



Lipid extraction techniques for stable isotope analysis of bird eggs: Chloroform–methanol leads to more enriched ^{13}C values than extraction via petroleum ether



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ARTICLE INFO

Article history:

Received 23 June 2015

Received in revised form 25 September 2015

Accepted 26 September 2015

Available online 8 October 2015

Keywords:

Ancient murrelet

Leach's storm-petrel

Lipid extraction

Pelagic cormorant

Rhinoceros auklet

Stable isotope analysis

ABSTRACT

Stable isotope analysis is often used to determine dietary origin in ecological studies. Lipids are depleted in ^{13}C compared with protein and, so, variation in lipid content can confound interpretations of diet. To avoid this issue, lipids can be extracted from samples prior to stable isotope analysis. The most common solvent used for lipid extraction, chloroform–methanol, is toxic and cannot be used in some laboratories. Here, the use of chloroform–methanol as a solvent was compared with an alternative method that uses petroleum ether as a solvent ($N = 32$ eggs from seven species). The $\delta^{13}\text{C}$ values using both methods were highly correlated ($R^2 = 0.99$) but values derived from samples that were lipid-extracted using chloroform–methanol were enriched in ^{13}C by $0.90 \pm 0.07\%$ compared with samples that were lipid-extracted using petroleum ether. The C:N ratio was 3.60 ± 0.02 (s.e.) for chloroform–methanol and 4.25 ± 0.03 for petroleum ether implying that chloroform–methanol (which is more polar) more completely extracted lipids than petroleum ether. Furthermore, $\delta^{15}\text{N}$ values derived from samples that were lipid-extracted using chloroform–methanol were enriched in ^{15}N by $0.41 \pm 0.05\%$ compared with samples that were lipid-extracted using petroleum ether. In conclusion, lipid extraction by chloroform–methanol more thoroughly removes lipids than lipid extraction by petroleum ether and consequently $\delta^{13}\text{C}$ is higher after lipid extraction by chloroform–methanol than after lipid extraction by petroleum ether. An algebraic correction formula for each method is provided.

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1. Introduction

Stable isotopes can be used as tracers for the dietary origin of tissue in wild animals (Rubenstein and Hobson, 2004; Inger and Bearhop, 2008). In particular, stable isotope ratios are often used to disentangle variation in contaminant levels associated with diet from variation associated with environmental factors (Elliott and Elliott, 2013; Braune et al., 2014, 2015; Miller et al., 2014, 2015). However, lipids are depleted in ^{13}C compared with protein and variation in lipid content can confound interpretation of diet (De Niro and Epstein, 1977; Post et al., 2007; Ricca et al., 2007; Ooppel et al., 2010). It is therefore usually necessary to chemically extract lipids from samples used to measure stable isotope ratios, or to algebraically account for such effects (Sotiropoulos et al., 2004; Sweeting et al., 2004, 2006; Post et al., 2007; Bodin et al., 2007; Kojadinovic et al., 2008; Mintenbeck et al., 2008; Kaufman et al., 2014).

Several methods have been used to chemically extract lipids from tissues. The most common method uses chloroform–methanol as a solvent (Folch et al., 1957; Bligh and Dyer, 1959). However, because

chloroform is toxic, those methods cannot be used in some laboratories, and petroleum ether, hexane and ethyl acetate/alcohol are used as alternative solvents (Chambellant et al., 2008; Elliott et al., 2014). As both chloroform–methanol and ethyl acetate are more polar than petroleum ether or hexane, those compounds extract a greater proportion of polar compounds, including proteins, than petroleum ether or hexane (Dobush et al., 1985). As a result, stable isotope values on tissue extracted with polar solvents tend to be more enriched in ^{13}C and ^{15}N than tissue extracted with non-polar solvents (Logan and Lutcavage, 2008). However, some studies have found no difference between techniques (Schlechtriem et al., 2003; Chambellant et al., 2008). To be able to compare among studies, it is important to understand whether different chemical extraction methods affect stable isotope values. To the best of our knowledge, no study has compared different lipid extraction techniques on lipid-rich tissue, such as avian egg tissue, which would be expected to be particularly susceptible to such bias.

