Journal of Ornithology
https://doi.org/10.1007/s10336-021-01942-5

ORIGINAL ARTICLE

Measuring circulating triglycerides in free-living birds: evaluation of a field-usable point-of-care analyzer for American woodcock

Christopher M. Roelandt[1] · **Amber M. Roth**[2] · **Scott R. McWilliams**[3] · **Jill C. Witt**[1]

Received: 20 July 2021 / Revised: 25 September 2021 / Accepted: 31 October 2021

Abstract

Plasma metabolites such as triglyceride (TRIG) can be useful indicators of when birds are in a state of fattening or fasting, although the challenges of processing, storing, and analyzing field-collected plasma samples may limit its use by field ornithologists. We evaluated the use of a field-usable point-of-care (POC) analyzer (CardioChek PA analyzer) for measuring TRIG concentrations in the plasma of male American Woodcock (*Scolopax minor*) captured during their spring courtship period and compared those measures to those from standard laboratory analyses of the same plasma samples. Plasma TRIG measured in the field with the POC analyzer was highly repeatable and precise, but not accurate compared to lab-measured values. The inaccuracy of the POC analyzer may be due to the effects of environmental conditions on the analyzer's function or to specific problems associated with analyzing woodcock blood. We conclude that the field-usable POC analyzer does not provide an accurate alternative method for measuring circulating TRIG in woodcock during cold springs in northern breeding areas. Given the analyzer has proven accurate for estimating circulating TRIG in some other bird species, we outline a two-phase pilot study that field ornithologists can use to understand the operating limits of this analyzer for their target species prior to field use.

Keywords Body condition · Bird physiology · Plasma metabolite analysis · POC analyzer · Field comparison

Zusammenfassung

Messung von Triglyceriden bei frei lebenden Vögeln: Test und Bewertung eines vor Ort im Feld einsetzbaren Analysators bei Kanadaschnepfen

Plasmastoffwechselprodukte wie z.B. Triglyceride (TRIG) können nützliche Indikatoren dafür sein, wann sich Vögel in einem Gewichtszunahme- oder –abnahmestadium befinden, obwohl die Probleme bei der Verarbeitung, Lagerung und Analyse von im Feld gesammelten Plasmaproben ihre Verwendung durch Ornithologen im Feld vermutlich einschränken. Wir testeten die Benutzung eines vor Ort verwendbaren Analysegeräts (CardioChek PA-Analysator) zur Messung der TRIG-Konzentrationen im Plasma männlicher Kanadaschnepfen (*Scolopax minor*), die während ihrer Balzzeit im Frühjahr gefangen wurden und verglichen diese Messwerte mit denen von Standard-Laboranalysen derselben Plasmaproben. Die mit dem Analysegerät im Feld unmittelbar gemessene Plasma-TRIG-Konzentration war hochgradig wiederholbar und präzise, aber nicht wirklich genau im Vergleich zu den im Labor gemessenen Werten. Die Ungenauigkeit beim Vor-Ort-Analysegerät kann auf Einwirkungen

Communicated by I. Moore.

✉ Christopher M. Roelandt
croeland@umich.edu

[1] Biology Department, University of Michigan-Flint, Flint, MI 48502, USA

[2] Department of Wildlife, Fisheries and Conservation Biology and School of Forest Resources, University of Maine, Orono, ME 04469, USA

[3] Department of Natural Resources Science, University of Rhode Island, Kingston, RI 02881, USA

Published online: 25 November 2021

der Umgebungsbedingungen auf die Funktion des Geräts oder auf spezifische Probleme im Zusammenhang mit der Analyse von Kanadaschnepfenblut zurückzuführen sein. Wir schließen aus unseren Untersuchungen, dass der feldtaugliche Analysator keine ausreichend genaue, alternative Methode zur Messung des zirkulierenden TRIG bei Kanadaschnepfen während des kalten Frühjahrs in den nördlichen Brutgebieten darstellt, obwohl er unter günstigeren Bedingungen und bei anderen Vogelarten für Feldornithologen nützlich sein mag.

