raptors [56][57].
94 Conversely, species with high sugar intake, such as frugivores or nectarivores, are expected to
95 exhibit high glycaemia, as observed in hummingbirds [46]. In line with POL theory, we also
96 hypothesized that species with a slower POL (hence slower metabolism and/or having specific
97 resistance mechanisms) would show lower glycaemia and higher glycation resistance (glycation
98 levels adjusted for glycaemia) compared to species with a faster POL. Hence, we included four
99 parameters in our analysis: body mass, maximum lifespan, clutch mass and developmental time.
100 Body mass is one of the main factors affecting life history, with higher body mass associated
101 with "slower" strategies and vice versa [58]. Previous studies have reported a negative
102 relationship between body mass and glycaemia [59][31][12][13], although [46] and [60] found
103 non-significant trends in birds). Therefore, we predicted that bird species that live longer,
104 develop more slowly and invest less per reproductive event should show lower plasma glucose
105 levels and albumin glycation rates.
106

107 # MATERIALS AND METHODS

108 ## Species and sample collection

109 A total of 485 individuals from 87 species were included in this study. A detailed list with the
110 provenance of the samples is provided in ESM 3, with a textual description in ESM 6.
111 Blood samples were collected from the brachial or tarsal vein, or from the feet in the case of
112 swifts, using heparin-lithium as anticoagulant. Samples were centrifuged at 4°C, 3500 g for 10
113 min and plasma was aliquoted when a large volume was available. Subsequently, they were
114 transported on dry ice to the IPHC (Institut Pluridisciplinaire Hubert Curien) in Strasbourg and
115 stored at -80º C until analysis. Glycaemia was measured on plasma with a Contour Plus®
116 glucometer (Ascensia diabetes solutions, Basel, Switzerland) and expressed in mg/dl. Due to
117 methodological constraints, glycaemia values of 96 individuals from 40 species (coming from
118 different sources) were not measured as described. For these species, mean plasma glucose

values were obtained from the ZIMs from Species360 (Species360 Zoological Information Management System (ZIMS) (2023), zims.Species360.org).

Glycation levels

Glycation levels for each individual were determined using liquid chromatography-mass spectrometry (LC-MS). Briefly, 3 µl of plasma were diluted with 22 µl of distilled water containing 0.1% of formic acid, followed by injection of 5 µl into the system. Detailed information regarding parameters and data processing can be found in [50]). The glycation values used in the analyses represent the total percentage of glycated albumin, obtained by adding the percentages of singly and doubly glycated albumin. In cases where albumin glycation values dropped below the limit of detection, resulting in missing data, these individuals (10 individuals from 4 species) were excluded from the statistical analyses, as outlined below.

Data on ecology and life-history

Diets of individual species were extracted from the AVONET dataset ([61], coming from[62], and those adapted from [63]) and life history traits from the Amniote Database [64]. After realizing that diet classifications from AVONET were not always suitable for our purposes, minor changes were made after consulting the original Wilman et al. [63] database (see ESM 6).

For missing data after this stage, we extracted values, in order of preference, from the AnAge database [65] or the Birds of the World encyclopaedia [66], by calculating mean values if an interval was given, and then averaging if male and female intervals were provided separately. For European species, longevity records have always been checked against the most recent Euring database [67]. Maximum lifespans from *Chionis minor* and *Eudyptes chrysolophus* (not available from the previous sources) were extracted from the Centre d'Etudes Biologiques de Chizé, Centre National de la Recherche Scientifique (CNRS-CEBC) database. Several species from the zoo had maximum lifespan values available on the ZIMs from Species 360 (Species360 Zoological Information Management System (ZIMS) (2023), zims.Species360.org), so these were also compared with the data we had from other sources.

In the case of variables for which two different sources provided different records, an average value was calculated. For the maximum lifespan value, available sources were cross-checked and the highest value was always used. In the absence of satisfactory support from another source, values for maximum lifespan indicated as being anecdotal and of poor quality have been excluded from the analyses. A table with the adequate citations for each value is provided as

150 part of the online available data (see Data accessibility section). When the source is AVONET
151 [61], this database is cited, and when it is Amniote Database [64], we cite the sources provided
152 by them, so the references can be checked in [64]. A list with all the additional references not
153 coming from any of these databases or not provided by their authors (and that are not already
154 in the main text) is given as ESM 4.

155 **Statistical analyses**

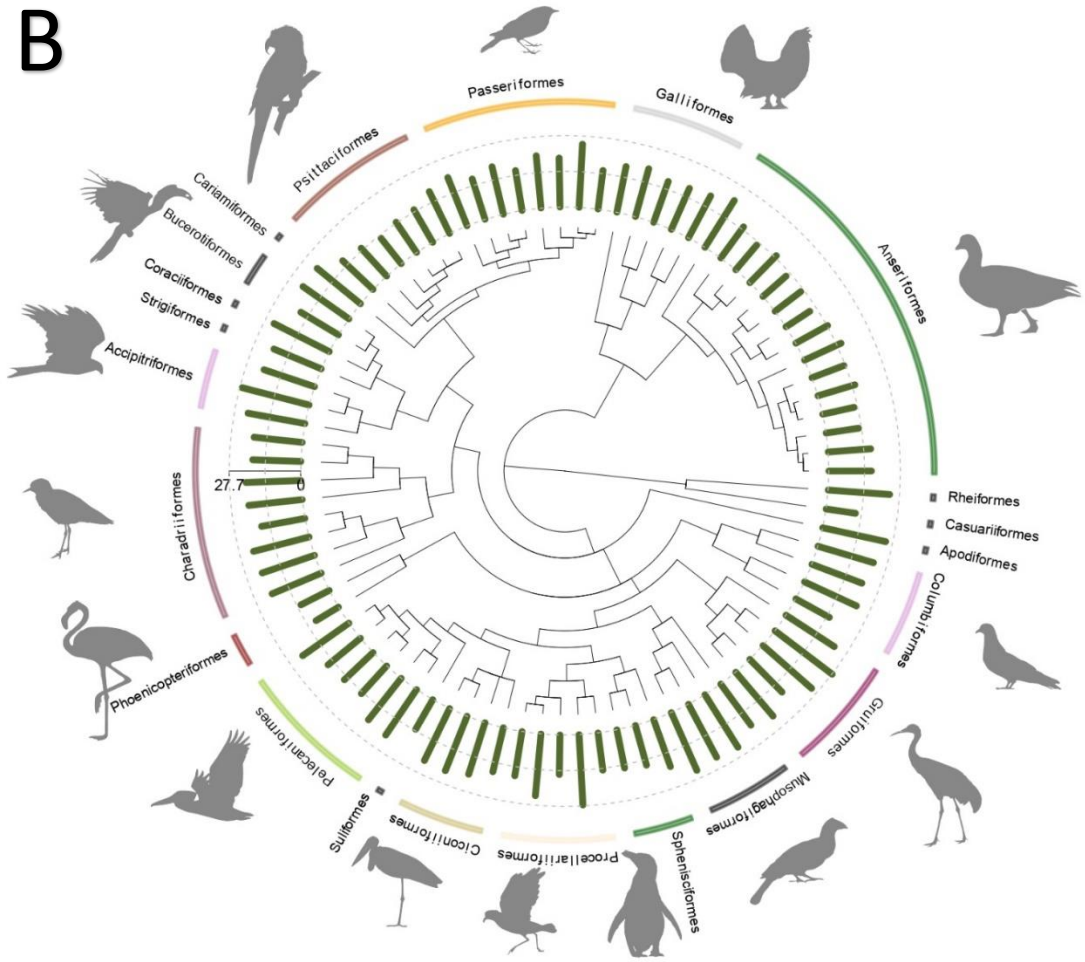
156 All analyses were performed in R v.4.3.2 [68]. Alpha less than 0.05 was considered as significant,
157 and between 0.05 and 0.1 as trends. All models were run with 6×10^6 iterations, with a thinning
158 interval of 50 and a burn-in of 1000. The models were simplified by eliminating quadratic terms
159 where they were not significant and selecting models with lower AIC (Akaike Information
160 Criterion) and BIC (Bayesian Information Criterion). For the phylogenetically controlled analyses,
161 consensus trees (each with the species included in the model) were obtained by using the
162 *consensus.edges* function (from the *phytools* package from R [69] from a total of 10,000 trees
163 downloaded from Birdtree.org (option "Hackett All species", [70]). The consensus trees were
164 included as *pedigree* in the models. We performed models with either glucose or glycation as
165 dependent variables and with the diet and life history traits as predicting variables. Models
166 testing the effects of age and sex on glucose and glycation levels and the number of exposed
167 lysine residues on glycation were also carried. A detailed description of all of them is given on
168 the ESM 6.
169

170 # RESULTS

171 **Plasma glucose and albumin glycation variability across the birds' tree**

172 Plasma glucose and albumin glycation values varied considerably across species (**Figure 1.A and**
173 **1.B, respectively**). We found significant differences between orders for both glucose (F=30.54,
174 p-value<0.001) and albumin glycation (F=21.9, p-value<0.001) with Passeriformes (mean=354.6,
175 se=±5.024 n=90, min=165, max=488; all values in mg/dl) and Apodiformes showing the highest
176 average glucose values (mean=350.5, se=±7.63, n=40, min=287.5, max=414.5) and the
177 Rheiformes, Suliformes and Phoenicopteriformes the lowest average values (mean=157.2,
178 se=±19.46, n=6, min=105, max=212). For glycation, Apodiformes had the highest average values
179 (mean=24.87, n=40 se=±0.59, min=12.46 max=28.73) while Phoenicopteriformes had the lowest

average levels (mean=10.57, se=±0.80, n=22, min=8.57, max=12.41). Graphs and a table with the difference between groups are shown on ESM2 (**Figure ESM2. 3 and Table ESM2. 1**). Raw outcomes of all models are available on ESM1.