An alternative to chemical extraction is algebraic correction whereby the effect of lipids is accounted for algebraically based on the ratio of carbon to nitrogen in the sample (Post et al., 2007; Logan et al., 2008; Lesage et al., 2010). Although such corrections are up to five times less precise (Ehrich et al., 2010; Tarroux et al., 2010; Yurkowski et al., 2015), algebraic corrections are common in the literature because

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of the time, cost and logistics required for chemical lipid extraction, and because chemical extraction alters nitrogen and sulfur stable isotope ratios (reviewed for avian egg tissue in Elliott et al., 2014) necessitating two sets of analyses. Furthermore, for analyses of lipophilic contaminants, that are principally stored within lipids, the dietary origin of lipids may be more important than the dietary origin of proteins. Algebraic correction methods may be more useful for such datasets (Elliott et al., 2014). Regardless, if different extraction methods influence stable isotope ratios, then different algebraic correction formulae will be needed for each method and the comparability of the different equations needs to be considered (Logan and Lutcavage, 2008).

The current manuscript compares the carbon and nitrogen stable isotope values derived from two methods of chemical extraction: chloroform–methanol and petroleum ether. Values in lipid-rich eggs were measured from the suite of aquatic birds used as indicator species for monitoring of environmental contamination by Environment Canada on the Pacific coast of Canada (Elliott et al., 1989; Elliott et al., 1992). As chloroform–methanol is more polar than petroleum ether, it was hypothesized that chloroform–methanol would extract more lipids while at the same time removing a higher proportion of proteins, such as membrane-bound proteins and proteins with a high proportion of hydrophobic amino acids. As such, it was predicted that chloroform–methanol would lead to enriched ^{13}C and ^{15}N and lower C:N ratio relative to petroleum ether.

2. Methods

Egg homogenates were obtained from the Environment Canada's Specimen Bank for seven species of aquatic birds: osprey (*Pandion haliaetus*, $N = 1$), double-crested cormorant (*Phalacrocorax auritus*, $N = 5$), Leach's storm-petrel (*Oceanodroma leucorhoa*, $N = 9$), rhinoceros auklet (*Cerorhinca monocerata*, $N = 8$), pelagic cormorant (*Phalacrocorax pelagicus*, $N = 4$), great blue heron (*Ardea herodias*, $N = 3$) and ancient murrelet (*Synthliboramphus antiquus*, $N = 2$). The suite of species included species that foraged over a range of habitats, from off the continental shelf (storm-petrels) to freshwater lakes (ospreys). As part of Environment Canada's contaminant monitoring program, many samples were lipid-extracted via petroleum ether in the past (petroleum ether was the primary option available at the Pacific Wildlife Research Centre, Ottawa, Canada, due to health and safety concerns with chloroform) while more recent samples were processed at the National Wildlife Research Centre using chloroform–methanol.

In each case, eggs were collected in the field, homogenized in the lab, frozen, thawed for the current analyses, freeze-dried, lipid-extracted, dried again and encapsulated for stable isotope analyses. One sub-sample was left non-lipid-extracted, one sub-sample was lipid-extracted using a Soxhlet apparatus with petroleum ether as the solvent, and one sub-sample was lipid-extracted using 2:1 chloroform:methanol. For the Soxhlet extractor, a thimble filled with dried sample was placed in the extractor and washed with petroleum ether at 94°C for 8 h. For the chloroform–methanol, approximately 2 mL of 2:1 chloroform:methanol was added to the samples and removed until the supernatant was clear, indicating that lipids had been extracted (Bligh and Dyer, 1959). The solvent was then distilled off and the residue dried for 60 min in a drying oven. Stable isotope analysis on encapsulated samples occurred at the Hatch laboratory (University of Ottawa) via combustion on a Cube elemental analyzer (Elementar, Hanau, Germany) followed by “trap and purge” separation and on-line analysis by continuous-flow with a DeltaPlus Advantage isotope ratio mass spectrometer coupled with a ConFlo III (both from Thermo Fisher Scientific, Waltham, USA). Internal standards covering the natural range of carbon and nitrogen isotope ratios were ($\delta^{15}\text{N}$, $\delta^{13}\text{C}$): C-51 Nicotiamide (0.07‰, -22.95%), C-52 mix of ammonium sulfate + sucrose (16.58‰, -11.94%), C-54 caffeine (-16.61% , -34.46%) and blind standard C-55: glutamic acid (-3.98% , -28.53%). All $\delta^{15}\text{N}$ values are reported relative to air and normalized to internal standards calibrated to international standards