Introduction

Assessing body condition in free-living birds is important for researchers and wildlife managers interested in understanding the refueling rate and overall health of individuals. Plasma metabolites can accurately predict a change in body mass of individuals, a good indicator of body condition, without the need to recapture individuals (Jenni-Eiermann and Jenni 1994; Williams et al. 1999; Guglielmo et al. 2005; Seaman et al. 2005). More specifically, circulating triglyceride (TRIG) is a plasma metabolite commonly used to predict change in body mass associated with fattening in a wide variety of birds including, for example, shorebirds (Albano et al. 2016), waterfowl (Anteau and Afton 2008; Smith et al. 2021), and songbirds (Jenni-Eiermann and Jenni 1994). Given that circulating TRIG concentrations can be a valuable indicator of changes in body condition, it has also been used as an indicator of habitat quality in a variety of bird studies (Schaub and Jenni 2001; Guglielmo et al. 2005; Smith et al. 2021).

Plasma metabolite concentrations are typically measured by collecting blood samples from birds in the field and transporting these samples to a lab for standard wet chemistry analysis. Once collected, blood samples must be handled appropriately to reduce degradation in the field that could influence the accuracy of the plasma analysis (Seaman et al. 2005; Owen 2011). For standard wet chemistry analysis, handling of blood samples includes centrifugation to separate plasma from the whole blood and then storage of samples at – 20 to – 80 °C (Guglielmo et al. 2002; Williams et al. 2007; Owen 2011; Sommers et al. 2017). These steps require transporting extra electronic equipment and a power source into the field. A field-portable point-of-care (POC) analyzer offers a possible alternative method for measuring plasma metabolite concentrations that could (1) eliminate some of the challenges of processing and storing samples in the field, (2) reduce the volume of blood collected, and (3) provide real-time estimates of body condition in the field that could be useful, for example, if individuals are to be assigned to experimental groups based on their condition.

One POC analyzer that shows promise in measuring TRIG concentrations in the field is the CardioChek PA analyzer (part number 1708, PTS Diagnostics, Indianapolis, IN, USA; hereinafter, analyzer). This analyzer was developed for human use in a clinical setting and is slightly larger and similar in function to a glucometer (Fig. 1). It can measure TRIG concentrations from 15-μL of whole blood. Irvine et al. (2018; 2019) validated the use of this analyzer for measuring TRIG concentrations in Domestic Chickens (*Gallus gallus domesticus*) and multiple captive psittacine species in controlled settings where environmental conditions associated with fieldwork did not impact the functioning of the analyzer. Morales et al. (2020) used this analyzer in a field setting and found that TRIG measurements were correlated with, although usually underestimated, those determined with standard laboratory analysis ($R^2 > 0.7$) for 11 of 12 species. For the one exception, Black-legged Kittiwake (*Rissa tridactyla*), TRIG measured with the analyzer was correlated with that measured using standard laboratory analysis ($R^2 = 0.84$), but the analyzer values overestimated TRIG concentration. Morales et al. (2020) suggested that

Fig. 1 The CardioChek PA analyzer is a small Point-of-care (POC) analyzer that can be easily transported and used in a field setting. A drop of blood (15 μL) is placed on the triglyceride test strips, inserted into the analyzer, and a measure of circulating triglycerides is produced within a few minutes

interspecific differences in these relationships could be caused by unknown species-specific blood biochemical parameters impacting the function of the analyzer; thus, they recommended that additional studies be conducted on other bird species to determine the broader efficacy of this field-portable analyzer. Our objective was to evaluate the efficacy and accuracy of the CardioChek PA analyzer as used in the field to measure circulating TRIG concentrations in free-living male American Woodcock (*Scolopax minor*; hereinafter, woodcock).

Methods

Woodcock arrive in the Great Lakes region of their North American range in the early spring (March—April) to breed following migration from their wintering grounds in the southeastern United States. As male woodcock arrive on their breeding areas, they establish territories used for courtship displays referred to as singing grounds that are clearings in early-successional forests (Straw et al. 1994). Male woodcock show strong site fidelity and remain near these singing grounds throughout the breeding season (Hudgins et al. 1985). Given that these singing grounds may vary in the quality of surrounding habitat (Brenner et al. 2019), assessing the body condition of territorial males may offer insights into how habitat quality varies with the male condition and thus inform habitat management practices to improve conservation of this species.