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185 **Figure 1.A** Average plasma glucose values in mg/dl from all the species used in this study (some of them
186 coming from ZIMs database; see methods) with the Orders they belong to. **B** Average albumin glycation
187 rate for all the species measured in this study. Tree from a consensus on 10,000 trees obtained from
188 Hackett All species on Birdtree.org, including 87 species from 22 orders (see methods).

189 **<u>Bird glycemia appears affected by body mass and maximum lifespan</u>**

190 After controlling for intraspecific variation in our analyses, we found that variation in glucose
191 levels were significantly explained by variations in body mass and the quadratic component of
192 mass-adjusted maximum lifespan, but not by variations in diet, clutch mass and developmental
193 time (referring to the model including life-history trait variables; **Table 1**). Heavier species had
194 lower glucose levels (see **Figure 2.A**, drawn with the estimates from the model without life
195 history traits, which includes more species). Glucose levels increase with increasing mass-
196 adjusted lifespan until reaching a plateau (**Figure 2.B**). Models that did not consider interspecific

variability show no significant effect of any of the aforementioned variables on glucose levels (see ESM1).

Table 1. Final glucose model with diet, body mass, and life history traits as explanatory variables, including the significant quadratic effect of maximum lifespan. Posterior means, CI_{95} and pMCMC from a phylogenetic MCMC GLMM model including n=326 individuals of 58 species. Both glucose and body mass are log transformed and life history traits are residuals from a linear model of log body mass and log of the trait in question. Body mass was also centred to better explain the intercept, as 0 body mass would make no biological sense. The intercept corresponds to the Omnivore diet, being used as the reference as it is considered the most diverse and "neutral" group for this purpose. Significant predictors are indicated in bold.

	Estimates	Lower 95% CI	Upper 95% CI	Sampling effort	pMCMC
Intercept	**2.409**	**2.310**	**2.508**	**118632**	**< 0.001**
Diet: Carnivore terrestrial	-0.009	-0.077	0.059	119800	0.796
Diet: Aquatic predator	-0.004	-0.079	0.071	119800	0.932
Diet: Herbivore	-0.055	-0.175	0.061	119800	0.345
Diet: Frugivore/granivore	-0.032	-0.177	0.115	119800	0.667
Centered log(Body mass)	**-0.045**	**-0.084**	**-0.007**	**118572**	**0.025**
Maximum lifespan	0.108	-0.001	0.220	119800	0.056
Maximum lifespan^2	**-0.588**	**-0.998**	**-0.150**	**119800**	**0.009**
Clutch mass	-0.114	-0.260	0.034	119800	0.122
Developmental time	0.027	-0.133	0.193	122686	0.746

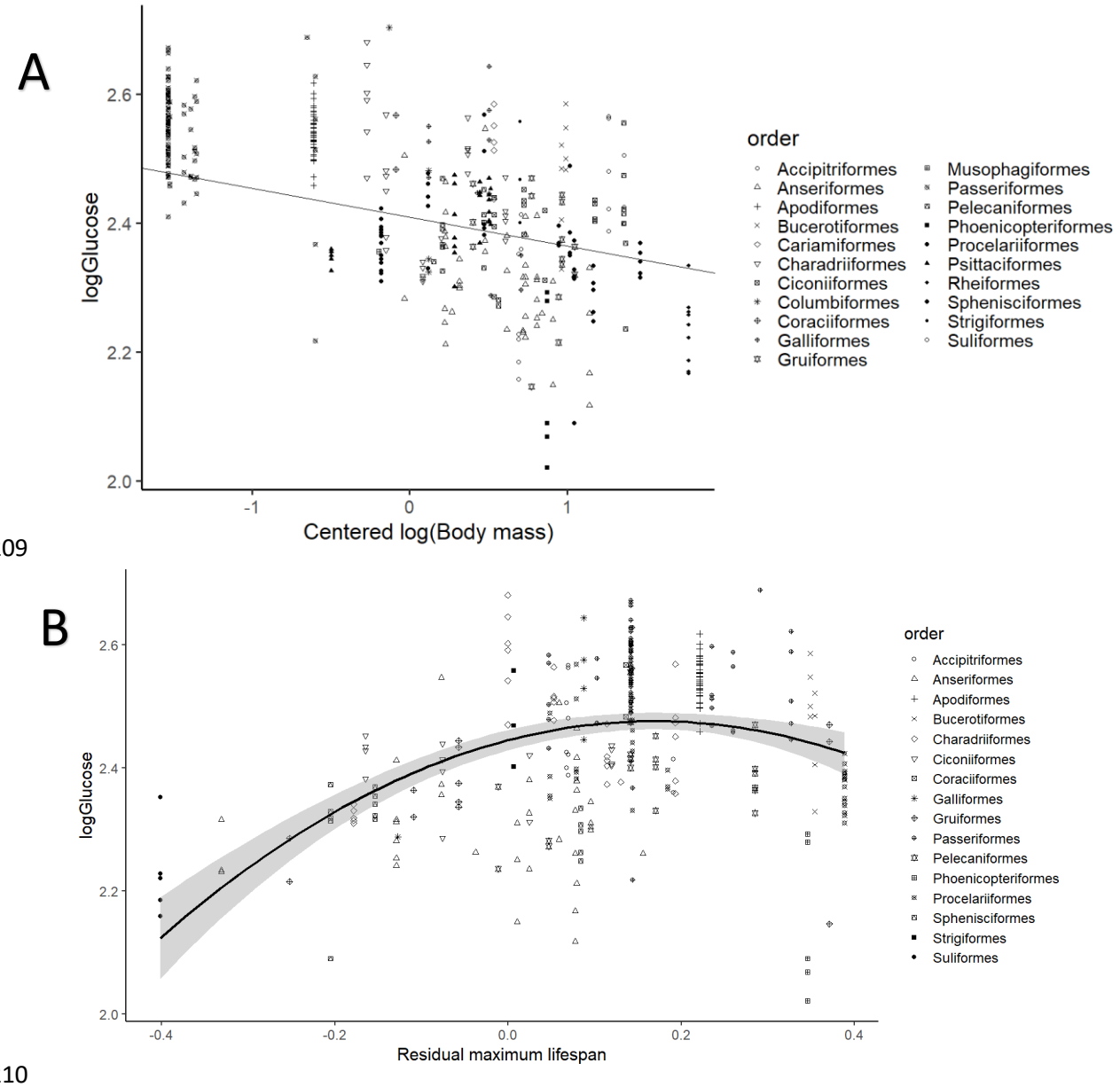


Figure 2. Plasma glucose levels (in mg/dl) variation as a function of **A** species mean centred body mass and **B** residual maximum lifespan. Both glucose and body mass are log transformed. Maximum lifespan (in years) is given as the residues of a linear model with body mass (in grams), both $\log_{10}$ transformed, so the effects of body mass on longevity are factored out. Different bird orders are indicated by symbols, as specified on the legends at the right side of the graphs. **Figure 2.A** uses the values and estimates from the glucose model without life history traits (n=389 individuals from 75 species), while **Figure 2.B** uses only the data points employed on the complete model (n=326 individuals of 58 species).

