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# Using point-of-care devices to examine covariation among blood nutritional-physiological parameters and their relationships with poxvirus infection, habitat urbanization, and male plumage coloration in house finches (*Haemorhous mexicanus*)

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## Abstract

The development of inexpensive and portable point-of-care devices for measuring nutritional physiological parameters from blood (e.g., glucose, ketones) has accelerated our understanding and assessment of real-time variation in human health, but these have infrequently been tested or implemented in wild animals, especially in relation to other key biological or fitness-related traits. Here we used point-of-care devices to measure blood levels of glucose, ketones, uric acid, and triglycerides in free-ranging house finches (*Haemorhous mexicanus*)—a common songbird in North America that has been well-studied in the context of urbanization, nutrition, health, and sexual selection—during winter and examined (1) repeatability of these methods for evaluating blood levels in these wild passerines, (2) intercorrelations among these measurements within individuals, (3) how blood nutritional-physiology metrics related to a bird's body condition, habitat of origin (urban vs. suburban), poxvirus infection, and sex; and (4) if the expression of male sexually selected plumage coloration was linked to any of the nutritional-physiological metrics. All blood-nutritional parameters were repeatable. Also, there was significant positive covariation between concentrations of circulating triglycerides and glucose and triglycerides and uric acid. Urban finches had higher blood glucose concentrations than suburban finches, and pox-infected individuals had lower blood triglyceride concentrations than uninfected ones. Last, redder males had higher blood glucose, but lower uric acid levels. These results demonstrate that point-of-care devices can be useful, inexpensive ways of measuring real-time variation in the nutritional physiology of wild birds.

**KEYWORDS**
glucose concentration, host-pathogen interactions, hue, ketone concentration, plumage ornamentation, triglyceride concentration, uric acid concentration

## 1 | INTRODUCTION

Real-time monitoring of blood parameters has emerged as a valuable tool for diagnosing or tracking many chronic illnesses, including diabetes and cardiovascular diseases (Prakashan et al., 2023). Rapid serum surveillance is now part of many global disease assessment programs (WHO Technical Report Series, 2020), and having accessible point-of-care (POC) testing devices is central to this mission. For example, during the SARS-CoV-2 pandemic, POC testing was used for disease self-assessment, with an accuracy of 80%, even though asymptomatic infections were misdiagnosed in some cases (Kalia et al., 2022). In addition, POC testing considerably reduces costs for disease diagnosis, as well as the length of patient hospitalization (Wang et al., 2017).

Veterinarians and wildlife health specialists may also use blood samples to assess the health and condition of domesticated and wild animals (Cooke et al., 2013). For example, subclinical mastitis and Johne's disease in cattle can be rapidly and inexpensively screened on farms away from veterinary hospitals using POC devices (Kimura et al., 2012; Wadhwa et al., 2012). Many POC tests of nutritional physiology are now affordable and widely available, including real-time measurement of blood glucose, ketones, triglycerides, cholesterol, uric acid, and other components related to disease/health status (Beattie et al., 2023; DePinto & McGraw, 2022; Kim & Yoon, 2021; McGraw et al., 2020; McQuinn et al., 2020; Roy et al., 2022; Vitale et al., 2021) in humans and nonhuman animals (Srinivasan et al., 2017).

However, concerns persist over measurement accuracy and comparability (i.e., to traditional lab assays) when using POC devices, especially in wild animals, where this has not been frequently investigated. Some studies using POC glucometers found accurate levels of blood glucose in foals (Wong et al., 2021), dogs (Lane et al., 2015), and birds (McGraw et al., 2020; Morales et al., 2020), but in house sparrows (*Passer domesticus*) researchers found only moderate repeatability of glucose, ketone, and uric acid compared with lab assays (Beattie et al., 2022). There is also the growing need to understand the extent to which these hematological measurements yield information about separate or linked physiological processes (i.e., are concentrations of different blood nutrients intercorrelated?) and about key fitness variables or proxies (e.g., sex, survival, disease). In the aforementioned study of house sparrows, for example, authors found that, when exposed to stress, house sparrows increased glucose and ketone levels (Beattie et al., 2022), which was similar to a study in great tits (*Parus major*; Kaliński et al., 2022). Glucose and triglyceride concentrations are often associated with overall energy intake (Alonso-Alvarez & Ferrer, 2001; Jackson et al., 2023), but ketones are usually related to lipid utilization and fasting (Castellini & Rea, 1992) and may be considered as a proxy for total mass loss in birds (Alonso-Alvarez & Ferrer, 2001). Uric acid, in contrast, may reveal information about oxidative stress (Klandorf et al., 1999). Ultimately, we need more larger-scale studies that compare several POC-device-generated blood metrics concerning various life-history traits in a free-ranging animal.