Capture and blood sampling

Male woodcock were captured from 20 April to 4 June 2018, and 18 April – 30 May 2019 ($N=15$ and 20, respectively) at 10 study sites located within two state-managed areas (Ackley State Wildlife Area and Northern Highland American Legion State Forest) in Langlade (45° 8' N 89° 24' W) and Oneida counties (45° 47' N 89° 32' W), Wisconsin, USA. The mean monthly temperatures at the Rhinelander, Wisconsin, USA, weather station during the two field seasons ranged from 5 to 23.9 °C (NOAA 2020). Study sites were identified by selecting clearings in early-successional forests where male woodcock were observed. Presence was determined by observing at least one male woodcock performing its evening crepuscular courtship display, which occurs for about an hour following sunset. The following evening, we returned to capture the male woodcock. We used audio lures (calls of male woodcock) and mist-nets in clearings to induce defensive responses from territorial males (McAuley and Longcore 1993).

Once entangled in the mist nets, woodcock were quickly removed to reduce stress and the chance of injury (< 5 min). Woodcock were sexed using morphometric measurements (e.g. exposed culmen and tarsus length) and plumage characteristics (e.g. width of outer three primaries) (Sepik 1994; Pyle 2008). To reduce any effects of time between capture and blood sample collection on analysis, blood samples were collected within 15 min of capture. Blood samples were collected from the brachial vein using a 25-gauge needle and syringe. We collected a maximum of 600 µL blood sample representing a maximum of 1% body mass from each male woodcock. Samples were placed into two 300-µL heparinized centrifuge tubes to prevent blood coagulation (Sheldon et al. 2008; Fair et al. 2010; Owen 2011). After blood collection, the venipuncture location on each male woodcock was treated with a clotting substance (Kwik-Stop®) and a cotton ball to prevent further bleeding. Each woodcock was then placed into a breathable cloth bag for 5 min and its condition was reevaluated before being released at the point of capture (Fair et al. 2010).

One of the 300 µL whole blood samples was used to measure TRIG concentrations in the field with the analyzer within 20 min of collecting the blood sample. We used TRIG test strips (part number 1716; PTS Diagnostics, Indianapolis, IN) and followed manufacturer protocols for using the analyzer (PTS Diagnostics 2020a, b). Both the analyzer and test strips were sensitive to environmental conditions including temperature, humidity, and light levels which may impact the ability of the analyzer to measure TRIG concentrations accurately. The analyzer and test strips required a temperature between 20 and 30 °C, relative humidity between 20 and 80%, and operated out of direct light for proper function. The analyzer is sensitive to direct light due to its dependence on light reflectance to measure enzymatic chemical reactions (PTS Diagnostics 2020a). Prior to our study, protocols for preventing negative environmental effects on the function of the analyzer were created with assistance from the manufacturer. To address the issue of ambient temperatures colder than required for the proper function of the analyzer, the analyzer and test strips were placed in an insulated bag with an air-activated hand warmer and a thermometer to monitor and maintain the manufacturer-recommended temperature between 20 and 30 °C. To reduce the effects of light, all headlamps and vehicle lights adjacent to the analyzer were turned off during operation. And to reduce the effect of humidity, the analyzer was operated inside a vehicle with climate control running.

Approximately 15 µL of whole blood was applied to the test strip and the device reported a TRIG value after a few minutes. To quantify the accuracy of the analyzer, a new 15 µL subsample of each blood sample was applied to each of 10 new test strips. We calculated the coefficient of variation (CV) to measure the repeatability of the analyzer (Altman and Bland 1983). The mean of the 10 TRIG measures for each blood sample was used for comparison with TRIG values measured in the laboratory.

