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The stable isotopic composition of *Daphnia* ephippia reflects changes in δ^{13}C and δ^{18}O values of food and water

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Abstract. The stable isotopic composition of fossil resting eggs (ephippia) of *Daphnia* spp. is being used to reconstruct past environmental conditions in lake ecosystems. However, the underlying assumption that the stable isotopic composition of the ephippia reflects the stable isotopic composition of the parent *Daphnia*, of their diet and of the environmental water have yet to be confirmed in a controlled experimental setting. We performed experiments with *Daphnia pulicaria* cultures, which included a control treatment conducted at 12 °C in filtered lake water and with a diet of fresh algae and three treatments in which we manipulated the stable carbon isotopic composition (δ^{13}C value) of the algae, stable oxygen isotopic composition (δ^{18}O value) of the water and the water temperature, respectively. The stable nitrogen isotopic composition (δ^{15}N value) of the algae was similar for all treatments. At 12 °C, differences in algal δ^{13}C values and in δ^{18}O values of water were reflected in those of *Daphnia*. The differences between ephippia and *Daphnia* stable isotope ratios were similar in the different treatments (δ^{13}C: $+0.2 \pm 0.4$ ‰ (standard deviation); δ^{15}N: -1.6 ± 0.4 ‰; δ^{18}O: -0.9 ± 0.4 ‰), indicating that changes in dietary δ^{13}C values and in δ^{18}O values of water are passed on to these fossilizing structures. A higher water temperature (20 °C) resulted in lower δ^{13}C values in *Daphnia* and ephippia than in the other treatments with the same food source and in a minor change in the difference between δ^{13}C values of ephippia and *Daphnia* (to -1.3 ± 0.3 ‰). This may have been due to microbial processes or increased algal respiration rates in the experimental containers, which may not affect *Daphnia* in natural environments. There was no significant difference in the offset between δ^{18}O and δ^{15}N values of ephippia and *Daphnia* between the 12 and 20 °C treatments, but the δ^{18}O values of *Daphnia* and ephippia were on average 1.2 ‰ lower at 20 °C than at 12 °C. We conclude that the stable isotopic composition of *Daphnia* ephippia provides information on that of the parent *Daphnia* and of the food and water they were exposed to, with small offsets between *Daphnia* and ephippia relative to variations in *Daphnia* stable isotopic composition reported from downcore studies. However, our experiments also indicate that temperature may have a minor influence on the δ^{13}C, δ^{15}N and δ^{18}O values of *Daphnia* body tissue and ephippia. This aspect deserves attention in further controlled experiments.

1 Introduction

The strong, positive relationships between the stable carbon isotopic composition (expressed as δ^{13}C values) of organisms and that of their diet can allow the identification of the

autotrophic sources of organic matter at the base of a food web (DeNiro and Epstein, 1978; Vander Zanden and Rasmussen, 1999; McCutchan et al., 2003). Likewise, stable nitrogen isotope ratios (expressed as δ^{15}N values) can be used to estimate the trophic position of consumers in food webs (DeNiro and Epstein, 1981; Minagawa and Wada, 1984), and stable oxygen isotope ratios (expressed as δ^{18}O values) have been found to reflect those of the water in the environment that organisms live in (Hobson, 2008; Soto et al., 2013).

Approaches are continuing to be developed that apply stable isotope ratio analysis to chitinous remains of aquatic invertebrates preserved in lake sediments (Heiri et al., 2012; Leng and Henderson, 2013). For example, the δ^{13}C values of the fossil head capsules of benthic larvae of non-biting midges (Chironomidae) and δ^{13}C values of the remains of water fleas of the genus *Daphnia* (Cladocera) have been used to investigate past changes in carbon cycling and energy pathways in lake food webs (Perga, 2011; Wooller et al., 2012; van Hardenbroek et al., 2013; Belle et al., 2014; Frossard et al., 2014). The δ^{15}N values of chironomid head capsules and of *Daphnia* resting eggs (ephippia) have also been examined to investigate changes in nitrogen sources in an arctic lake (Griffiths et al., 2010). Past variations in lake water δ^{18}O values have been reconstructed by analyzing the δ^{18}O values of fossil chironomid head capsules (Wooller et al., 2004; Verbruggen et al., 2010b), and a correspondence has been found between δ^{18}O values of lake water and of chironomid head capsules and *Daphnia* ephippia buried in surface sediments (Verbruggen et al., 2011).