Here, we investigated several POC-collected blood nutritional-physiological parameters in house finches (*Haemorhous mexicanus*), a free-ranging species that occurs in natural and human-modified habitats in Mexico and the United States of America (Badyaev et al., 2002). We used POC testing devices to screen for four different hematological variables - glucose, ketones, triglycerides, and uric acid concentrations—and first examined whether these could be measured repeatably (i.e., by taking two successive measurements). In prior work on house finches, we found that glucose and ketones were also highly repeatable (DePinto & McGraw, 2022), but the repeatability of triglycerides and uric acid measured with POC devices has not been examined. In addition, we analyze intercorrelations among the nutritional parameters, and we believe that this is the first study showing multiple correlations among POC-testing parameters examined in a single wild-bird species. We also tested if several organismal traits, including body condition, poxvirus infection, sex, and urbanization (urban house finches may have higher levels of glucose due to greater dietary intake; Gadau et al., 2019), predict concentrations of each blood nutritional variable. Previous studies in house finches found that birds circulating higher levels of glucose were in a better body condition and were more likely to be infected with poxvirus (McGraw et al., 2020), but triglycerides and ketones were not related to body condition or infection (Madonia et al., 2017). These results suggest that different blood nutritional-physiological parameters may relate to different traits in this species, but we still lack a more comprehensive analysis to better understand how these POC-measured components relate to life-history variation and health status. Lastly, we analyzed if male plumage color expression—a condition-dependent, sexually selected trait in this species (Badyaev et al., 2002)—was related to nutritional variables.

## 2 | METHODS

### 2.1 | Data collection

From 17 to 23 December 2021, we captured 35 wild house finches of unknown age (due to time of year) from two sites—an urban site (Arizona State University—Tempe campus; $n = 16$ females and 7 males), and a suburban site (Tempe residential neighborhood; $n = 6$ females and 6 males) separated by 8.2 km (McGraw et al., 2020)—in live traps surrounding sunflower-seed feeders. At capture, we measured body mass to the nearest 0.1 g with a digital scale and tarsus length to the nearest 0.01 mm with digital calipers, so that we could calculate body condition (using the residuals of a body mass-tarsus length regression; estimate 0.48; $p$-value = 0.11, $R^2 = 0.04$; McGraw et al., 2020). We also scored the presence/absence of poxvirus infection based on the occurrence of lesions on the legs, feet, bill, or eyes (Giraudeau, et al. 2014) and drew fresh blood from the brachial vein to measure four nutritional-physiological parameters using POC hand-held devices and test strips—(a) glucose (AccuChek® Guide blood glucosemeter; Roche Diabetes Care Inc., Indianapolis, IN), (b) ketones (β-hydroxybutyrate; Precision Xtra® blood glucose and ketone monitoring system; Abbott Laboratories), (c) uric acid (Fora® 6 Connect meter; ForaCare Inc.), and (d) triglycerides (CURO L5 at-home blood testing meter; CUROfit). The time that elapsed between trapping and blood collection was relatively similar among individuals. Units for all measurements are in mg/dL, except for ketones where it is mmol/L. Across the devices, we took duplicate blood measurements for a subset of birds and evaluated repeatability (Lessells & Boag, 1987), using the *blandr.statistics* function from the *blandr* package (Datta, 2017). In short, the package estimates the bias, which uses the mean difference and the standard deviation among all measurements (Martin Bland & Altman, 1986). We considered two measurements as repeatable if the upper and lower 95% confidence intervals did not include zero (Gerke, 2020). We also estimated the coefficient repeatability of the physiological-nutritional parameters. For that we used the following equation: $RC = 1.96\sqrt{\frac{\Sigma(m2-m1)^2}{n}}$, where *RC* is the repeatability coefficient, *m*2, and *m*1 are the second and first measurements, and *n* is the sample size (Martin Bland & Altman, 1986). We released all females at their site of capture after blood sampling but brought males into a dark room to take digital photos of the carotenoid-pigmented crown, breast, and rump plumage (Giraudeau et al., 2013). We placed the birds against a Kodak gray card, next to a color reference (Kodak color strip, Kodak, Kodak Color Control Patches 2007), and took two photos per patch (following McGraw et al., 2001). We analyzed photos using Adobe Photoshop CS6 (Adobe System), selecting the color patch with the *lasso* marquee and using the red-green-blue (RGB) values obtained from the Histogram window (Giraudeau et al., 2013) to determine hue values (McGraw & Hill, 2004) using the Color Picker function. We found a positive, significant correlation of hue scores between the two photos per patch ($R^2 = 0.97$, estimate = 0.97, SE = 0.04, *p*-value < 0.001); mean values were used in statistical analyses. After taking photos, we released males at their capture site.