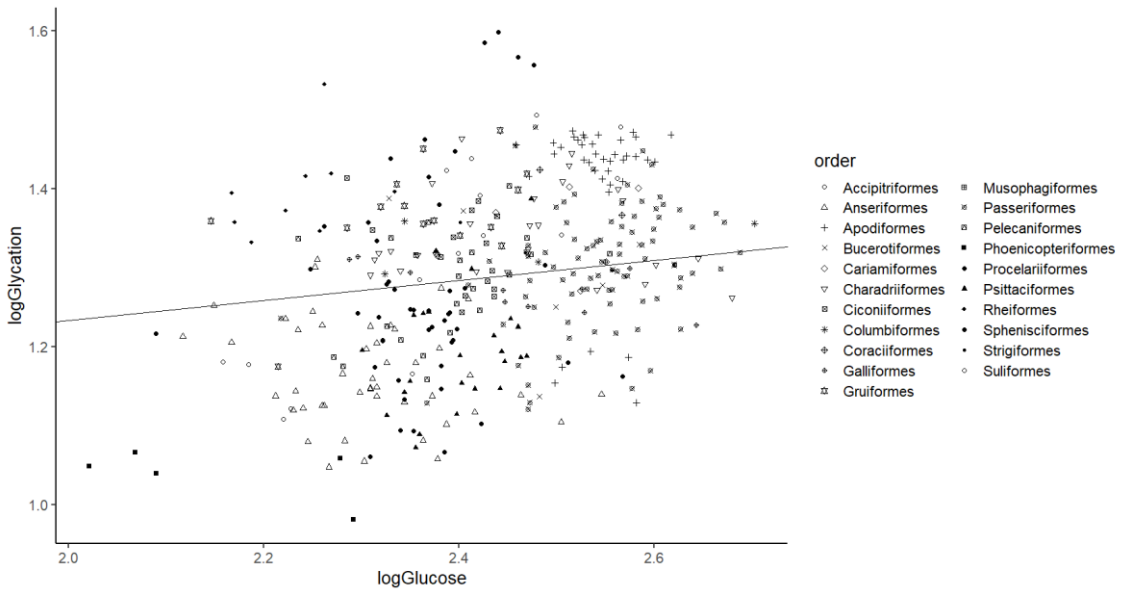
<u>Bird albumin glycation is related to glycemia, diet and clutch mass</u>

After controlling for intraspecific variability, we found that diet was affecting variation in albumin glycation rates, with carnivorous species having higher glycation levels than omnivorous species (**Table 2**; **Figure 4.B**). There were trends for species with greater investment into reproduction (i.e. clutch mass) to have higher glycation levels (**Table 2**), and glycation levels to increase with glucose levels (**Table 2**). The relation between glycation and glucose levels was significant in the model that did not include life history traits (β=0.127, CI_{95}[0.0217, 0.232], P_{MCMC}=0.0188; n=389 individuals from 75 species; **Figure 3**). Given that both plasma glucose and albumin glycation rates are logarithm transformed and the estimated slope of their relationship is lower than one, this implies that birds with higher glucose levels have relatively lower albumin glycation rates. Models that did not consider intraspecific variability show no effects of the diet, body mass, life history traits or glucose levels on albumin glycation rates (ESM1).

Additional analyses looking at the number of exposed lysines in the albumin sequence of a species show no effect of this variable on albumin glycation rates (β=0.243, CI_{95}[-0.106, 0.578], P_{MCMC}=0.154).

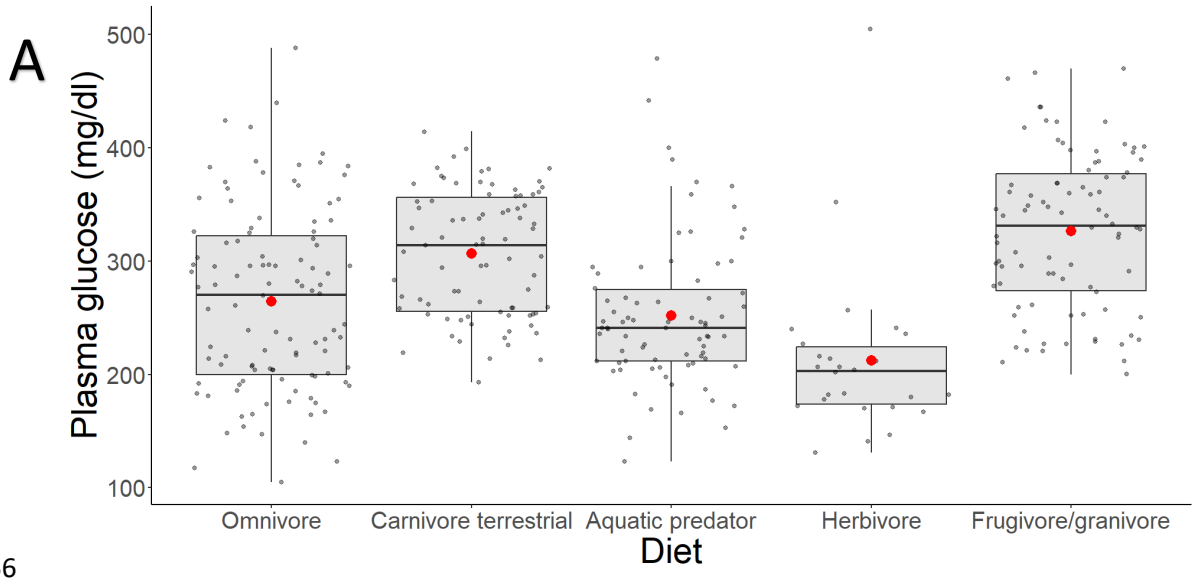
Table 2. Final glycation model with diet, body mass, glucose and life history traits as explanatory variables. Posterior means, CI_{95} and pMCMC from a phylogenetic MCMC GLMM model including n=326 individuals of 58 species. Both glucose and body mass are log transformed and life history traits are residuals from a linear model of log body mass and log of the trait in question. Body mass was also centred to better explain the intercept. The intercept corresponds to the Omnivore diet, being used as the reference as it is considered the most diverse and "neutral" group for this purpose. Significant predictors are indicated in bold.

	Estimates	Lower 95% CI	Upper 95% CI	Sampling effort	pMCMC
Intercept	**1.027**	**0.712**	**1.334**	**121,142**	**< 0.001**
Diet: Carnivore terrestrial	**0.101**	**0.014**	**0.187**	**119,800**	**0.023**
Diet: Aquatic predator	0.036	-0.063	0.134	119,800	0.470
Diet: Herbivore	-0.009	-0.167	0.154	118,625	0.906
Diet: Frugivore/granivore	0.101	-0.103	0.302	119,800	0.317
Centered log(Body mass)	0.005	-0.045	0.057	119,800	0.833
log(Glucose)	0.101	-0.014	0.217	119,800	0.088
Maximum lifespan	0.084	-0.058	0.227	120,728	0.239
Clutch mass	0.173	-0.008	0.358	119,800	0.060
Developmental time	0.069	-0.149	0.282	118,454	0.519



250 **Figure 3.** Albumin glycation rates (as a percentage of total albumin) variation as a function of individual
251 plasma glucose values (mg/dl). Different bird orders are indicated by symbols, as specified on the legends
252 at the right side of the graphs. The values and estimates used are from the glycation model without life
253 history traits (n=389 individuals from 75 species).

254 Regarding diet, the only significant effect observed was a higher level of albumin glycation in
255 terrestrial carnivores compared with omnivores (see **Table 2 and Figure 4.B**).



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257

258 **Figure 4.** Effects of diet on (**A**) plasma glucose levels and (**B**) albumin glycation in birds. Glucose levels are
259 given in mg/dl, while glycation levels are a percentage of total plasma albumin, which is found to be
260 glycated. Terrestrial carnivores showed significantly higher glycation levels than omnivores
261 (Estimate=0.101, p_{MCMC}=0.0231). Raw data shown.