The second of the two 300 µL heparinized centrifuge tubes was handled in the field using standard methods in preparation for wet chemistry analysis in the laboratory (Guglielmo et al. 2005; Cerasale and Guglielmo 2006; Smith and McWilliams 2010). In brief, we centrifuged blood samples to separate plasma from the rest of the whole blood (4800 × *g* for 10 min on an HWLAB min centrifuge). After centrifugation, plasma was transferred to a 1-mL cryotube that was placed in a cooler and transported to and stored in a – 20 °C freezer that is not "frost-free" until the end of the field season (< 7 weeks; Seaman et al. 2005; Williams et al. 2007; Smith et al. 2007; Owen 2011; Devost et al. 2014). At the end of the field season, plasma samples were packed in coolers with dry ice and shipped overnight to the University of Rhode Island for analysis. In the lab, colorimetric assay kits (Triglyceride Reagent part number T2449, Sigma-Aldrich Inc., St. Louis, MO) were used to determine TRIG concentrations of each plasma sample (detailed protocol in Smith et al. 2007).

Statistical analysis

We used Model IIA ordinary least products (OLP) regression analysis to assess the correlation between TRIG concentrations completed with the field analyzer and those completed in the lab while also addressing possible errors in the measured values (Ludbrook 2010, 2012; Lindhom et al. 2016). We also tested for heteroscedasticity using the Breusch-Pagan test and Bland–Altman plot method to evaluate bias and the limit of agreement (LOA) between TRIG concentrations determined with the analyzer and in the lab analysis (Altman and Bland 1983; Bland and Altman 1986, 1999; Atkinson and Nevill 1998; Lindhom et al. 2016). The Bland–Altman plot method allowed us to evaluate bias between the two methods by plotting the difference between corresponding values from laboratory analysis and those from the analyzer, then plotting these differences against the mean TRIG concentration between the two corresponding values. Analyses were conducted in the R statistical environment, using packages blandr, lmtest, smatr, and stats (Zeileis and Hothorn 2002; Warton et al. 2012; Datta 2017; R Core Team 2020).

Results

TRIG concentrations determined in the lab analysis had a weak positive correlation with the values produced by the analyzer ($N = 35$, $R^2 = 0.23$, $P = 0.004$; 95% CI = − 0.102–0.321; slope = 0.45, $x = 0.14$; Fig. 2). We found poor agreement between the values resulting from

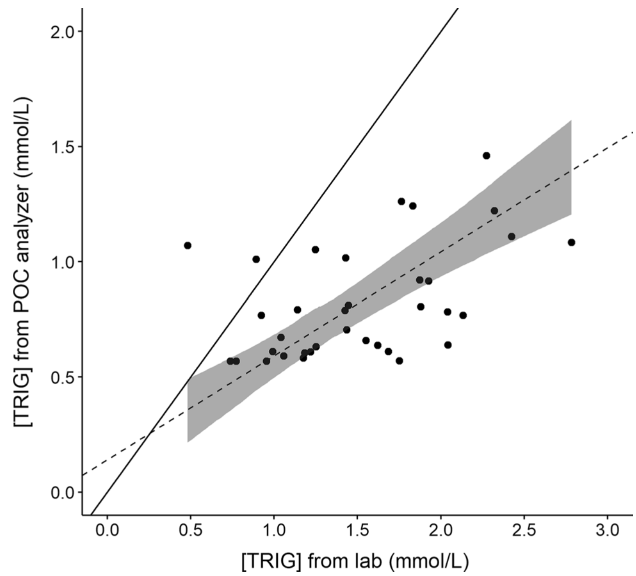

Fig. 2 Triglyceride (TRIG) values from the CardioChek PA Point-of-care (POC) analyzer were weakly correlated with values completed in the laboratory using colorimetric assays. The line of best fit from the Model IIA OLP regression analysis is indicated by the dotted line ($R^2 = 0.23$, $P = 0.004$; CI = − 0.102–0.321; slope = $0.45x$). The 95% confidence interval (gray shaded area) for the slope of the line of best fit does not include the line of equality (solid line) indicating a difference in POC analyzer values and expected values