IAEA-N1 (+0.4‰), IAEA-N2 (+20.3‰), USGS-40 (-4.52%) and USGS-41 (47.57‰). All $\delta^{13}\text{C}$ values are reported relative to Pee Dee Belemnite and normalized to internal standards calibrated to international standards IAEA-CH-6 (-10.4%), NBS-22 (-29.91%), USGS-40 (-26.24%) and USGS-41 (37.76‰). The blind C-55 standards ($N = 3$), not used for calibration, had an average value of $\delta^{15}\text{N} = -3.97$ (expected value of -3.89) and $\delta^{13}\text{C} = -28.57$ (expected value of 28.50). The analytical precision on the standards was 0.05 (s.d.) for $\delta^{13}\text{C}$ and 0.10 for $\delta^{15}\text{N}$ and on egg duplicates was 0.11 for $\delta^{13}\text{C}$ and 0.15 for $\delta^{15}\text{N}$. Samples were included in the same set of eggs used by Guigueno et al. (2012) and Elliott et al. (2014), and more details are described therein. All of the stable isotope raw data used in this manuscript are in the Data Appendix, which also provides the location of collection.

Linear regressions (R 3.0.3) were used to correlate lipid-extracted values of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ using petroleum ether as a solvent with lipid-extracted values using chloroform–methanol as a solvent. Pairwise t-tests were used to test for significant differences between the lipid-extraction methods at an α -value of 0.05. All values shown are mean \pm SE.

3. Results

Carbon isotope values ($\delta^{13}\text{C}$) for petroleum ether-extracted tissue were highly correlated with values for chloroform–methanol extracted tissue (linear regression: $t_{30} = 54.85$, $P < 0.0001$, $R^2 = 0.99$). Nitrogen isotope values ($\delta^{15}\text{N}$) petroleum ether-extracted tissue were also highly correlated with values for chloroform–methanol extracted tissue (linear regression: $t_{30} = 29.12$, $P < 0.0001$, $R^2 = 0.97$). However, the $\delta^{13}\text{C}$ values for petroleum ether-extracted tissues were significantly lower than $\delta^{13}\text{C}$ values for chloroform/methanol-extracted tissues by $0.90 \pm 0.07\%$ for $\delta^{13}\text{C}$ (pairwise $t_{30} = 12.92$, $P < 0.0001$) and $0.41 \pm 0.05\%$ for $\delta^{15}\text{N}$ (pairwise $t_{30} = 8.91$, $P < 0.0001$; Fig. 1). The C:N ratio was higher for petroleum ether-extracted tissue (4.26 ± 0.03) than chloroform–methanol extracted tissue (3.61 ± 0.02 ; pairwise $t_{30} = 15.60$, $P = 0.04$; Table 1). There was no relationship between C:N ratio after lipid-extraction and the change in $\delta^{13}\text{C}$ (petroleum ether: $t_{31} = -0.06$, $P = 0.95$, $R^2 = 0.00$; chloroform–methanol: $t_{31} = -1.46$, $P = 0.15$, $R^2 = 0.09$) implying that lipids were uniformly extracted.