262

263 We observed no significant effect of age relative to maximum lifespan nor sex on either
264 glycaemia or glycation (see **Figure ESM 2.1**).
265

266 DISCUSSION

267 Plasma glucose level and albumin glycation rate (co)variation suggests resistance 268 mechanisms

269 Our findings show that glucose levels vary widely among different bird groups. Interspecific
270 differences are partly explained by the allometric relationship of glycaemia with body mass
271 (**Figure 2.A**), which has already been reported in previous studies [59][31][12][13]. Indeed,
272 Passeriformes, Apodiformes and some Columbiformes (e.g. *Nesoenas mayeri* holds the highest
273 value in our dataset) are found at the higher end of the glucose level continuum, in accordance
274 with their relatively small body mass and powered flight, while groups of larger birds such as
275 Phoenicopteriformes, Anseriformes, Rheiformes and Suliformes tend to show low glycaemia
276 levels. This pattern is similar for glycation, with some groups of large birds (such as
277 Phoenicopteriformes, Anseriformes and Suliformes) showing the lowest levels of glycated
278 albumin, while small birds (such as Apodiformes) had the highest values. Nevertheless, glycation
279 remains high in some birds in relation to their glucose levels, as in Rheiformes, or low as in
280 Psittaciformes or Passeriformes. The case of Procellariiformes, which are typically long-lived
281 birds, is particularly striking, with some species exhibiting some of the highest glycation levels
282 (*Calonectris diomedea* and *Macronectes giganteus*) and others some of the lowest (*Procellaria*
283 *aequinoctialis*). This suggests that, if birds are protected against the deleterious effects of high
284 glycaemia, certain species may have evolved mechanisms to efficiently prevent proteins to be
285 glycated at high rates while others may have evolved mechanisms to resist the consequences of
286 protein glycation. We should also bear in mind that some taxonomic groups may be
287 underrepresented in our study, or biases in species selection due to availability contingencies
288 (e.g. species common in zoos or present in European countries) may exist, so further studies
289 should target this underrepresented groups in order to confirm our predictions.
290 As expected for a non-enzymatic reaction, just by the law of mass action, bird albumin glycation
291 rates increase with plasma glucose concentration. However, the logarithmic nature of the
292 relationship, together with a scaling factor lower than 1, suggests that species with higher

293 plasma glucose levels exhibit relatively greater resistance to glycation. This finding aligns with
294 previous research indicating that *in vitro* glycation levels of chicken albumin increase at a slower
295 rate than those of human albumin when glucose concentration is elevated [71]. Moreover, these
296 levels are consistently lower than those of bovine serum albumin regardless of glucose
297 concentration and exposition time [34]. As discussed in previous studies comparing chicken to
298 bovine serum albumin [34], or zebra finch to human haemoglobin [50], the lower glycation rates
299 observed in bird proteins may result from a lower number of glycatable amino acids (e.g. lysines)
300 in their sequence and/or their lesser exposure at the protein surface.
301 Our analyses indicate that average glycation levels increase with the number of glycatable
302 lysines in the albumin sequence, but not significantly. This may be attributed to the limited
303 number of species employed or the weak variation in the number of glycatable lysine residues,
304 which are mostly ranging from 33 to 39. An interesting exception are the 18 glycatable lysine
305 residues of flamingos (*Phoenicopterus ruber*), which also shows very low glycation levels
306 (mean=10.1%). However, the exceptions of 44 in zebra finches and 20 in godwits (*Limosa*
307 *lapponica*, used in place of *Limosa limosa*) are nevertheless associated with very similar average
308 glycation levels of 20.2% and 20.7% respectively.

309 **Plasma glucose relates with longevity and may be influenced by reproductive**
310 **strategies**

311 Our results were only partially in agreement with predictions from POLS theory. The only
312 previous comparative study of glycaemia and life history traits to our knowledge [13] shows no
313 relationship with mass-adjusted maximum lifespan in passerines. However, our study over 87
314 bird species on 22 orders revealed an increase in glucose with mass-adjusted longevity up to a
315 plateau (see **Figure 2.B**). Thus, the relationship between glucose and maximum lifespan may
316 depend on differences between bird orders or be tied to specific species particularities not
317 explored in our study. Such species particularities might involve additional undetermined
318 ecological factors that modify the relationship of glycaemia with longevity. Further exploration
319 of glucose metabolism in relation with lifestyle will bring further light on species-specific life-
320 history adaptations concerning glucose.
321 Regarding reproductive investment (i.e. clutch mass), our results show an apparent positive
322 linear relationship with glycation (see **Table 2**), while previous studies reported positive
323 relationships with glycaemia in passerines [13][72]. Interestingly, most of the species with high
324 clutch mass included in our study belong to the Anseriformes (**Figure ESM 2.2**). While these

species exhibit very low glycaemia and albumin glycation rates, they are also characterized by a particular reproductive strategy compared to passerines, for whom clutch mass does not imply the same in terms of parental investment. For instance, Anseriformes, unlike Passeriformes, are precocial and their offspring are not very dependent on parental care. Furthermore, they are capital breeders, accumulating the energetic resources required for reproduction in advance rather than collecting them during reproduction. These species typically have large clutch sizes and incubation is usually carried out by females, who store internal fat resources to support this main part of the parental investment. In addition, ducklings are born highly developed, reducing the amount of care required post-hatching (see e.g. [73][74]). Consequently, their dependence on glucose as a rapid energy source for reproduction may be lower, with investment in this activity likely more closely linked to lipid accumulation. This could explain why we did not detect previously reported effects of clutch mass on glucose levels, even if they may be present for glycation.

Terrestrial carnivores show a paradoxically increased albumin glycation rate without increased plasma glucose levels

Contrary to our expectation of finding differences across dietary groups, plasma glucose did not significantly vary with species diet. Nevertheless, this aligns with results previously reported by [13] for Passeriformes or by [52] for 160 species of vertebrates among which 48 were birds. Additionally, intraspecific data indicates that changes in diet composition hardly affects glycaemia in birds [75]. Together, these studies suggest that glycaemia is tightly regulated independently of dietary composition.

Although terrestrial carnivore species did not have significantly higher glycaemia levels, they nonetheless demonstrated significantly higher albumin glycation rates, suggesting a potential susceptibility to protein glycation. Besides unique structural features, this phenomenon could be due to lower albumin turnover rates in terrestrial carnivores. Studies in humans have linked higher oxidative damage to albumin with lower turnover rates (reviewed in [76]), which may extend to other species and post-translational modifications of albumin, such as bird's albumin glycation. However, the contrary outcome would be anticipated if protein intake were high as seen in carnivorous species [77][76].

Interestingly, the contrast between terrestrial and aquatic predators, which did not show such high glycation rates, suggests the beneficial influence of a substantial difference in food composition or the pre-eminence of another ecological factor, yet to be determined, which may

357 explain lower glycation levels in aquatic predators. In terms of food composition, the proportion
358 of essential n-3 PUFA (polyunsaturated fatty acids), particularly long-chain ones such as DHA and
359 EPA compared with n-6 PUFA and short-chain n-3 PUFA, is different in aquatic and terrestrial
360 environments [78] and therefore in the diet of predators in each environment (e.g. [79]). For
361 instance, low n-6 PUFA/n3- PUFA ratio have been shown to decrease insulin levels and improve
362 insulin resistance in humans [80]. On the other hand, while some studies report that an increase
363 in dietary n3-PUFA reduces the levels of glycated haemoglobin (HbA1c) in humans, this effect
364 was not detected in many other studies and therefore remains inconclusive (reviewed in [81]).
365 The detailed study of the fat composition of the diets of terrestrial and aquatic predators, in
366 particular the ratio between different types of PUFA, merits more attention. In addition,
367 micronutrient content, such as circulating antioxidant defences, should also be taken into
368 consideration. Indeed, a positive relationship between oxidative stress and glycated levels of
369 bovine serum albumin has been reported [82]. One hypothesis is that terrestrial predators have
370 higher systemic oxidative stress levels compared to other species, which may be explained by
371 defects in their antioxidant defences. Uric acid is one of the main non-enzymatic antioxidants in
372 birds [83][84][85]**,** and uric acid levels are especially high in carnivore species that have a rich
373 protein diet [86][84][87][88][89]. We should therefore tale into account other important
374 antioxidants such as vitamin E, vitamin A and carotenoids, which may be less abundant in the
375 diets of terrestrial carnivores (e.g. [90], but see [49]). The question of whether the diet of aquatic
376 carnivores provides a better intake of antioxidants would therefore requires a more detailed
377 description of dietary habits. The herbivorous diet, meanwhile, despite the expected possibility
378 contributing to lower glycaemia and glycation levels due to higher levels of PUFA compared to
379 SFA (saturated fatty acids) (effects reviewed in [81] for humans) and higher fibre content (see
380 [91]), did not lead to significantly lower levels of either of these two parameters. However, the
381 relatively low sample size in that group or the presence of outliers as *Nesoenas mayeri*, with the
382 highest glucose levels of this dataset, makes the interpretation of the obtained results somehow
383 limited. Therefore, further research should be carried out on these species to determine if the
384 expected pattern would emerge with a better sampling.
385 Finally, differences between captive and wild populations could be considered as a source of
386 variation in glucose or glycation levels, due to a more sedentary lifestyle in captivity, with lower
387 activity levels and a higher food intake likely to lead to increased circulating glucose levels in
388 captive individuals. Additionally, differences in nutrient intake, such as antioxidants, specific
389 fatty acids or amino acids, between captive and wild populations could contribute to variations

390 in glycation levels, as we saw above. Nevertheless, we believe that this factor may not
391 significantly affect our findings, as our study encompasses species from both captive and wild
392 populations across various diet groups, particularly those exhibiting significant differences (e.g.,
393 omnivores versus terrestrial carnivores).
394