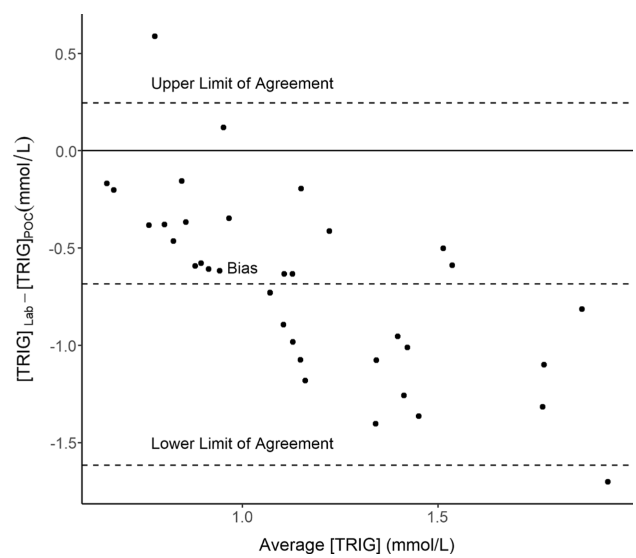

Fig. 3 Bland–Altman plot of average triglyceride (TRIG) concentrations measured using the standard laboratory analysis and POC analyzer vs. the difference between TRIG measured using the standard laboratory analysis and POC analyzer. The negative bias (− 0.68 mmol/L) relative to the limits of agreement (upper LOA = 0.25 mmol/L, lower LOA = − 1.62 mmol/L) indicates that the CardioChek PA analyzer underestimates triglyceride concentrations compared to laboratory analysis

these two methods using the Bland–Altman plot method, with the analyzer underestimating TRIG concentrations compared to values determined in the lab analysis (− 0.68 ± 1.86 mmol/L, bias ± LOA; Fig. 3). This bias is also apparent in the regression analysis where the 95% confidence intervals did not include the line of equality (Model IIA OLP regression: 95% CI = − 0.102–0.321; Fig. 2). We found the TRIG concentration values to be homoscedastic (BP = 0.06, $P = 0.81$), consistent, and repeatable (intra-assay CV = 7.62%; CV = 10.28% at 0.57–0.99 mmol/L and 8.98% at > 1.00 mmol/L; Roelandt 2020). We also found no correlation between body mass and TRIG concentrations ($F_{1,74} = 0.004$, $P = 0.95$, $R^2 = -0.013$). And finally, we found no correlation between the temperature at the time of capture and variation in the analyzer's values ($F_{1,33} = 1.037$, $P = 0.316$, $R^2 = 0.316$).

Discussion

In this study, we provide the first evaluation of the efficacy and accuracy of the CardioChek PA analyzer for measuring TRIG concentrations in a shorebird species, the woodcock. We found that the analyzer underestimated the TRIG concentrations compared to those from standard laboratory analyses conducted on the same blood samples. Importantly, the analyzer's underestimation of TRIG concentrations was not consistent over the range of TRIG values measured in woodcock which compromises the applicability of the POC analyzer for comparative studies. In contrast, Morales et al. (2020) found that the analyzer accurately measured TRIG concentrations of 11 bird species, and the analyzer consistently underestimated those obtained using the standard laboratory analyses. More consistent with our results, Morales et al. (2020) also found that the analyzer inconsistently (over)estimated TRIG concentrations for a twelfth species, the Black-legged Kittiwake; they hypothesized that an unknown blood chemistry parameter may have negatively affected the analyzer measurements for this species.

The analyzer is known to be sensitive to ambient temperature, which may have influenced its ability to accurately measure TRIG concentrations of woodcock in our study. The analyzer was developed for use in the controlled environment of a clinical setting where environmental conditions are stable, unlike the field conditions during the spring (March–June) in Wisconsin, USA. All concerns about environmental and field conditions that may affect the accuracy of the analyzer were communicated with the manufacturer before use in the field. Based on recommendations in *Guidelines for Quality Assurance for Point-of-Care in Veterinary Medicine* (American Society for Veterinary Clinical Pathology 2013), best methods for using the analyzer in the field were created and put into practice using the manufacturer's user guides and responses to our concerns. The analyzer has internal sensors that display warning signs when the temperature reaches a high or low threshold and/or if the light was too bright (PTS Diagnostics 2020a). A "low temperature" warning was the only warning sign displayed during our use of the analyzer. When this occurred the analyzer was placed back into the insulated lunch bag and given time to reach operating temperature. Even with the preventive methods that we adopted to reduce the effect of temperature, the infrequent occurrence of the "low temperature" warning sign indicated that temperature may have still impacted the analyzer's function.