## 2.2 | Statistical analysis

All analyses were performed in R software (R Core Team, 2019). We visually inspected the numeric values (blood concentrations of glucose, ketones, uric acid, and triglycerides, as well as body condition and plumage hue) for normality assumptions and, when necessary, corrected their distribution using square-root or logarithmic transformations, which was the case for uric acid, which became normally distributed after logarithmic correction. We also scaled all variables using *scale* function from base R packages to make variables comparable to one another. We then ran three separate sets of analyses: (a) We examined intercorrelations among glucose, ketones, uric acid, and triglyceride levels within individuals, using *cor.test* function from the stats package in R (R Core Team, 2019). We then used single values, or averaged ones for duplicate measurements, in the following statistical analyses. (b) We ran separate linear models using each blood-nutritional measurement as a response variable (glucose, ketones, uric acid, and triglycerides), and with poxvirus, body condition, sex, and sampling site (urban vs. suburban location) as predictors, using the *lm* function from *lme4* package (Bates et al. 2015). We tested for multicollinearity among predictors using the *pairs.pannel* function from the *regclass* package (Petrie, 2020) and found that body condition was negatively correlated with the presence of poxvirus infection ($R^2 = 0.39$; $p = 0.01$), so we included only poxvirus infection in our models. We also tested for the effects of the sex × sampling site interaction on hematological metrics and present these results only if statistically significant. We performed a theoretic-information approach (Burnham et al., 2011), and using the *dredge* function from the *MuMIn* package (Barton, 2019), we generated all possible models and averaged them using the *model.avg* function from the *MuMIn* package as well. We considered a variable as statistically significant in the averaged model if the 95% confidence interval did not include zero (Burnham & Anderson, 2002). (c) Because we only had plumage-color data for males (and thus could not incorporate it into the aforementioned linear models), we ran separate linear models with each blood-nutritional variable (glucose, ketones, uric acid, and triglycerides) as the response variable and with plumage hue as the predictor. We compared the full models against a null model (without hue) to test for model significance and considered the model as statistically significant if the *p* value was lower than 0.05 and the 95% confidence interval did not include zero. Significant variable plots were performed using the *ggplot2* package (Wickham, 2016).

# 3 | RESULTS

## 3.1 | Repeatability of blood-parameter measurements

First and second measurements of each blood-nutritional parameter (ketone, uric acid, triglycerides, and glucose levels in house finches) were repeatable (Table 1); we previously showed significant repeatability of glucose and ketone measures in finches as well (DePinto & McGraw, 2022; McGraw et al., 2020). Precision was higher for uric acid and ketones, and lower for triglycerides and glucose (Table 1).

**TABLE 1** Repeatability of blood levels of several nutritional-physiological parameters in wild house finches.

| Parameter | # | Bias | SE | U.C.I. | L.C.I. | CR |
|---|---|---|---|---|---|---|
| Glucose | 16 | −0.31 | 4.59 | 9.48 | −10.11 | 34.90 |
| Ketones | 16 | −0.13 | 0.08 | 0.04 | −0.32 | 0.71 |
| Uric acid | 20 | −0.06 | 0.03 | 0.00 | −0.13 | 2.96 |
| Triglycerides | 19 | 0.68 | 18.13 | 38.79 | −37.42 | 150.84 |

*Note*: We took duplicate measurements (i.e., from successive drops of blood within seconds) from a haphazard subset of animals for this analysis. Entries with an asterisk below indicate statistically significant and positive repeatability measurements. Here we show the number of replicates (#), the bias, the standard error of the bias (SE), the upper 95% confidence interval (CI) of the bias (U.C.I.), the lower 95% confidence interval of the bias (L.C.I.), and the coefficient of repeatability (CR).

### 3.2 | Covariation among blood nutritional-physiological parameters

We compared mean (or single, if no duplicate was run for a bird) values of ketone, glucose, uric acid, and triglyceride levels for all birds sampled and found significant intercorrelations between blood glucose and triglyceride levels and between triglyceride and uric acid concentrations (Table 2; Figure 1a,b); birds with higher blood triglyceride concentrations circulated more glucose and more uric acid. No other blood parameters showed significant covariation (Table 2).

### 3.3 | Links between blood parameters and habitat of origin, sex, body condition, and poxvirus infection

We examined the effects of capture-site, sex, poxvirus infection, and the capture-site × sex interaction on levels of all four blood measurements (models with weight lower than two can be found in Supporting Information S1: Table 1) and found a significant effect of capture site on blood glucose (Table 3); circulating glucose concentration was higher in urban birds compared with suburban birds (Figure 2a). Poxvirus infection significantly explained variation in triglyceride concentration (Table 3); uninfected birds had higher levels of circulating triglycerides compared with infected birds (Figure 2b). No predictors were significant in models involving ketones and uric acid (Table 3).