395 **CONCLUSION AND PERSPECTIVES**

396 In conclusion, the avian plasma glucose levels measured here are generally higher or in the high
397 range of values recorded for mammalian species [25]. Our study also concludes that there is
398 considerable variation in plasma glucose levels and albumin glycation rates between bird
399 species, with those with the highest glucose levels showing greater resistance to glycation. The
400 correlation between plasma glucose and life history traits proves complex, primarily influenced
401 by its inverse association with body mass, along with non-linear, mass-independent effects of
402 longevity and potentially clutch mass. Finally, although diet does not explain plasma glucose
403 levels, terrestrial carnivores have higher albumin glycation rates. Whether these intriguing
404 results are explained by specific effects of certain dietary components, such as PUFAs and/or
405 antioxidants, remains to be determined. Differences in plasma glucose levels and albumin
406 glycation rates across bird species are only partially consistent with predictions according to the
407 POL hypothesis. Further investigation is needed to elucidate the correlation between these traits
408 and specific life conditions, such as reproductive strategy, migration patterns, flight mode or
409 detailed diet composition. In addition, more in-depth exploration of high glycaemic groups such
410 as the Passeriformes and other small birds, which make up a significant proportion of avian
411 species, could provide valuable new insights. Similarly, investigating groups such as the
412 Phoenicopteriformes or Anseriformes, which are at the other end of the glycaemic-glycation
413 spectrum, could shed light on the origin of differences between avian orders. Furthermore,
414 notable variations were observed between species within orders, as in the Procellariiformes,
415 which given their high mass-adjusted longevity, seems to suggest that some species may not be
416 intrinsically resistant to glycation, but rather to its adverse consequences for health. Future
417 studies should focus on specific species to unravel the physiological mechanisms mediating the
418 effects of blood glucose and protein glycation on life-history trade-offs, in particular mechanisms
419 that may vary between taxa and contribute to characteristic adaptations in birds to mitigate the
420 potentially negative effects of relative hyperglycaemia.

421

CONFLICTS OF INTEREST

None declared.

DATA ACCESSIBILITY

All data used, including references for the values taken from bibliography or databases, will be available as Electronic Supplementary Material (ESM5).

ETHICS STATEMENT

This study followed all the legal considerations, with the ethic authorisations from the French Ministry of Secondary Education and Research, n°32475 for the zebra finches sampling, the Swiss Veterinary Office (FSVO) nº 34497 for the Alpine swifts, the Ethics Committee of the University of Extremadura (licenses112//2020 and 202//2020) and the Government of Extremadura (licenses CN0012/22/ACA and CN0063/21/ACA) for the godwits and terns from Spain, and Sampling in Terres Australes et Antarctic Françaises was approved by a Regional Animal Experimentation Ethical Committee (French Ministry of Secondary Education and Research permit APAFIS #31773-2019112519421390 v4 and APAFIS#16465–2018080111195526 v4) and by the Comité de l'Environnement Polaire and CNPN (A-2021-55). The samples from the Mulhouse zoo were taken by its licensed veterinary with capacity number: 2020-247-SPAE-162.

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AUTHORS' CONTRIBUTIONS

F. Criscuolo and F. Bertile conceived the idea, directed most of the sample collection and logistics and contributed significantly to the writing. A. Moreno-Borrallo contributed to the development of the questions, gathered the diet and life-history data, performed the statistical analyses, and led the writing. S. Jaramillo Ortiz and C. Schaeffer performed the mass spectrometry analyses for protein glycation measurements, and S. Jaramillo Ortiz contributed to the glucose measures and commented on the manuscript. T. Boulinier. and V. A. Viblanc coordinated the ECONERGY and ECOPATH polar programs, organised the collection of samples on subantarctic seabirds, and commented on the manuscript. B. Rey contributed with the collection of samples from Parc des Oiseaux (Villars-les-Dombes, France) and commented on the manuscript. P. Bize leads the monitoring of Alpine swifts' populations from which the samples were obtained, he helped collecting them and commented on the manuscript. J. S Gutiérrez and J. A. Masero contributed with samples from Spain and part of the statistic scripts and commented on the manuscript. B. Quintard leads the health monitoring of Mulhouse zoo bird collection, organized and realized

most of Mulhouse zoo samplings and commented on the manuscript. All authors gave their approval for publication.

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REFERENCES

[1]. Wikelski, Martin and Robert E. Ricklefs. 2001. The physiology of life histories. *Trends in Ecology & Evolution*, 16 (9): 479–81. DOI:https://doi.org/10.1016/S0169-5347(01)02279-0

[2]. Ricklefs, Robert E. and Martin Wikelski. 2002. The physiology/life-history nexus. Trends in Ecology and Evolution, 17 (10): 462–68. https://doi.org/10.1016/S0169-5347(02)02578-8

[3]. Wikelski, Martin, Laura Spinney, Wendy Schelsky, Alexander Scheuerlein and Eberhard Gwinner. 2003. Slow pace of life in tropical sedentary birds: a common-garden experiment on four stonechat populations from different latitudes. *Proceedings of the Royal Society London B: Biological Sciences*, 270: 2383–88. https://doi.org/10.1098/rspb.2003.2500.

[4]. Stearns, Stephen C. 1989. Trade-offs in life-history evolution. *Functional Ecology*, 3, (3): 259-268. https://doi.org/10.2307/2389364

[5]. Gaillard, Jean-Michel and Dominique Pontier. 1989. An analysis of demographic tactics in birds and mammals. *Oikos*, 56: 59-76. https://doi.org/10.2307/3566088.

[6]. Stearns, Stephen C. 1992. The evolution of life histories. Oxford university press.

[7]. Vasilieva, N. A. 2022. Pace-of-Life Syndrome (POLS): evolution of the concept. *Biology bulletin*, 49 (7): 750–62, translated by M. Batrukova. https://doi.org/10.1134/S1062359022070238.

[8]. Trevelyan, Author R., P. H. Harvey and M. D. Pagel. 1990. Metabolic rates and life histories in birds. *Functional Ecology*, 4, (2), 135-141. https://doi.org/10.2307/2389332

[9]. Austad, Steven N. and Kathleen E. Fischer. 1991. Mammalian aging, metabolism, and ecology: evidence from the bats and marsupials. *Journal of Gerontology: Biological sciences*, 46 (2): 47–53. https://doi.org/10.1093/geronj/46.2.B47

[10]. Speakman, John R. 2005. Body size, energy metabolism and lifespan. *Journal of Experimental Biology*, 208 (9): 1717–30. https://doi.org/10.1242/jeb.01556.

[11]. Magalhães, João Pedro de, Joana Costa and George M. Church. 2007. An analysis of the relationship between metabolism, developmental schedules, and longevity using Phylogenetic Independent Contrasts. *The Journals of Gerontology: Series A*, 62 (2): 149–60. https://doi.org/10.1093/gerona/62.2.149

[12]. Kjeld, M and Ö. Ólafsson. 2007. Allometry (scaling) of blood components in mammals: connection with economy of energy? *Canadian Journal of Zoology*, 899: 890–99. https://doi.org/10.1139/Z08-061.

[13]. Tomášek, Oldřich, Lukáš Bobek, Tereza Kauzálová, Marie Adamkova and Tomáš Albrecht. 2019. Fuel for the pace of life: baseline blood glucose concentration co-evolves with life-history traits in songbirds. *Functional Ecology*, 33 (2): 239–49. https://doi.org/10.1111/1365-2435.13238

[14]. Umminger, Bruce L. 1977. Relation of whole blood sugar concentrations in vertebrates to standard metabolic rate. *Comparative Biochemistry and Physiology A*, 56, 457-460.

[15]. Guo, Hai, Dilihumaier Duolikun and Qiaoling Yao. 2023. Associations between basal metabolic rate and insulin resistance in non-diabetic obese adults: evidence from NHANES 2011–2018. International Journal of Diabetes in Developing Countries. https://doi.org/10.1007/s13410-023-01190-8.

[16]. Maillard, L. C. 1912. Action des acides amines sur les sucres; formation des melanoidies par voie methodique. *Comptes rendus de l'Académie des sciences*, 154, 66-68.

[17]. Suji, George and S. Sivakami. 2004. Glucose, glycation and aging. *Biogerontology*, 5: 365–373. https://doi.org/10.1007/s10522-004-3189-0

[18]. Cerami, Anthony, Helen Vlassara and Michael Brownlee. 1986. Role of nonenzymatic glycosylation in atherogenesis. *Journal of Cellular Biochemistry*, 30:111-120. https://doi.org/10.1002/jcb.240300203

[19]. Poulsen, Malene W., Rikke V. Hedegaard, Jeanette M. Andersen, Barbora de Courten, Susanne Bügel, John Nielsen, Leif H. Skibsted and Lars O. Dragsted. 2013. Advanced Glycation End-products in food and their effects on health. *Food and Chemical Toxicology*, 60: 10–37. https://doi.org/10.1016/j.fct.2013.06.052.