As for whether we recommend this analyzer for future research, we must consider not only the findings of our study but of other studies (i.e., Irvine et al. 2018, 2019; Morales et al. 2020) which found the analyzer to be a viable field tool for measuring plasma metabolites in other birds. Therefore, we recommend that this analyzer be considered for future research on woodcock and other species but only in conjunction with a two-phase pilot study to understand the operating limits of this analyzer prior to field use. The first phase should test the analyzer in an environmentally controlled clinical setting to rule out any species-specific blood biochemical parameters preventing the analyzer from properly functioning. If phase one results were satisfactory, then the second phase should test the analyzer in the field to understand how expected environmental and weather conditions may affect the function of the analyzer. Only when results from the analyzer in the field correlate strongly and consistently with the standard laboratory analysis, thus demonstrating high accuracy and precision, should the analyzer be considered a reliable field tool for the target species.

Using an analyzer in a field setting has many advantages because it gives researchers the ability to quickly assess body condition while reducing the challenges associated with handling and analyzing plasma samples. Our results indicated that there are limitations to using the analyzer to estimate TRIG in male woodcock under the field conditions common during spring in northern latitudes of North America. The consistent precision values could lead to a false sense of the analyzer's accuracy and cause researchers to believe an individual's body condition is better or worse than actuality. The poor performance of the POC analyzer for woodcock suggests that researchers should validate the analyzer with other species and field conditions prior to relying on it in the field as a substitute for traditional laboratory analysis.

Acknowledgements We are grateful to the volunteers and technicians (V. Haese-Lehman, A. Gatchell, and J. Roelandt) for their hard work throughout the field season. Thanks to A. Frawley for completing the lab analyses. Thanks to A. Buckardt Thomas, M. Spriggs, A. Fish, and E. Blomberg for their training in mist-netting, blood collection, and sample handling. Thanks to the Wisconsin Department of Natural Resources and the Wisconsin Young Forest Partnership for their support in logistics throughout the field season. Funding was provided from the University of Michigan-Flint Graduate Fund and the Association of Field Ornithologists through the E. Alexander Bergstrom Memorial Research Award. Finally, we thank PTS Diagnostics for donating the analyzer and test strips. Mist-netting and blood collection protocols followed the guidelines for the use of wild birds (Fair et al. 2010), were approved by the Unit for Laboratory Animal Medicine at the University of Michigan (IACUC protocol number PRO00008018), and comply with current federal laws.

Author contribution All authors contributed to the study design and the writing of this manuscript. Project preparation, data collection, and analysis were performed by CMR with critical input from AMR, SRM, and JCW.

Funding The research was supported through funds from the University of Michigan-Flint Graduate Fund and the Association of Field Ornithologists E. Alexander Bergstrom Memorial Research Award. This project was supported by the USDA National Institute of Food and Agriculture, Hatch (or McIntire-Stennis, Animal Health, etc.) Project number ME042018 through the Maine Agricultural & Forest Experiment Station.

Data availability The datasets generated during and analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare no conflict of interest.

Ethical approval This study was performed under a master bander permit from the U.S. Geological Survey Bird Banding Laboratory and complied with current federal laws. Mist-netting and blood collection protocols followed the guidelines for the use of wild birds (Fair et al. 2010) and were approved by the Unit for Laboratory Animal Medicine at the University of Michigan (IACUC protocol number PRO00008018).

References

Albano N, Santiago-Quesada F, Villegas A, Sànchez-Guzmàn J, Masero J (2016) Plasma metabolites correlate with weekly body mass changes in migrating Black-tailed Godwits *Limosa limosa* feeding on different diets. Ornithology 157:201–207. https://doi.org/10.1007/s10336-015-1268-4

Altman D, Bland J (1983) Measuring in medicine: the analysis of method comparison studies. J Roy Stat Soc 32:307–317. https://doi.org/10.2307/2987937

American Society for Veterinary Clinical Pathology (2013) Quality assurance for point-of-care testing in veterinary medicine. http://www.asvcp.org/pubs/qas/index.cfm. Accessed 20 Mar 2021. https://doi.org/10.1111/vcp.12099