### 3.4 | Links between blood parameters and male plumage hue

Models comparing male plumage hue with mean glucose (residual sum of squares = 22,170; $p$ value < 0.01) and with uric acid (residual sum of squares = 290.76; $p$ value = 0.02) were significantly different from the null model (Table 4). Redder male house finches had

**TABLE 2** Intercorrelations among blood parameters (glucose, ketones, uric acid, and triglycerides) in wild house finches ($n$ = 35 for all comparisons).

| Parameters | Glucose level (mg/dL) | Ketone level (mmol/L) | Uric-acid level (mg/dL) | Triglyceride level (mg/dL) |
|---|---|---|---|---|
| Glucose level (mg/dL) | - | - | - | - |
| Ketone levels (mmol/L) | 0.05; 0.76 | - | - | - |
| Uric-acid level (mg/dL) | −0.06; 0.69 | 0.09; 0.58 | - | - |
| Triglyceride level (mg/dL) | 0.47; <0.01* | 0.00; 1.00 | 0.48; <0.01* | - |

*Note*: Here and elsewhere, asterisk entries denote statistically significant relationships. We show $R^2$ and $p$ values (separated by a semicolon) for each correlation.

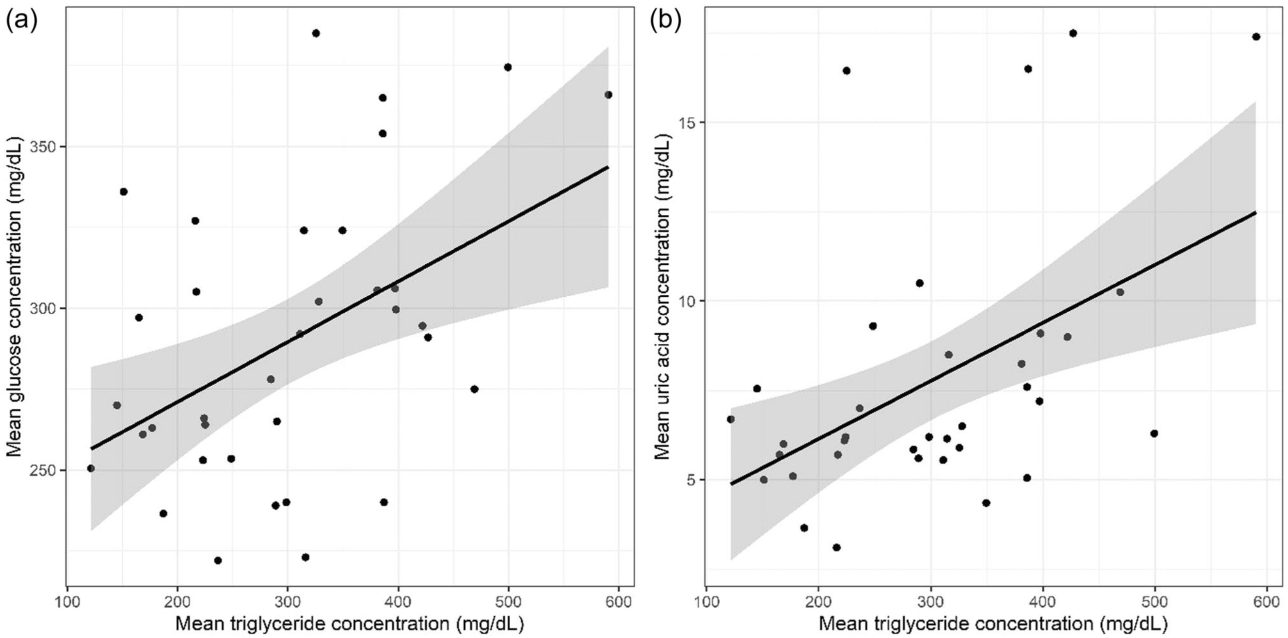


**FIGURE 1** Relationship between mean glucose and triglyceride concentration (a) and mean uric acid and triglyceride concentration (b). Gray area within the regression line indicates the confidence intervals.