[20]. Chaudhuri, Jyotiska, Yasmin Bains, Sanjib Guha, Arnold Kahn, David Hall, Neelanjan Bose, Alejandro Gugliucci and Pankaj Kapahi. 2018. The role of advanced glycation end products in aging and metabolic diseases: bridging association and causality. *Cell Metabolism*, 28 (3): 337–52. https://doi.org/10.1016/j.cmet.2018.08.014.

[21]. Khalid, Mariyam, Georg Petroianu and Abdu Adem. 2022. Advanced Glycation End products and diabetes mellitus: mechanisms and perspectives. *Biomolecules*, 12 (4), 542. https://doi.org/10.3390/biom12040542

[22]. Twarda-Clapa, Aleksandra, Aleksandra Olczak, Aneta M. Białkowska and Maria Koziołkiewicz. 2022. Advanced Glycation End-products (AGEs): formation, chemistry,

565 classification, receptors, and diseases related to AGEs. *Cells*, 11(8): 1312.
566 https://doi.org/10.3390/cells11081312
567 [23]. Hofmann, Marion A., Steven Drury, Caifeng Fu, Wu Qu, Akihiko Taguchi, Yan Lu, Cecilia
568 Avila, Neeraja Kambham, Angelika Bierhaus, Peter Nawroth, Markus F. Neurath,
569 Timothy Slattery, Dale Beach, John McClary, Mariko Nagashima, John Morser, David
570 Stern and Ann Marie Schmidt. 1999. RAGE mediates a novel proinflammatory axis: a
571 central cell surface receptor for S100/Calgranulin polypeptides. *Cell*, 97 (7): 889–901.
572 DOI:https://doi.org/10.1016/S0092-8674(00)80801-6
573 [24]. Schmidt, Ann Marie, Shi Du Yan, Shi Fang Yan and David M. Stern. 2001. The multiligand
574 receptor RAGE as a progression factor amplifying immune and inflammatory responses.
575 *Journal of Clinical Investigation*, 108 (7): 949–55.
576 https://doi.org/10.1172/JCI200114002.
577 [25]. Polakof, Sergio, Thomas P. Mommsen and José L. Soengas. 2011. Glucosensing and
578 glucose homeostasis: from fish to mammals. *Comparative Biochemistry and Physiology,*
579 *Part B* 160 (4): 123–49. https://doi.org/10.1016/j.cbpb.2011.07.006.
580 [26]. Lasiewski, Robert C. and William R. Dawson. 1967. A re-examination of the relation
581 between standard metabolic rate and body weight in birds. *The Condor*, 69 (1): 13–23.
582 https://doi.org/10.2307/1366368
583 [27]. King, J. R. and Farner, D. S. (1961). Energy metabolism, thermoregulation and body
584 temperature. In Biology and Comparative Physiology of Birds, vol. II (ed. A. J. Marshall),
585 pp. 215–288. New York: Academic Press.
586 [28]. Dawson, Terence J. and A. J. Hulbert. 1970. Standard metabolism, body temperature,
587 surface areas of australian marsupials. *American Journal of Physiology*, 218 (4).
588 https://doi.org/10.1152/ajplegacy.1970.218.4.1233
589 [29]. Marsh, Richard L., David J. Ellerby, Jennifer A. Carr, Havalee T. Henry and Cindy I.
590 Buchanan. 2004. Partitioning the energetics of walking and running: swinging the limbs
591 is expensive. *Science*, 303 (5654): 80-83 https://doi.org/10.1126/science.1090704.
592 [30]. Weber, Jean-Michel. 2011. Metabolic fuels: regulating fluxes to select mix. *Journal*
593 *Experimental Biology*, 214 (2): 286–94. https://doi.org/10.1242/jeb.047050.
594 [31]. Braun, Eldon J. and Karen L. Sweazea. 2008. Glucose regulation in birds. *Comparative*
595 *Biochemistry and Physiology - B Biochemistry and Molecular Biology*, 151 (1): 1–9.
596 https://doi.org/10.1016/j.cbpb.2008.05.007.

597 [32]. Szwergold, Benjamin S. and Craig B. Miller. 2014b. Potential of birds to serve as
598 pathology-free models of type 2 diabetes, Part 2: Do high levels of carbonyl-scavenging
599 amino acids (e.g., taurine) and low concentrations of methylglyoxal limit the production
600 of Advanced Glycation End-products? *Rejuvenation Research*, 17 (4): 347–58.
601 https://doi.org/10.1089/rej.2014.1561.
602 [33]. Lindstedt, Stan L. and William A. Calder. 1976. Body size and longevity in birds. *The*
603 *Condor*, 78 (1): 91-94. https://doi.org/10.2307/1366920
604 [34]. Anthony-Regnitz, Claire M., Amanda E. Wilson, Karen L. Sweazea and Eldon J. Braun.
605 2020. Fewer exposed lysine residues may explain relative resistance of chicken serum
606 albumin to in vitro protein glycation in comparison to bovine serum albumin. *Journal of*
607 *Molecular Evolution*, 88 (8–9): 653–61. https://doi.org/10.1007/s00239-020-09964-y.
608 [35]. Muramatsu, Tatsuo. 1990. Nutrition and whole-body protein turnover in the chicken
609 in relation to mammalian species. *Nutrition Research reviews*, 3: 211-228
610 [36]. Makino, Ryosuke and Kazumi Kita. 2018. Half-Life of Glycated Tryptophan in the Plasma
611 of Chickens. *Journal of Poultry Science*, 55 (2): 117–19.
612 https://doi.org/10.2141/jpsa.0170158.
613 [37]. Schweigert, F. J., Stephanie Uehlein-Harrell, Giesela v. Hegel and H. Wiesner. 1991.
614 Vitamin A (retinol and retinyl esters), α-tocopherol and lipid levels in plasma of captive
615 wild mammals and birds. *Journal of Veterinary Medicine Series A*, 42: 35–42.
616 https://doi.org/10.1111/j.1439-0442.1991.tb00981.x
617 [38]. Ku, Hung-Hai and R.S. Sohal. 1993. Comparison of mitochondrial prooxidant
618 generation and antioxidant defenses between rat and pigeon possible basis of variation
619 in longevity and metabolic potential. *Mechanisms of Ageing and Development*, 72: 67–
620 76. https://doi.org/10.1016/0047-6374(93)90132-B
621 [39]. Hickey, Anthony J.R., Mia Jüllig, Jacqueline Aitken, Kerry Loomes, Mark E. Hauber and
622 Anthony R.J. Phillips. 2012. Birds and longevity: does flight driven aerobicity provide an
623 oxidative sink? *Ageing Research Reviews*, 11 (2): 242–53.
624 https://doi.org/10.1016/j.arr.2011.12.002.
625 [40]. Eythrib, Jalil. 2013. The search for the receptor for Advanced Glycation End-products
626 in avian vasculature. Bachelor thesis, The University of Arizona.
627 [41]. Szwergold, Benjamin S. and Craig B. Miller. 2014a. Potential of birds to serve as a
628 pathology-free model of type 2 diabetes, Part 1: Is the apparent absence of the rage

gene a factor in the resistance of avian organisms to chronic hyperglycemia? *Rejuvenation Research*, 17 (1): 54–61. https://doi.org/10.1089/rej.2013.1498.

[42]. Wein, Yossi, Enav Bar Shira and Aharon Friedman. 2020. Increased serum levels of advanced glycation end products due to induced molting in hen layers trigger a proinflammatory response by peripheral blood leukocytes. *Poultry Science*, 99 (7): 3452–62. https://doi.org/10.1016/j.psj.2020.04.009.

[43]. Rendell, Marc, P. M. Stephent, Robert Paulsent, J. L. Valentine, Kathy Rasbold, T. I. M. Hestorfe, Susan Eastberg and Daniel C Shintt. 1985. An interspecies comparison of normal levels of glycosylated hemoglobin and glycosylated albumin. *Comparative Biochemistry and physiology. B, Comparative Biochemistry*, 81 (4): 819–22. https://doi.org/10.1016/0305-0491(85)90072-0

[44]. Miksik, I. and Z. Hodny. 1992. Glycated hemoglobin in mute swan (*Cygnus olor*) and rook (*Corvus frugilegus*). *Comparative Biochemistry and Physiology Part B: Comparative Biochemistry*, 103 (3): 553–55. https://doi.org/10.1016/0305-0491(92)90369-3

[45]. Andersson, M. S. and L. Gustafsson. 1995. Glycosylated haemoglobin: a new measure of condition in birds. *Proceedings of the Royal Society B: Biological Sciences*, 260 (1359): 299–303. https://doi.org/10.1098/rspb.1995.0095.