Daphnia can occur in high abundances and often dominate the zooplankton community in lakes (Lampert, 2011). Being first-order consumers of algae, bacteria and detritus (Geller and Müller, 1981; Gophen and Geller, 1984; Kamjunke et al., 1999; Lampert, 2011), they form an important link between primary production and the higher orders of the pelagic food web. This makes *Daphnia* particularly suited for ecological investigations of freshwater ecosystems and food webs using stable isotopes. While *Daphnia* usually reproduce parthenogenetically, they may also reproduce sexually. Environmental cues such as food availability, photoperiod and population density (Kleiven et al., 1992; Cáceres and Tessier, 2004) may trigger sexual reproduction, upon which eggs are formed enclosed by rigid sheaths (ephippia). The chitinous ephippia are found abundantly in a wide range of lake sediment types and remain well preserved in sediments hundreds to thousands of years old (Szeroczyńska and Samarja-Korjonen, 2007). Since the chemical composition of chitinous invertebrate remains stays largely unchanged even in fossils more than 10 000 years old (Miller et al., 1993; Verbruggen et al., 2010a), they are believed to retain their isotopic composition after deposition (Heiri et al., 2012). Therefore, ephippia may provide material for reconstructing the past stable isotopic composition of *Daphnia* in lakes and, consequently, for investigating past conditions in aquatic food webs (e.g., Wooller et al., 2012; van Hardenbroek et al., 2013, 2014; Schilder et al., 2015).

The use of δ^{13}C and δ^{15}N values of organisms to infer likely organic carbon and nitrogen sources relies heavily on assumptions regarding the difference between δ^{13}C and δ^{15}N values of organisms and their diet (Δ^{13}C, Δ^{15}N). There is a need for more controlled laboratory studies investigating Δ^{13}C and Δ^{15}N (Martínez del Rio et al., 2009) as well as the relationships between the δ^{18}O values of organisms and those of environmental water (Rubenstein and Hobson, 2004). Δ^{13}C, which is generally assumed to be between 0 and +1 ‰ for a range of animals, including invertebrates (DeNiro and Epstein, 1978; McCutchan et al., 2003), has been studied for chironomids under controlled laboratory conditions (Goedkoop et al., 2006; Wang et al., 2009; Heiri et al., 2012; Frossard et al., 2013) and ranges from −0.8 to +1.2 ‰. For *Daphnia magna*, Δ^{13}C values range from +1.7 to +3.1 ‰ (Power et al., 2003). Δ^{15}N, which is usually assumed to be between +3 and +4 ‰ (DeNiro and Epstein, 1981; Minagawa and Wada, 1984) ranges from −1.5 to +3.4 ‰ for chironomids (Goedkoop et al., 2006; Wang et al., 2009; Heiri et al., 2012) and from +1 to +6 ‰ for *Daphnia* (Adams and Sterner, 2000; Power et al., 2003; Matthews and Mazumder, 2008). In terms of oxygen, the δ^{18}O values of lacustrine invertebrates are strongly and positively related to the δ^{18}O values of local precipitation and the water in which the invertebrates live (Wang et al., 2009; Nielson and Bowen, 2010; Verbruggen et al. 2011; van Hardenbroek et al., 2012; Soto et al., 2013), although laboratory studies have shown that the oxygen isotopic composition of the diet can also affect invertebrate δ^{18}O values (Wang et al., 2009; Nielson and Bowen, 2010).

There can be distinct offsets in isotopic composition between whole-body tissue and chitinous structures of invertebrates. Culturing experiments comparing cephalopod soft tissue and their chitinous mouthparts have shown that their chitinous structures can have δ^{15}N values 3 to 4 ‰ lower than soft body tissue (Hobson and Cherel, 2006). Heiri et al. (2012) reported that offsets of up to 2 ‰ between chironomid body tissue and chitinous head capsule δ^{13}C and δ^{15}N values are possible. For *Daphnia*, field studies suggest that (non-ephippial) exoskeleton parts can have 0.8 ‰ lower δ^{13}C and 7.9 ‰ lower δ^{15}N values than whole *Daphnia* (Perga, 2010), while no clear differences in δ^{13}C and δ^{15}N values between *Daphnia* and ephippia have been reported in the only available study which examined this offset for *Daphnia* and free ephippia collected in a vertical net trawl in Lake Geneva, Switzerland (Perga, 2011). For vertebrates, differences in stable C and N isotopic composition between tissue types have been related to differences in contents of specific compounds (e.g., relative abundance of lipids, carbohydrates and protein or of different amino acids; e.g., DeNiro and Epstein, 1978; Pinnegar and Polunin, 1999). Differences in biochemical composition also provide a potential explanation for the observed differences in δ^{13}C and δ^{15}N values