**TABLE 3** Variables, estimate, standard error (SE), *p* value, and 95% confidence intervals of the results from the model averaging per response variable, namely: mean, glucose, ketone, uric acid, and triglyceride concentration.

| Variables | Estimate | SE | 95% confidence intervals |
|---|---|---|---|
| *Mean glucose concentration* | | | |
| Intercept | 304.74 | 9.34 | 285.80, 323.68* |
| Site (suburban) | −48.83 | 14.65 | −78.65, −19.02* |
| Sex (male) | 16.45 | 14.86 | −13.87, 46.77 |
| Poxvirus infection (absence) | −13.77 | 19.78 | −54.07, 26.53 |
| *Mean ketone concentration* | | | |
| Intercept | 3.22 | 0.25 | 2.71, 3.74* |
| Site (suburban) | −0.14 | 0.32 | −1.33, 0.48 |
| Sex (male) | −0.01 | 0.21 | −0.92, 0.81 |
| Poxvirus infection (absence) | −0.35 | 0.15 | −1.95, 0.36 |
| *Mean uric acid concentration* | | | |
| Intercept | 7.37 | 0.83 | 5.67, 9.07* |
| Site (suburban) | 1.27 | 1.49 | −1.76, 4.30 |
| Sex (male) | 1.41 | 1.42 | −1.46, 4.30 |
| Poxvirus infection (absence) | 0.46 | 1.88 | −3.37, 4.30 |
| *Mean triglyceride concentration* | | | |
| Intercept | 320.52 | 25.41 | 269.22, 371.81* |
| Site (suburban) | −47.10 | 41.54 | −131.83, 37.01 |
| Sex (male) | 10.37 | 39.43 | −69.91, 90.66 |
| Poxvirus infection (infected) | −120.10 | 52.57 | −227.00, −13.19* |

*Note*: Statistically significant results are marked with an asterisk.

significantly higher blood glucose (Figure 3a), but lower mean uric acid, concentrations than did less-red males (Figure 3b).

## 4 | DISCUSSION

POC blood nutritional-physiological parameters measured in a free-ranging desert songbird species were highly repeatable and these parameters did not all vary independently, such that birds who circulated higher triglyceride concentration also had higher levels of glucose and uric acid. We also found several important environmental or fitness-related predictors of these hematological measurements, such that (a) urban finches circulated higher glucose levels than suburban birds, (b) pox-infected birds had lower triglyceride levels than uninfected individuals, and (c) males with redder plumage had higher glucose and lower uric acid concentrations.

First, there was high repeatability of multiple measurements of glucose, ketones, triglycerides, and uric acid in house finches. Previous studies found that POC-measured blood parameters in one or several bird species were also comparable to traditional laboratory assays, even though POC testing devices had slightly higher values compared with the laboratory tests (Beattie et al., 2022; Morales et al., 2020). Our results had similar value ranges (Supporting Information S1: Table 2) compared with many other studies of different passerine species (Beattie et al., 2022; Dulisz et al., 2021; Gadau et al., 2019; Glądalski et al., 2018; Kaliński et al., 2014, 2022; Lieske et al., 2002; McGraw et al., 2020; Morales et al., 2020), which makes POC devices affordable and accessible tools that could be used to study life-history and blood nutritional physiological parameters in other wild animals. We note that POC devices can measure other hematological variables, such as cholesterol, electrolytes, and hemoglobin concentrations (Livingston et al., 2022; Morales et al., 2020; Sahoo et al., 2022), and we encourage other studies to investigate these additional blood parameters to understand the full efficacy and utility of POC devices with wildlife species.

Second, there was a positive association between circulating glucose and triglyceride concentrations in house finches. To our knowledge, our study is the first to directly compare blood triglycerides levels with glucose and uric acid concentrations in birds, with only indirect links made in previous studies (e.g., Remage-Healey & Romero, 2001). In diabetic mellitus and arterial diseases in humans, the positive relationship between blood glucose and triglyceride concentrations is well-known (Jin et al., 2018; West et al., 1983), and in non-fasting rats, hyperglycemia stimulates triglyceride synthesis (Hirano et al., 1990). We propose two hypotheses to explain the relationship between blood glucose and triglycerides in house finches: (a) birds circulating more glucose and triglycerides had a higher energy intake (Alonso-Alvarez & Ferrer, 2001); or (b) glucose and triglycerides may co-increase during stress, mainly as a consequence of the increased production and release of corticosterone through adrenocorticotropic hormone mediation (Olanrewaju et al., 2006). Therefore, triglycerides may be used for ATP synthesis (Starzec & Berger, 1986), and glucose to stimulate gluconeogenesis (Strack et al., 1995). For example, after being handled and restrained, captive European starlings (*Sturnus vulgaris*) had higher blood triglyceride and glucose concentrations, suggestive that multiple types of energy are being mobilized to cope with stress (Remage-Healey & Romero, 2001). There was also a positive association between uric acid and triglyceride concentrations in wild birds. Uric acid is a by-product of amino acid metabolism, such as purines, an important structure for DNA (Yu et al., 1998), which may be used to ameliorate oxidative stress (Klandorf et al., 1999). In children, high levels of serum uric acid were associated wither higher triglyceride levels, and the authors discussed that uric acid promotes lipid peroxidation, and may increase blood-vessel wall inflammation (Baldwin et al., 2011; Chu et al., 2021). Therefore, we suggest that the underlying mechanism for covariation between uric acid and triglyceride concentrations in house finches might also be stress related. For instance, chickens (*Gallus domesticus*) infected with nephropathogenic infectious bronchitis virus had higher levels of uric acid compared with uninfected ones, suggesting that uric acid increases NLRP3-inflammasome, which enhances inflammatory response against the virus (Xu et al., 2019). Similar results were