[46]. Beuchat, Carol A. and Curtis R. Chong. 1998. Hyperglycemia in hummingbirds and its consequences for hemoglobin glycation. *Comparative Biochemistry and Physiology - A Molecular and Integrative Physiology*, 120 (3): 409–16. https://doi.org/10.1016/S1095-6433(98)10039-9.

[47]. Ardia, Daniel R. 2006. Glycated hemoglobin and albumin reflect nestling growth and condition in american kestrels. *Comparative Biochemistry and Physiology - A Molecular and Integrative Physiology*, 143 (1): 62–66. https://doi.org/10.1016/j.cbpa.2005.10.024.

[48]. Récapet, Charlotte, Adélaïde Sibeaux, Laure Cauchard, Blandine Doligez and Pierre Bize. 2016. Selective disappearance of individuals with high levels of glycated haemoglobin in a free-living bird. *Biology Letters*, 12: 20160243. https://doi.org/10.1098/rsbl.2016.0243.

[49]. Ingram, Tana, Jessica Zuck, Chad R. Borges, Patrick Redig and Karen L. Sweazea. 2017. Variations in native protein glycation and plasma antioxidants in several birds of prey. *Comparative Biochemistry and Physiology Part - B: Biochemistry and Molecular Biology*, 210 (January): 18–28. https://doi.org/10.1016/j.cbpb.2017.05.004.

[50]. Brun, Charlotte, Oscar Hernandez-Alba, Agnès Hovasse, François Criscuolo, Christine Schaeffer-Reiss and Fabrice Bertile. 2022. Resistance to glycation in the zebra finch: mass spectrometry-based analysis and its perspectives for evolutionary studies of aging. *Experimental Gerontology*, 164 (March). https://doi.org/10.1016/j.exger.2022.111811.

[51]. Borger, M. J. (2024). How to prime your offspring: putting behavioural ecology to the test. PhD thesis. University of Groningen. https://doi.org/10.33612/diss.849300689

[52]. Kapsetaki, Stefania E., Anthony J. Basile, Zachary T. Compton, Shawn M. Rupp, G. Duke, Amy M. Boddy, Tara M. Harrison, Karen L. Sweazea and Carlo C. Maley. 2023. The relationship between diet, plasma glucose, and cancer prevalence across vertebrates. Version 1. bioRxiv. Preprint. 2023 Aug 2. doi: 10.1101/2023.07.31.551378

[53]. Coulson, Roland A. and Thomas Hernandez. 1983. Alligator Metabolism studies on chemical reactions in vivo. *Comparative Biochemistry and Physiology Part B: Comparative Biochemistry*, 74(1), 1–175. https://doi.org/10.1016/0305-0491(83)90418-2

[54]. Dobbs, J. C. (1985). Avian carnivore: food recognition, nutrient intakes, and utilization of nitrogen. PhD thesis, University of California-Davis, Davis, CA.

[55]. Verbrugghe, Adronie and Myriam Hesta. 2017. Cats and carbohydrates: the carnivore fantasy? *Veterinary Sciences*, 4 (55): 1–22. https://doi.org/10.3390/vetsci4040055.

[56]. Migliorini, R. H., J. C. Linder, L. Moura and J. A. S. Veiga. 1973. Gluconeogenesis in a carnivorous bird (black vulture). *American journal of physiology*, 225 (6): 1389–1392. https://doi.org/10.1152/ajplegacy.1973.225.6.1389

[57]. Myers, Merrick R. and Kirk C. Klasing. 1999. Low glucokinase activity and high rates of gluconeogenesis contribute to hyperglycemia in barn owls (*Tyto alba*) after a glucose challenge. *The Journal of Nutrition*, 129 (10): 1896–1904. https://doi.org/10.1093/jn/129.10.1896

[58]. Stearns, Stephen C. 1983. The Influence of size and phylogeny on patterns of covariation among life-history traits in the mammals. *Oikos*, 41 (2): 173-187.

[59]. Umminger, Bruce L. 1975. Body size and whole blood sugar concentrations in mammals. *Comparative Biochemistry and Physiology A*, 52, 455-458.

[60]. Scanes, Colin G. 2016. A re-evaluation of allometric relationships for circulating concentrations of glucose in mammals. *Food and Nutrition Sciences*, 7 (4): 240–51. DOI: 10.4236/fns.2016.74026

[61]. Tobias, Joseph A., Catherine Sheard, Alex L. Pigot, Adam J. M. Devenish, Jingyi Yang, Ferran Sayol, Montague H. C. Neate-Clegg, Nico Alioravainen, Thomas L. Weeks, Robert A. Barber, Patrick A. Walkden, Hannah E. A. MacGregor, Samuel E. I. Jones, Claire Vincent, Anna G. Phillips, Nicola M. Marples, Flavia A. Montaño-Centellas, Victor Leandro-Silva, Santiago Claramunt, Bianca Darski, Benjamin G. Freeman, Tom P. Bregman, Christopher R. Cooney, Emma C. Hughes, Elliot J. R. Capp, Zoë K. Varley, Nicholas R. Friedman, Heiko Korntheuer, Andrea Corrales-Vargas, Christopher H. Trisos, Brian C. Weeks, Dagmar M. Hanz, Till Töpfer, Gustavo A. Bravo, Vladimír Remeš, Larissa Nowak, Lincoln S. Carneiro, Amilkar J. Moncada R., Beata Matysioková, Daniel T. Baldassarre, Alejandra Martínez-Salinas, Jared D. Wolfe, Philip M. Chapman, Benjamin G. Daly, Marjorie C. Sorensen, Alexander Neu, Michael A. Ford, Rebekah J. Mayhew, Luis Fabio Silveira, David J. Kelly, Nathaniel N. D. Annorbah, Henry S. Pollock, Ada M. Grabowska-Zhang, Jay P. McEntee, Juan Carlos T. Gonzalez, Camila G. Meneses, Marcia C. Muñoz, Luke L. Powell, Gabriel A. Jamie, Thomas J. Matthews, Oscar Johnson, Guilherme R. R. Brito, Kristof Zyskowski, Ross Crates, Michael G. Harvey, Maura Jurado Zevallos, Peter A. Hosner, Tom Bradfer-Lawrence, James M. Maley, F. Gary Stiles, Hevana S. Lima, Kaiya L. Provost, Moses Chibesa, Mmatjie Mashao, Jeffrey T. Howard, Edson Mlamba, Marcus A. H. Chua, Bicheng Li, M. Isabel Gómez, Natalia C. García, Martin Päckert, Jérôme Fuchs, Jarome R. Ali, Elizabeth P. Derryberry, Monica L. Carlson, Rolly C. Urriza, Kristin E. Brzeski, Dewi M. Prawiradilaga, Matt J. Rayner, Eliot T. Miller, Rauri C. K. Bowie, René-Marie Lafontaine, R. Paul Scofield, Yingqiang Lou, Lankani Somarathna, Denis Lepage, Marshall Illif, Eike Lena Neuschulz, Mathias Templin, D. Matthias Dehling, Jacob C. Cooper, Olivier S. G. Pauwels, Kangkuso Analuddin, Jon Fjeldså, Nathalie Seddon, Paul R. Sweet, Fabrice A. J. DeClerck, Luciano N. Naka, Jeffrey D. Brawn, Alexandre Aleixo, Katrin Böhning-Gaese, Carsten Rahbek, Susanne A. Fritz, Gavin H. Thomas and Matthias Schleuning. 2022. AVONET: Morphological, ecological and geographical data for all birds. *Ecology Letters*, 25: 581–97. https://doi.org/10.1111/ele.13898

[62]. Pigot, Alex L., Catherine Sheard, Eliot T. Miller, Tom P. Bregman, Benjamin G. Freeman, Uri Roll, Nathalie Seddon, Christopher H. Trisos, Brian C. Weeks and Joseph A. Tobias. 2020. Macroevolutionary convergence connects morphological form to ecological function in birds. *Nature Ecology & Evolution*, 4: 230–239. https://doi.org/10.1038/s41559-019-1070-4.

[63]. Wilman, Hamish, Marcelo M. Rivadeneira Jonathan Belmaker, Jennifer Simpson, Carolina de la Rosa and Walter Jetz. 2014. EltonTraits 1.0: species-level foraging attributes of the world's birds and mammals. *Ecology*, 95(7), 2027. https://doi.org/10.1890/13-1917.1

[64]. Myhrvold NP, Baldridge E, Chan B, Sivam D, Freeman DL, Ernest SKM. An amniote life-history database to perform comparative analyses with birds, mammals, and reptiles. *Ecology*. 2015. 96:3109.