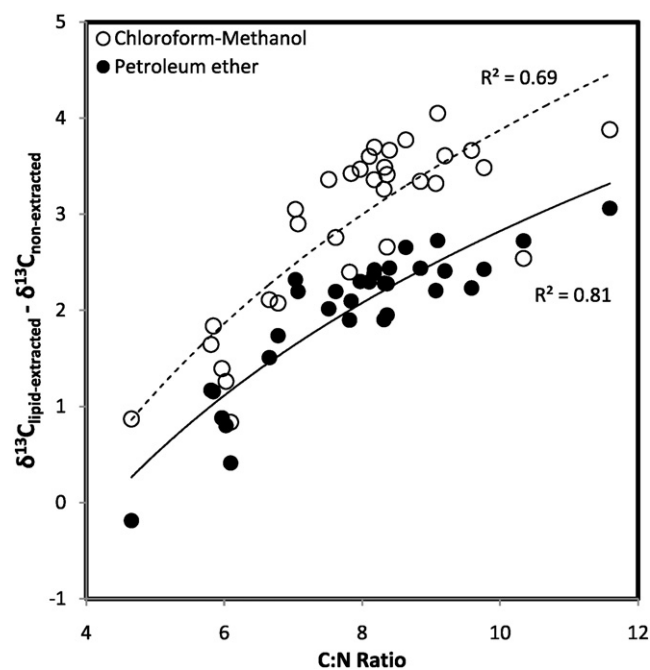


Fig. 1. The effect of lipid extraction method on carbon stable isotope ratios as a function of the C:N ratio. For petroleum ether (solid line): $\delta^{13}\text{C}_{\text{lipid-extracted}} = \delta^{13}\text{C}_{\text{non-extracted}} + 3.35 * \text{Ln}(\text{C:N Ratio}) - 4.89$. For chloroform–methanol (dashed line): $\delta^{13}\text{C}_{\text{lipid-extracted}} = \delta^{13}\text{C}_{\text{non-extracted}} + 3.94 * \text{Ln}(\text{C:N Ratio}) - 5.21$.

Table 1.

The carbon and nitrogen stable isotope values and bulk mass ratios for seven species of seabird eggs collected in British Columbia that had either not been extracted or lipid extracted with chloroform-methanol or petroleum ether.

	Non-extracted	Chloroform–methanol	Petroleum ether
C:N ratio ¹	7.91 ± 0.26	3.61 ± 0.02	4.26 ± 0.03
Average δ ¹³ C	−21.14 ± 0.69	−18.26 ± 0.63	−19.16 ± 0.66
Average δ ¹⁵ N	13.57 ± 0.27	14.69 ± 0.24	14.28 ± 0.24

¹ According to the chicken albumin sequence from McReynolds et al. (1978), pure albumin consists of 1746 carbon atoms and 458 nitrogen atoms for a C:N ratio of ~3.3.

4. Discussion

Lipid extraction method influenced the stable isotope values with both δ¹³C and δ¹⁵N being enriched in the heavier isotopes when using the polar solvent (chloroform–methanol) compared with the non-polar solvent (petroleum ether). Logan and Lutcavage (2008) likewise found that polar solvents caused increases in δ¹³C and δ¹⁵N compared with non-polar solvents. Given the influence on δ¹⁵N and the C:N ratio, it is likely that, compared with non-polar solvents, polar solvents extract a greater degree of nitrogenous waste products (i.e. uric acid), hydrophobic proteins, including membrane-bound proteins, and hydrophobic free amino acids, as well as lipids (Bearhop et al., 2000; Hussey et al., 2012). Specifically, polar solvents remove proteins rich in hydrophobic amino acids (Dobush et al., 1985), some of which, such as phenylalanine, do not enrich with trophic level and therefore have a low value of δ¹⁵N. Given that values derived from both polar and non-polar solvents were highly correlated, either method is likely reliable for studies that rely on relative δ¹³C/δ¹⁵N values, such as toxicological studies that simply correlate contaminant levels against δ¹³C/δ¹⁵N values. However, the absolute δ¹³C/δ¹⁵N values derived from each method cannot be directly compared. For instance, it is not reliable to estimate diet of predators using δ¹³C values for predators derived using one lipid extraction method and δ¹³C values for prey derived using another lipid extraction method, as such diet reconstruction relies upon absolute δ¹³C values.

Due to the differences between the methods, two different arithmetic correction equations for bird eggs are available dependent on solvent:

Petroleum ether: $\delta^{13}\text{C}_{\text{lipid-extracted}} = \delta^{13}\text{C}_{\text{non-extracted}} + 3.35 * \text{Ln}(\text{C:N Ratio}_{\text{non-extracted}}) - 4.89$.

Chloroform-methanol: $\delta^{13}\text{C}_{\text{lipid-extracted}} = \delta^{13}\text{C}_{\text{non-extracted}} + 3.94 * \text{Ln}(\text{C:N Ratio}_{\text{non-extracted}}) - 5.21$.

Provided such equations are applied uniformly, either equation can be used. The C:N ratio for chloroform–methanol-extracted tissue was only 8% above the expected value for pure albumin, whereas the C:N ratio for petroleum-ether-extracted tissue was 28% above the expected value for pure albumin. As the C:N ratio correlates with percent lipid in tissue (Post et al., 2007; Logan et al., 2008; Yurkowski et al., 2015), it is clear that chloroform–methanol extracted almost all lipids whereas petroleum ether did not extract all lipids—which is also to be expected because petroleum ether is less polar than chloroform–methanol and therefore will not extract polar lipids. Although chloroform–methanol may appear to be a better choice because it more completely extracted all lipids, the goal of lipid extraction is to provide a homogeneous matrix, and in that case petroleum ether may perform equally well; the petroleum ether equation explained more of the variance, implying that the end result was more homogeneous.