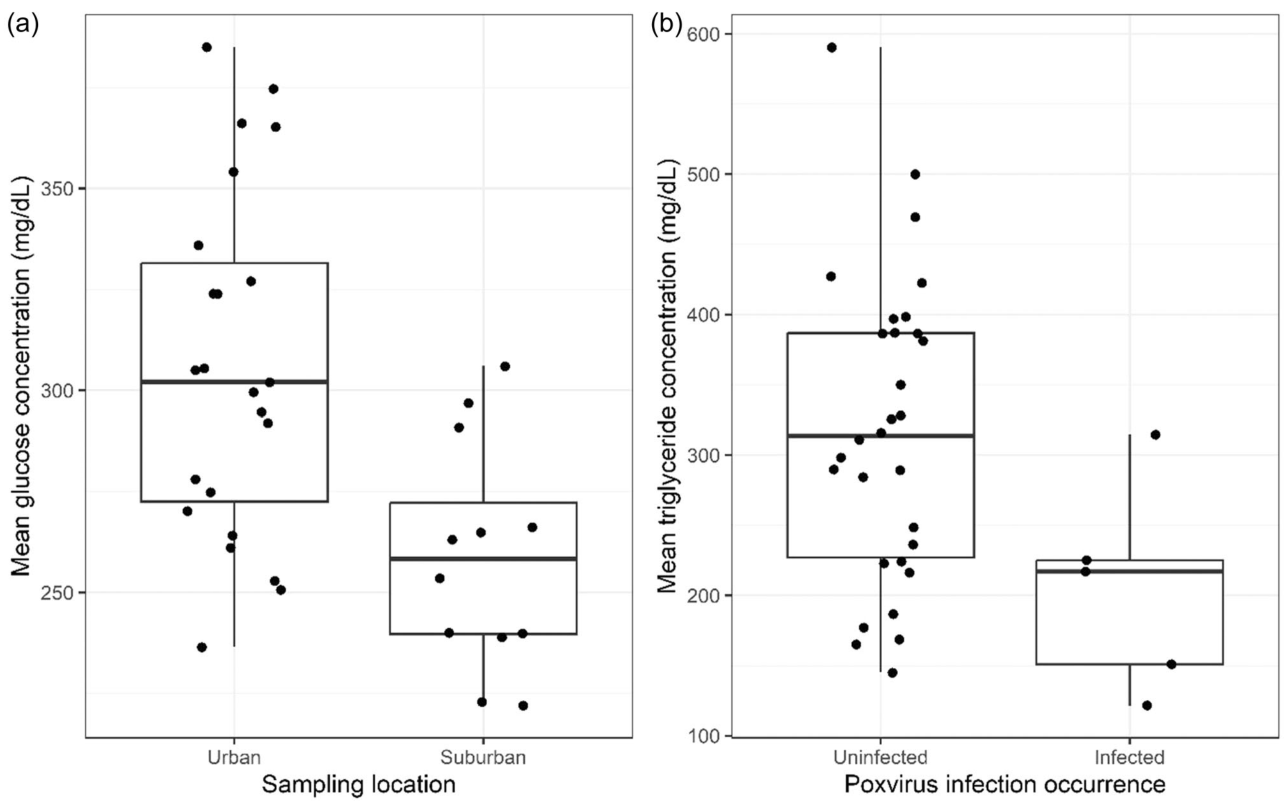


**FIGURE 2** Relationship between mean glucose concentration and sampling location (a); and between mean triglyceride concentration and poxvirus infection occurrence (b).