[65]. Tacutu, Robi, Daniel Thornton, Emily Johnson, Arie Budovsky, Diogo Barardo, Thomas Craig, Eugene Diana, Gilad Lehmann, Dmitri Toren, Jingwei Wang, Vadim E. Fraifeld and João P. de Magalhães. 2018. Human Ageing Genomic Resources: new and updated databases. *Nucleic Acids Research*, 46 (D1): D1083–D1090. https://doi.org/10.1093/nar/gkx1042

[66]. Billerman, S. M., B. K. Keeney, P. G. Rodewald, and T. S. Schulenberg (Editors) (2022). Birds of the World. Cornell Laboratory of Ornithology, Ithaca, NY, USA. https://birdsoftheworld.org/bow/home

[67]. Fransson, T., Kolehmainen, T., Moss, D. & Robinson, R. 2023. EURING list of longevity records for European birds.

[68]. R: A language and environment for statistical computing. 2023. R Foundation for Statistical Computing, Vienna, Austria, https://www.R-project.org/

[69]. Revell, L. J. 2024. phytools 2.0: an updated R ecosystem for phylogenetic comparative methods (and other things). PeerJ, 12:e16505. https://doi.org/10.7717/peerj.16505

[70]. Hackett, Shannon J., Rebecca T. Kimball, Sushma Reddy, Rauri C. K. Bowie, Edward L. Braun, Michael J. Braun, Jena L. Chojnowski, W. Andrew Cox, Kin-lan Han, John Harshman, Christopher J. Huddleston, Ben D. Marks, Kathleen J. Miglia, William S. Moore, Frederick H. Sheldon, David W. Steadman, Christopher C. Witt and Tamaki Yuri. 2008. A phylogenomic study of birds reveals their evolutionary history. *Science*, 320 no. 5884: 1763–68. DOI: 10.1126/science.1157704

[71]. Zuck, Jessica, Chad R. Borges, Eldon J. Braun and Karen L. Sweazea. 2017. Chicken albumin exhibits natural resistance to glycation. *Comparative Biochemistry and Physiology Part - B: Biochemistry and Molecular Biology*, 203: 108–114. https://doi.org/10.1016/j.cbpb.2016.10.003.

[72]. Tomášek, Oldřich, Lukáš Bobek, Tereza Kauzálová, Ondřej Kauzál, Marie Adámková, Kryštof Horák, Sampath Anandan Kumar, Judith Pouadjeu Manialeu, Pavel Munclinger,

Eric Djomo Nana, Télesphore Benoît Nguelefack, Ondřej Sedláček, Tomáš Albrecht. 2022. Latitudinal but not elevational variation in blood glucose level is linked to life history across passerine birds. *Ecology Letters*, 25 (10): 2203-2216. https://doi.org/10.1111/ele.14097

[73]. Moreno, J. 1989. Strategies of mass change in breeding birds. *Biological Journal of the Linnean Society*, 37 (4): 297–310. https://doi.org/10.1111/j.1095-8312.1989.tb01907.x

[74]. Winkler, D. W. 2016. Breeding biology of birds. In: *Handbook of bird biology.* Edited by Irby J. Lovette, John W. Fitzpatrick. Cornell laboratory of ornithology, 407-450.

[75]. Basile, Anthony J., Kavita C. Singh, Deborah F. Watson and Karen L. Sweazea. 2022. Effect of macronutrient and micronutrient manipulation on avian blood glucose concentration: a systematic review. *Comparative Biochemistry and Physiology, Part A*, 272 (July). https://doi.org/10.1016/j.cbpa.2022.111279

[76]. Wada, Yasuaki, Yasuhiro Takeda and Masashi Kuwahata. 2018. Potential role of amino acid/protein nutrition and exercise in serum albumin redox state. *Nutrients,* 10 (1), 17, 1–11. https://doi.org/10.3390/nu10010017.

[77]. Honma, Ayaka, Chiaki Ogawa, Misaki Sugahara, Shinobu Fujimura and Kazumi Kita. 2017. Influence of varying dietary protein levels on glycation of albumin, tryptophan and valine in the plasma of chickens. *Journal of Poultry Science*, 54 (3): 242–46. https://doi.org/10.2141/jpsa.0160146.

[78]. Colombo, Stefanie M., Alexander Wacker, Christopher C. Parrish, J. Martin, Michael T. Arts, Stefanie M. Colombo, Alexander Wacker, Christopher C. Parrish, Martin J. Kainz and Michael T. Arts. 2017. A fundamental dichotomy in long-chain polyunsaturated fatty acid abundance between and within marine and terrestrial ecosystems. *Environmental Reviews*, 25 (2): 163–74. https://doi.org/10.1139/er-2016-0062

[79]. Charles, Apostolos-Manuel Koussoroplis, Lemarchand Alexandre, Philippe Berny and Gilles Bourdier. 2008. From aquatic to terrestrial food webs: decrease of the docosahexaenoic acid/linoleic acid ratio. *Lipids*, 43:461–66. https://doi.org/10.1007/s11745-008-3166-5.

[80]. Li, Na, Hao Yue, Min Jia, Wei Liu, Bin Qiu, Hanxue Hou, Fenghong Huang and Tongcheng Xu. 2019. Effect of low-ratio n-6/n-3 pufa on blood glucose: a meta-analysis. *Food and Function*, 10 (8): 4557–65. https://doi.org/10.1039/c9fo00323a.

790 [81]. Vibeke H. Telle-Hansen, Line Gaundal and Mari C.W. Myhrstad. 2019. Polyunsaturated
791 fatty acids and glycemic control in type 2 diabetes. *Nutrients*, 11 (1067): 12–15.
792 doi:10.3390/nu11051067
793 [82]. Bavkar, Laxman N., Rahul S. Patil, Sheetalnath B. Rooge, Megha L. Nalawade and
794 Akalpita U. Arvindekar. 2019. Acceleration of protein glycation by oxidative stress and
795 comparative role of antioxidant and protein glycation inhibitor. *Molecular and Cellular*
796 *Biochemistry*. https://doi.org/10.1007/s11010-019-03550-7.
797 [83]. Klandorf, H., I. L. Probert and M. Iqbal. 1999. In the defence against hyperglycamiea:
798 an avian strategy. *World's Poultry Science Journal*, 55 (3): 251–68.
799 https://doi.org/10.1079/WPS19990019.
800 [84]. Machín, M., M. F. Simoyi, K. P. Blemings and H. Klandorf. 2004. Increased dietary
801 protein elevates plasma uric acid and is associated with decreased oxidative stress in
802 rapidly-growing broilers. *Comparative Biochemistry and Physiology Part B*, 137: 383–90.
803 https://doi.org/10.1016/j.cbpc.2004.01.002.
804 [85]. Stinefelt, Beth, Stephen S. Leonard, Kenneth P. Blemings, Xianglin Shi and Hillar
805 Klandorf. 2005. Free radical scavenging, dna protection, and inhibition of lipid
806 peroxidation mediated by uric acid. *Anals of clinical and laboratory science*, 35 (1): 37–
807 45.
808 [86]. Harr, Kendal E. 2002. Clinical chemistry of companion avian species: a review.
809 *Veterinary Clinical Pathology* 31 (3). DOI:10.18637/jss.v033.i02
810 [87]. Smith, Susan B., Scott R. Mcwilliams and Christopher G. Guglielmo. 2007. Effect of diet
811 composition on plasma metabolite profiles in a migratory songbird. *The Condor*, 109 (1):
812 48–58, https://doi.org/10.1093/condor/109.1.48
813 [88]. Cohen, Alan A., Kevin J. Mcgraw and W. Douglas Robinson. 2009. Serum antioxidant
814 levels in wild birds vary in relation to diet, season, life history strategy, and species.
815 *Oecologia*, 161: 673–83. https://doi.org/10.1007/s00442-009-1423-9.
816 [89]. Alan, Rebecca R. and Scott R. Mcwilliams. 2013. Oxidative stress, circulating
817 antioxidants, and dietary preferences in songbirds. *Comparative Biochemistry and*
818 *Physiology, Part B*, 164 (3): 185–93. https://doi.org/10.1016/j.cbpb.2012.12.005.
819 [90]. Schneeberger, Karin, Gábor Á. Czirják and Christian C. Voigt. 2014. Frugivory is
820 associated with low measures of plasma oxidative stress and high antioxidant
821 concentration in free-ranging bats. *Naturwissenschaften*, 101: 285–90.
822 https://doi.org/10.1007/s00114-014-1155-5.

[91]. Goff, H. Douglas, Nikolay Repin, Hrvoje Fabek, Dalia El Khoury and Michael J. Gidley. 2018. Dietary fibre for glycaemia control: towards a mechanistic understanding bioactive. carbohydrates and dietary fibre. *Bioactive Carbohydrates and Dietary Fibre*, 14, 39-53