Anteau M, Afton A (2008) Using plasma-lipid metabolites to index changes in lipid reserves of free-living Lesser Scaup (*Aythya affinis*). Auk 125:354–357. https://doi.org/10.1525/auk.2008.06255

Atkinson G, Nevill A (1998) Statistical methods for assessing measurement error (reliability) in variables relevant to sports medicine. Sports Med 26:217–238. https://doi.org/10.2165/00007256-199826040-00002

Bland J, Altman D (1986) Statistical methods for assessing agreement between two methods of clinical measurements. The Lancet 1:307–310

Bland J, Altman D (1999) Measuring agreement in method comparison studies. Stat Methods Med Res 8:135–160. https://doi.org/10.1177/096228029900800204

Brenner S, Buffum J, Tefft B, McWilliams S (2019) Landscape context matters when American woodcock select singing grounds: results from a reciprocal transplant experiment. Condor 121:1–11. https://doi.org/10.1093/condor/duy005

Cerasale D, Guglielmo C (2006) Dietary effects on prediction of body mass changes in birds by plasma metabolites. Auk 123:836–846. https://doi.org/10.1093/auk/123.3.836

Datta D (2017) blandr: a Bland-Altman method comparison package for R. Zenodo. https://doi.org/10.5281/zenodo.824514

Devost I, Hallot F, Milbergue M, Petit M, and Vézina F (2014) Lipid metabolites as markers of fattening rate in a non-migratory passerine: effects of ambient temperature and individual variation. Comp Biolchem Physiol Part A 177:18–26. https://doi.org/10.1016/j.cbpa.2014.07.014

Fair J, Paul E, Jones J, Clark A, Davie C, Kaiser G (2010) Guidelines to the use of wild birds in research. Ornithological Council, Washington, D.C.

Guglielmo C, O'Hara P, Williams T (2002) Extrinsic and intrinsic sources of variation in plasma lipid metabolites of free-living Western Sandpipers (*Calidris mauri*). Auk 119:437–445. https://doi.org/10.1093/auk/119.2.437

Guglielmo C, Cerasale D, Eldermire C (2005) A field validation of plasma metabolite profiling to assess refueling performance of migratory birds. Physiol Biochem Zool 78:116–125. https://doi.org/10.1086/425198

Hudgins J, Storm G, Wakeley J (1985) Local movements and diurnal-habitat selection by male American woodcock in Pennsylvania. J Wildl Manag 49:614–619. https://doi.org/10.2307/3801682

Irvine K, Mans C, Friedrichs K (2018) Validation of 2 point-of-care meters for measuring triglycerides in chickens using whole blood and plasma. J Vet Diagn Invest 30:197–204. https://doi.org/10.1177/1040638717739059

Irvine K, Mans C, Friedrichs K (2019) Method comparison using 2 point-of-care meters and a reference meter for measuring blood triglycerides in psittacine birds. J Avian Med Surg 33:229–234. https://doi.org/10.1647/2018-374

Jenni-Eiermann S, Jenni L (1994) Plasma metabolite levels predict individual body-mass changes in a small long-distance migrant, the Garden Warbler. Auk 111:888–899. https://doi.org/10.2307/4088821

Lindholm C, Altimiras J (2016) Point-of-care devices for physiological measurements in field conditions. A smorgasbord of instruments and validation procedures. Comp Biochem Physiol A 202:99–111. https://doi.org/10.1016/j.cbpa.2016.04.009

Ludbrook J (2010) Linear regression analysis for comparing two measurers or methods of measurement: but which regression? Clin Exp Pharmacol Physiol 37:692–699. https://doi.org/10.1111/j.1440-1681.2010.05376.x

Ludbrook J (2012) A primer for biomedical scientists on how to execute model II linear regression analysis. Clin Exp Pharmacol Physiol 39:329–335. https://doi.org/10.1111/j.1440-1681.2011.05643.x

Mcauley D, Longcore J (1993) Techniques for research into woodcock: experiences and recommendations. In: Proceedings of the Eighth American Woodcock Symposium (J. R. Longcore and G. F. Sepik, eds.), pp. 5–11. U.S. Fish and Wildlife Service, Washington, D.C.