**TABLE 4** Variable, estimate, standard error (SE), *p* value, and 95% confidence interval for the mean glucose and uric acid concentration, the response variables, and male plumage hue as the predictor.

| Variable | Estimate | SE | 95% confidence interval |
|---|---|---|---|
| *Mean glucose concentration* | | | |
| Intercept | 355.30 | 23.47 | 303.63, 406.98* |
| Hue | −4.53 | 1.55 | −7.88, −1.04* |
| *Mean uric acid concentration* | | | |
| Intercept | 2.82 | 2.96 | −3.69, 9.34 |
| Hue | 0.43 | 0.19 | 0.00, 0.86* |

*Note*: Statistically significant variables are marked with an asterisk.

found in white-crowned sparrows (*Zonotrichia leucophrys*) (Tsahar et al., 2006) and in house sparrows (*P. domesticus*) (Beattie et al., 2023), with individuals under higher stress having higher circulating levels of uric acid and triglycerides, suggesting a similar pattern in different songbirds. Hence, it is most likely that the sampled house finches with higher circulating uric acid and triglyceride concentrations were under stress, compared with the individuals with lower levels of both. We suggest that future studies should employ different stress manipulations to better understand the mechanisms underlying covariation between uric acid and triglycerides.

In our analysis examining various biological predictors of levels of each nutritional-physiological metric, we found that urban house finches in this winter (pre-breeding) study had higher glucose concentrations than did suburban birds. Previous studies in great tits (*P. major*; Glądalski et al., 2018), blue tits (*Cyanistes caeruleus*; Kaliński et al., 2014), and house sparrows (*P. domesticus*; Dulisz et al., 2021; Gadau et al., 2019) also found a higher concentration of blood glucose in urban birds. These results suggest that food sources in urban locations (e.g., bird feeders) might be more readily available compared with suburban locations, as well as a lower usage of carbohydrates for shorter-distance flights to forage for energy-rich resources (Rothe et al., 1987). Poxvirus-infected house finches had lower levels of triglycerides. To our knowledge, this is the first avian study to find a negative association between poxvirus infection and triglyceride concentration. Previous studies on *Plasmodium*-infected tropical birds (Messina et al., 2022), wood warblers infected with haematozoan protists (DeGroote & Rodewald, 2010), and adenovirus-infected chickens (Dhurandhar et al., 1992) found that infected individuals had lower levels of triglycerides. These results suggest two non-mutually exclusive hypotheses: (a) to meet the immunological costs to fight-off pathogens or parasites, birds may increase lipid catabolism or feed intake to increase resources to cope with infection; or (b) individuals circulating lower levels of

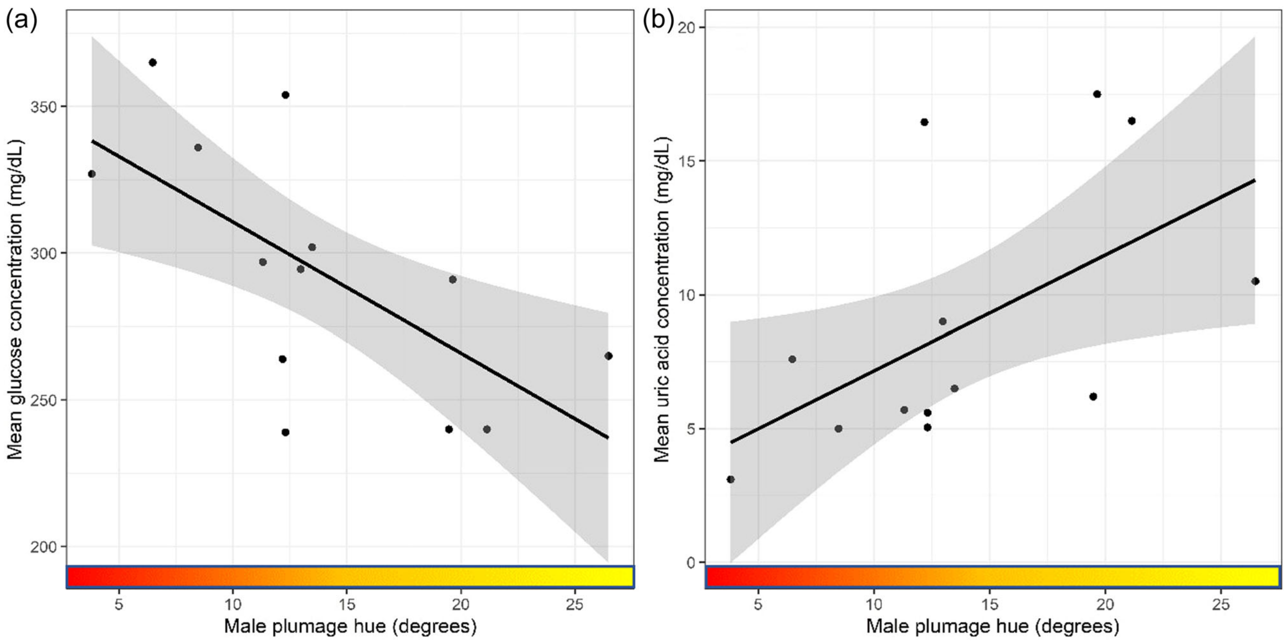


**FIGURE 3** Relationship between male plumage hue (in degrees) and mean glucose concentration (a) and mean uric acid concentration (b).

triglycerides may be more vulnerable to infection. Future experimental manipulations of pathogen/parasite infection and/or triglyceride status will help to identify the causal direction of this relationship.