between the whole-body tissue and chitinous structures of aquatic invertebrates. For oxygen and hydrogen, studies examining the offsets between the stable isotopic composition of the whole-body tissue of lacustrine invertebrates and their chitinous structures are still lacking.

To date, no controlled experiments investigating the offset between δ^{13}C, δ^{15}N and δ^{18}O values of whole-body tissue and ephippia have been published for *Daphnia*. Similarly, no laboratory experiments have been performed examining the relationship between δ^{18}O values of environmental water and *Daphnia* or their ephippia. Quantifying these offsets and relationships is essential for the further development of palaeoecological approaches based on stable isotope analyses of *Daphnia* remains and for interpreting results from the fossil record.

We present results from an experiment developed to examine the relationships between the δ^{13}C values of diet and the δ^{18}O values of environmental water, on the one hand, and the δ^{13}C and δ^{18}O values of *Daphnia*, on the other. The experiment was specifically designed to examine whether offsets in δ^{13}C, δ^{15}N and δ^{18}O values exist between *Daphnia* and their ephippia. Furthermore, we investigated whether the stable isotopic compositions of *Daphnia* and their ephippia are influenced by temperature by performing the experiment at two different temperatures.

2 Methods

2.1 *Daphnia* cultivation

Three ex-ephippial *Daphnia pulicaria* clones (LC PUL 53, 99 and 101; Möst, 2013) from Lower Lake Constance (Switzerland) that showed extensive ephippia production in culture in pre-tests were selected for the experiment. For each clone, 20 neonate *Daphnia* (< 48 h old) were grown in 2.5 L batch cultures prior to the experiment. From these batch cultures, seven to eight second to third clutch neonates (< 48 h old) were transferred to 180 mL jars, containing 160 mL of filtered lake water (natural abundance or labeled water, according to treatment conditions described below). The lake water was filtered with 0.45 µm glass fiber filters (Sartorius Stedim AG, Switzerland). Initially, *Daphnia* were fed three times per week with fresh algae, concentrated to an equivalent of 1 mg C L^{-1}. After day 21 of the experiment, the amount of food was doubled because the number of *Daphnia* in most jars exceeded 30 individuals. Experimental water was exchanged once per week and ephippia (if present) were retained in the cultures. Due to potentially higher productivity and evaporation, the water was exchanged twice per week in Treatment 4 (20 °C).

2.2 Food and water sources in the experiment

Three weeks before the experiment, two 1 L chemostats were started simultaneously to produce the algae (*Acutodesmus obliquus*, Turpin) to be used as food for *Daphnia* in the experiment. The algae were cultivated in a "WC"-medium (Guillard, 1975). For one of the chemostats, 45 % of the sodium bicarbonate in the medium (5.67 of 12.6 mg L^{-1}) was replaced by sodium bicarbonate containing 99.9 % ^{12}C (Sigma Aldrich, USA), lowering the δ^{13}C values of the algae from this chemostat by, on average, 1.8 ± 1.2 ‰ (one standard deviation (1 SD)) (see results). Once per week, the chemostat-grown algae were harvested, centrifuged (5000 rpm) to remove residual medium, stored at 9 °C in the dark and used to feed the *Daphnia* during the following week. Seven days before the start of the experiment, 250 L of lake water were collected from Greifensee (Switzerland) (pH 8.0, TP 0.04 mg L^{-1}, TN 1.6 mg L^{-1}; data provided by the Cantonal Bureau for Waste, Water, Energy and Air (AWEL, Zürich; www.awel.zh.ch)). This water was stored in the dark at 12 °C for the duration of the experiment. Of this water, 50 L were stored in a separate container, and 0.9 mL of water containing 97 % ^{18}O (Sigma Aldrich, USA) were added to increase the δ^{18}O value of the water by 5.6 ‰ relative to the unlabeled water (see results). Before exchanging the water in Treatment 4, the water was allowed to equilibrate with the ambient laboratory air temperature (20 °C).