Morales A, Frei B, Leung C, Titman R, Whelan S, Benowitz-Fredericks Z, Elliott K (2020) Point-of-care analyzers measure the nutritional state of eighteen free-living bird species. Comp Biochem Physiol A 240:110594. https://doi.org/10.1016/j.cbpa.2019.110594

National Oceanic and Atmospheric Administration (NOAA) (2020) https://www.climate.gov/. Accessed 29 Jan 2020

Owen J (2011) Collecting, processing, and storing avian blood: a review. J Field Ornithol 89:339–354. https://doi.org/10.1111/j.1557-9263.2011.00338.x

Pts Diagnostics (2020a) CardioChek PA analyzer. https://ptsdiagnostics.com/cardiochek-pa-analyzer/. Accessed 6 Mar 2020

Pts Diagnostics (2020b) PTS panels test strips and controls. https://ptsdiagnostics.com/pts-panels-test-strips-and-controls/. Accessed 6 Mar 2020

Pyle P (2008) Identification guide to North American birds: part II. Slate Creek Press, Bolinas, CA

R Core Team (2020) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna

Roelandt CM (2020) Assessing habitat quality of American Woodcock (*Scolopax minor*) and validating a handheld meter using plasma metabolites. M.S. thesis, University of Michigan-Flint, Flint, MI.

Schaub M, Jenni L (2001) Variation of fueling rates among sites, days, and individuals in migrating passerine birds. Funct Ecol 15:584–594. https://doi.org/10.1046/j.0269-8463.2001.00568.x

Seaman D, Guglielmo C, Williams T (2005) Effects of physiological state, mass change, and diet on plasma metabolite profiles in the Western Sandpiper (*Calidris mauri*). J Exp Biol 208:761–769. https://doi.org/10.1242/jeb.01451

Sepik G (1994) A woodcock in the hand: tips for examining, aging, and sexing American woodcock. Ruffed Grouse Society, Coraopolis, PA

Sheldon L, Chin E, Gill S, Schmaltz G, Newman A, Soma K (2008) Effects of blood collection on wild birds: an update. J Avian Biol 39:369–378. https://doi.org/10.1111/j.0908-8857.2008.04295.x

Smith S, McWilliams S (2010) Patterns of fuel use and storage in migrating passerines in relation to fruit resources at autumn stopover sites. Auk 127:108–118. https://doi.org/10.1525/auk.2009.09139

Smith S, McWilliams S, Guglielmo C (2007) Effect of diet composition on plasma metabolite profiles in a migratory songbird. Condor 109:48–58. https://doi.org/10.1093/condor/109.1.48

Smith E, Anteau M, Hagy J, Jacques C (2021) Plasma metabolite indices are robust to extrinsic variation and useful indicators of foraging habitat quality in Lesser Scaup. Ornithology 138:1–11. https://doi.org/10.1093/ornithology/ukab029

Sommers A, Boyle W, McGuire L (2017) Validation of a field-ready handheld meter for plasma beta-hydroxybutyrate analysis. J Field Ornithol 88:399–404. https://doi.org/10.1111/jofo.12233

Straw J, Krementz D, Olinde M, Sepik G (1994) American Woodcock. In: Tacha T, Braun C (eds) Migratory shore and upland bird management in North America. International Association of Fish and Wildlife Agencies in cooperation with the Fish and Wildlife Services, Washington, D.C., pp 97–114

Warton D, Duursma R, Falster D, Taskinen S (2012) smart 3—an R package for estimating and inference about allometric lines. Methods Ecol Evol 3:257–259

Williams T, Guglielmo C, Egeler O, Martyniuk C (1999) Plasma lipid metabolites provide information on mass change over several days in captive Western Sandpipers. Auk 116:994–1000. https://doi.org/10.2307/4089679

Williams T, Warnock N, Takekawa J, Bishop M (2007) Flyway-scale variation in plasma triglyceride levels as an indicator of refueling rate in spring-migrating Western Sandpipers (*Calidris mauri*). Auk 124:887–897. https://doi.org/10.1093/auk/124.3.886

Zeileis A, Hothorn T (2002) Diagnostic checking in regression relationships. R News 2:7–10