The discrepancy between the two solvents explains why the slope in the equation for petroleum ether is lower than that proposed by other researchers using chloroform–methanol (Fig. 1D Elliott et al., 2014), and may also explain discrepancies among the different equations present in the literature (Ehrich et al., 2010; Yurkowski et al., 2015). Sardenne et al. (2015) found little correlation between δ¹³C values in tuna muscle lipid-extracted using dichloromethane and δ¹³C estimated using arithmetic correction factors derived from experiments using chloroform–methanol, and concluded that “published estimates from

other species cannot be used”. The difference may be partially due to variation in solvent rather than species-specific differences. Within studies that use chloroform–methanol as a solvent, the ratio of chloroform to methanol varies from 2:1 to 9:1, and some of the variation in the transferability of equations from one study to another may be due to variation in solvent ratio.

No extraction technique extracts all lipids and leaves all non-lipids intact, and ‘lipid extraction’ is an approximate term (Bearhop et al., 2000; Hussey et al., 2012). Indeed, some studies have found a weak relationship between percent lipids and the C:N ratio because lipid extraction techniques extract more than just lipids (Yurkowski et al., 2015). The polar solvents presumably removed a larger proportion of lipids and non-lipids alike and the simpler matrix provided by chloroform–methanol extraction would therefore be more appropriate for quantitative diet studies.

Arithmetic correction may be preferable to chemical extraction for many contaminants studies because it is the dietary origin of lipids that determines the tissue burden of many contaminants (Elliott et al., 2014). For instance, the brominated flame retardants measured in ancient murrelet eggs likely originated from winter feeding off Asia (Miller et al., 2014, 2015). If murrelets switched their winter, but not pre-breeding, diet from invertebrates to fish over the course of several years, with a consequent increase in flame retardant levels associated with a change in carbon isotope signature, the association with a dietary switch would not be detected in the stable isotope values measured on lipid-extracted egg samples because the remaining protein would be derived from pre-breeding diet in British Columbia. In that case, researchers would erroneously conclude that flame retardant levels were increasing when, in fact, they may have been stable while it was diet that changed. Although chemical extraction is more precise than arithmetic correction (e.g. 95% of average triplicate values within 0.1% instead of 0.3% within the current dataset), it is not clear that it is more accurate as ¹⁵N and ¹³C may be incorporated into different compounds, including hydrophobic amino acids, between diet and consumer. Given that most researchers do not know exactly what compounds are removed by the solvents they are employing, arithmetic correction is a useful alternative to chemical extraction.

Acknowledgments

Thanks to G. Savard for arranging the chloroform–methanol extractions and J. Roth for the access to the Soxhlet apparatus. D. Jamieson, J. Jamieson and L. Jamieson did the Soxhlet lipid extraction. [SS]

Appendix A. Supplementary data

Supplementary data to this article can be found online at <http://dx.doi.org/10.1016/j.jembe.2015.09.017>.

References

- Bearhop, S., Teece, M.A., Waldron, S., Furness, R.W., 2000. Influence of lipid and uric acid on δ¹³C and δ¹⁵N values of avian blood: implications for trophic studies. *Auk* 117, 504–507.
- Bligh, E.G., Dyer, W.J., 1959. A rapid method of total lipid extraction and purification. *Can. J. Biochem. Physiol.* 37, 911–917.
- Bodin, N., Le Loch, F., Hily, C., 2007. Effect of lipid removal on carbon and nitrogen stable isotope ratios in crustacean tissues. *J. Exp. Mar. Biol. Ecol.* 341, 168–175.
- Braune, B.M., Gaston, A.J., Hobson, K.A., Gilchrist, H.G., Mallory, M.L., 2014. Changes in food web structure alter trends of mercury uptake at two seabird colonies in the Canadian Arctic. *Environ. Sci. Technol.* 48, 13246–13252.
- Braune, B.M., Gaston, A.J., Hobson, K.A., Gilchrist, H.G., Mallory, M.L., 2015. Changes in trophic position affect rates of contaminant decline at two seabird colonies in the Canadian Arctic. *Ecotoxicol. Environ. Saf.* 115, 7–13.
- Chambellant, M., Loseto, L.L., Kelley, T., Ferguson, S.H., 2008. Use of different solvents for lipid removal and effects on carbon and nitrogen stable isotope ratios in Arctic marine species. *Isoscape Conference Proceedings*, Santa Barbara CA.
- De Niro, M.J., Epstein, S., 1977. Mechanism of carbon isotope fractionation associated with lipid synthesis. *Science* 197, 261–263.
- Dobush, G.R., Ankney, C.D., Krementz, D.G., 1985. The effect of apparatus, extraction time, and solvent type on lipid extractions of snow geese. *Can. J. Zool.* 63, 1917–1920.