Lastly, redder males had lower circulating concentrations of uric acid. Previous studies found that antioxidant capacity is highly correlated with plasma uric acid (Hõrak et al., 2010; Perez-Rodriguez et al., 2008), and that the circulating levels of uric acid is sensitive to stressors (Cohen et al., 2007), such that plasma corticosterone increased with a higher mean uric acid concentration in migratory birds (Jenni et al., 2000). Therefore, our results suggests that yellower birds were under greater stress (especially disease stress; Balenger et al., 2015; Hill & Farmer, 2005; Hill et al., 2019), compared with redder birds, with a higher necessity to cope with the stressor by increasing circulating uric-acid concentrations. It is worth noting that all birds had already completed molt at least two and half months previously; thus, it is unlikely that the development of their colorful feathers played a strong, direct role in the relationship between carotenoid plumage pigmentation and uric acid concentration in our sampled birds. Redder birds also had higher circulating levels of glucose. Glucose is used mainly for immediate energy utilization and suggests a higher food intake by redder males (Alonso-Alvarez & Ferrer, 2001). Higher levels of glucose were previously shown to be associated with higher body condition and infection with poxvirus in house finches during winter (McGraw et al., 2020), but there also was a lack of association between plumage hue and glucose in a study performed later in the winter time in the same population of house finches (DePinto & McGraw, 2022). Our results suggest two non-mutually exclusive hypotheses: (a) that redder males may be better-equipped to find energy-rich resources and increase food intake during early winter. In addition, a month later, when birds start to form breeding pairs, the physiological trade-offs related to pair formation may deplete resources faster for all male finches (regardless of plumage color), which may explain why, in a study in late January, plumage hue was not related to circulating glucose concentrations in the same population (DePinto & McGraw, 2022). (b) individuals that were already in better condition could invest in plumage coloration without compromising their overall health/nutritional status. Nevertheless, our results support that redder males might be under lower stress and might ingest more energy-rich resources compared with yellower birds, which may have important consequences for female mate choice, since females tend to select redder males over yellower ones (Toomey & McGraw, 2012).

It is important to acknowledge a potential limitation in our findings. Despite the fact that we kept a generally consistent timeframe between trapping and blood data collection, there is a possibility that the handling process may have influenced some of the physiological-nutritional blood parameters (Müller et al., 2006; Parks et al., 2023; Vleck et al., 2000). To address this concern, we recommend that future studies utilizing POC devices specifically take into account the trapping and processing time as a factor to assess any potential impact on blood metrics. Nevertheless, our study's outcomes carry significant implications for animal physiology, health, and conservation. Wider use of POC devices has the potential to enhance the monitoring of wildlife health, facilitating early disease detection and offering insights into how environmental stress impacts wild animals. Particularly in human-impacted areas, real-time data on animal nutritional physiology could guide conservation efforts toward particularly sensitive species or habitats.

In summary, affordable and accessible POC devices can generate highly repeatable, real-time nutritional-physiology data in wild birds, which may be a valuable tool for tracking real-time health and nutritional state in many avian species. We also found important correlations between a few, but not all, blood nutritional parameters in house finches, suggesting that birds circulating more glucose and triglycerides ingested more energy-rich resources or are under a greater stress burden, which is also consistent with the positive correlation we observed between blood triglycerides and uric acid levels. Also, other nutritional parameters varied independently and may reveal different underlying physiological processes. We also found important links between some blood nutrients and both urbanization and infection state, suggesting that, because urban birds had higher glucose concentration, they may have higher resource availability compared with suburban birds. In addition, birds with lower triglyceride levels might be more exposed to poxvirus infection or may use a greater fat reserve to fight-off disease. Lastly, males with redder, sexually attractive plumage had higher glucose levels but lower uric acid levels, suggesting that redder birds feed on more energy-rich resources and may be under a lower oxidative stress burden, as suggested by the low levels of uric acid. We hope that our broad set of analyses using affordable POC nutritional devices inspires many to include these in their research and expand our understanding of real-time variation in nutritional physiology and health of wild birds, especially in areas experiencing significant and rapid anthropogenic impacts.

## AUTHOR CONTRIBUTIONS

Kevin J. McGraw and Victor Aguiar de Souza Penha designed the idea, collected data, processed information, analyzed the results, and wrote the manuscript.

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## CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

## DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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## SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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