- Ehrich, D., Tarroux, A., Stien, J., Lecomte, N., Killengreen, S., Berteaux, D., Yoccoz, N.G., 2010. Stable isotope analysis: modeling lipid normalization for muscle and eggs from Arctic mammals and birds. *Methods Ecol. Evol.* 2, 66–76.
- Elliott, J.E., Elliott, K.H., 2013. Tracking marine pollution. *Science* 340, 556–558.
- Elliott, K.H., Davis, M., Elliott, J.E., 2014. Equations for lipid normalization of carbon stable isotope ratios in aquatic bird eggs. *PLoS ONE* 9, e83597.
- Elliott, J.E., Noble, D.G., Norstrom, R.J., Whitehead, P.E., Simon, M., 1992. Patterns and trends of organic contaminants in Canadian seabirds, 1968–1990. In: Walker, C.H., Livingston, D.R. (Eds.), *Persistent Pollutants in the Marine Environment*. Pergamon Press, Oxford, pp. 181–194.
- Elliott, J.E., Whitehead, P.E., Noble, D.G., Norstrom, R.J., 1989. Organochlorine contaminants in seabird eggs from the Pacific coast of Canada, 1971–1986. *Environ. Monit. Assess.* 12, 67–82.
- Folch, J., Lees, M., Sloane-Stanley, G.H., 1957. A simple method for the isolation and purification of total lipids from animal tissues. *J. Biol. Chem.* 226, 497–509.
- Guigueno, M.F., Elliott, K.H., Levac, J., Wayland, M., Elliott, J.E., 2012. Differential exposure of alpine ospreys to mercury: Melting glaciers, hydrology or deposition patterns? *Environ. Int.* 40, 24–32.
- Hussey, N.E., Olin, J.A., Kinney, M.J., McMeans, B.C., Fisk, A.T., 2012. Lipid extraction effects on stable isotope values ($\delta^{13}\text{C}$ and $\delta^{15}\text{N}$) of elasmobranch muscle tissue. *J. Exp. Mar. Biol. Ecol.* 434, 7–15.
- Inger, R., Bearhop, S., 2008. Applications of stable isotope analyses to avian ecology. *Ibis* 150, 447–461.
- Kaufman, T.J., Pajuelo, M., Bjorndal, K.A., Bolten, A.B., Pfaller, J.B., Williams, K.L., Vander Zanden, H.B., 2014. Mother–egg stable isotope conversions and effects of lipid extraction and ethanol preservation on loggerhead eggs. *Conserv. Physiol.* 2, 049.
- Kojadinovic, J., Richard, P., Le Corre, M., Cosson, R.P., Bustamante, P., 2008. Effects of lipid extraction on $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values in seabird muscle, liver and feathers. *Waterbirds* 31, 169–178.
- Lesage, V., Morin, Y., Rioux, È., Pomerleau, C., Ferguson, S.H., Pelletier, È., 2010. Stable isotopes and trace elements as indicators of diet and habitat use in cetaceans: predicting errors related to preservation, lipid extraction, and lipid normalization. *Mar. Ecol. Prog. Ser.* 419, 249–265.
- Logan, J.M., Lutcavage, M.E., 2008. A comparison of carbon and nitrogen stable isotope ratios of fish tissues following lipid extractions with non-polar and traditional chloroform/methanol solvent systems. *Rapid Commun. Mass Spectrom.* 22, 1081–1086.
- Logan, J.M., Jardine, T.D., Miller, T.J., Bunn, S.E., Cunjak, R.A., Lutcavage, M.E., 2008. Lipid corrections in carbon and nitrogen stable isotope analyses: comparison of chemical extraction and modelling methods. *J. Anim. Ecol.* 77, 838–846.
- McReynolds, L., O'Malley, B.W., Nisbet, A.D., Fothergill, J.E., Givol, D., Fields, S., Robertson, M., Brownlee, G.G., 1978. Sequence of chicken ovalbumin mRNA. *Nature* 273, 723–728.
- Miller, A., Elliott, J.E., Elliott, K.H., Guigueno, M.F., Wilson, L.K., Lee, S., Idrissi, A., 2014. Spatial and temporal trends in brominated flame retardants in seabirds from the Pacific coast of Canada. *Environ. Pollut.* 195, 48–55.
- Miller, A., Elliott, J.E., Elliott, K.H., Guigueno, M.F., Wilson, L.K., Lee, S., Idrissi, A., 2015. Brominated flame retardant trends in aquatic birds from the Salish Sea region of the west coast of North America, including a mini-review of recent trends in marine and estuarine birds. *Sci. Total Environ.* 502, 60–69.
- Mintenbeck, K., Brey, T., Jacob, U., Knust, R., Struck, U., 2008. How to account for the lipid effect on carbon stable-isotope ratio ($\delta^{13}\text{C}$): sample treatment effects and model bias. *J. Fish Biol.* 72, 815–830.
- Oppel, S., Federer, R.N., O'Brien, D.M., Powell, A.N., Hollmen, T.E., 2010. Effects of lipid extraction on stable isotope ratios in avian egg yolk: is arithmetic correction a reliable alternative? *Auk* 127, 1–7.
- Post, D.M., Layman, C.A., Arrington, D.A., Takimoto, G., Quattrochi, J., Montaña, C.G., 2007. Getting to the fat of the matter: models, methods and assumptions for dealing with lipids in stable isotope analyses. *Oecologia* 152, 179–189.
- Ricca, M.A., Miles, A.K., Anthony, R.G., Deng, X., Hung, S.S.O., 2007. Effect of lipid extraction on analyses of stable carbon and stable nitrogen isotopes in coastal organisms of the Aleutian archipelago. *Can. J. Zool.* 85, 40–48.
- Rubenstein, D.R., Hobson, K.A., 2004. From birds to butterflies: animal movement patterns and stable isotopes. *Trends Ecol. Evol.* 19, 256–263.
- Sardenne, F., Ménard, F., Degroote, M., Fouché, E., Guillou, G., Lebreton, B., Bodin, N., 2015. Methods of lipid-normalization for multi-tissue stable isotope analyses in tropical tuna. *Rapid Commun. Mass Spectrom.* 29, 1253–1267.
- Schlechtriem, C.H., Focken, U., Becker, K., 2003. Effect of different lipid extraction methods on $\delta^{13}\text{C}$ of lipid and lipid-free fractions of fish and different fish feeds. *Isot. Environ. Health Stud.* 39, 135–140.
- Sotiropoulos, M.A., Tonn, W.M., Wassenaar, L.L., 2004. Effects of lipid extraction on stable carbon and nitrogen isotope analyses of fish tissues: potential consequences for food web studies. *Ecol. Freshw. Fish* 13, 155–160.
- Sweeting, C.J., Polunin, N.V.C., Jennings, S., 2004. Tissue and fixative dependent shifts of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ in preserved ecological material. *Rapid Commun. Mass Spectrom.* 18, 2587–2592.
- Sweeting, C.J., Polunin, N.V.C., Jennings, S., 2006. Effects of chemical lipid extraction and arithmetic lipid correction on stable isotope ratios of fish tissues. *Rapid Commun. Mass Spectrom.* 20, 595–601.
- Tarroux, A., Ehrich, D., Lecomte, N., Jardine, T.D., Bêty, J., Berteaux, D., 2010. Sensitivity of stable isotope mixing models to variation in isotopic ratios: evaluating consequences of lipid extraction. *Methods Ecol. Evol.* 1, 231–241.
- Yurkowski, D.J., Hussey, N.E., Semeniuk, C., Ferguson, S.H., Fisk, A.T., 2015. Effects of lipid extraction and the utility of lipid normalization models on $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values in Arctic marine mammal tissues. *Polar Biol.* 38, 131–143.