2.3 Experimental design

The experiment consisted of four cultivation treatments: a control treatment in which *Daphnia* were cultivated in untreated, filtered lake water at 12 °C on a diet of fresh chemostat-grown algae (Treatment 1), and treatments with conditions identical to Treatment 1, with the exception of the algae in Treatment 2, which had 1.8 ± 1.2 (1 SD) ‰ lower δ^{13}C values. The culturing water in Treatment 3 had δ^{18}O values that were 5.6 ‰ higher than in the other treatments and Treatment 4 had a temperature (20 °C) that was higher than the other treatments.

Each treatment consisted of 30 glass jars, which were sterilized using an autoclave. Prior to the experiment, each glass jar was assigned to one of three replicate groups (A, B, C). The neonate *Daphnia* were evenly distributed in the jars to ensure that every experimental replicate group contained 10 jars, with 3 to 4 jars per clone. All the jars for a given treatment were held in one large tray, and the jars within each treatment were evenly distributed within the trays. The trays were held in the dark in temperature-controlled incubators.

The experiment was designed to assess the following: (a) the effect of a change in algal δ^{13}C values on those of *Daphnia* and their ephippia (Treatment 2); (b) the effect of a change in environmental water δ^{18}O values on those of *Daphnia* and their ephippia (Treatment 3); (c) the effect of a difference in temperature (i.e., 12 and 20 °C) on the δ^{13}C, δ^{15}N and δ^{18}O values of *Daphnia* and their ephippia (Treatment 4); and (d) the offset between *Daphnia* and ephippia in terms of their δ^{13}C, δ^{15}N and δ^{18}O values (Treatments 1–4). Statistical analyses were performed with the PAST software

package, version 1.97 (Hammer et al., 2001), except for tests used to compare the algae from both chemostats. To account for repeated measures, linear mixed effects models (LMEs) were applied, fitting a random intercept for each probing date with the lme function in the nlme package in the R statistical package (R Core team, 2013). Significance was analyzed using an F test. A Bonferroni correction was applied to the multiple (six) comparisons of the stable isotopic composition of *Daphnia* between the treatments (Tukey post hoc tests).

2.4 Sample collection

After the weekly harvest, a small portion of algae from each chemostat was rinsed with deionized water and centrifuged five times to remove the culturing medium. The concentrated algae were freeze-dried and a small aliquot (150 to 200 µg) was loaded into tin cups (6×4 mm, Lüdi Swiss, Switzerland) to measure the δ^{13}C, δ^{15}N and δ^{18}O values of the algae ($\delta^{13}C_{algae}$, $\delta^{15}N_{algae}$ and $\delta^{18}O_{algae}$). In each treatment, one jar was assigned to monitoring variation in δ^{18}O values of the water ($\delta^{18}O_{water}$). Once per week, before discarding the water, 12 mL were transferred to a 12 mL glass vial with no head space (Labco, UK) and stored in the dark at 7 °C. Every second sample was analyzed for $\delta^{18}O_{water}$ values. Every third week a sample of the water in the storage barrels was collected, stored and measured for $\delta^{18}O_{water}$ values.

The experiment was terminated after 62 days. He and Wang (2006) have demonstrated that the *Daphnia* carbon turnover rate is 11 to 36 % per day, which suggests that after 62 days our *Daphnia* likely had achieved isotopic equilibrium with the experimental diet and water. *Daphnia* and ephippia were harvested and pooled according to treatment (1–4) and replicate group (A, B, C). Adult *Daphnia* were hand-picked from a Bogorov sorting tray (Gannon, 1971) with fine forceps under a binocular and freeze-dried, after which they were loaded into tin cups (6×4 mm, Lüdi Swiss, Switzerland; $\sim$ 10 to 12 individuals per measurement) for analysis of $\delta^{13}C_{Daphnia}$, $\delta^{15}N_{Daphnia}$ and $\delta^{18}O_{Daphnia}$ values. For each treatment replicate group, three samples were prepared and measured, resulting in 36 measurements for each chemical element. Ephippia were collected and treated in 10 % KOH for 2 h to remove any algal matter and egg yolk. Replicate measurements (three each for C, N and O) of ephippia not treated with KOH were prepared to assess any influence of this treatment on the isotopic compositions of ephippia. The ephippia were loaded into pre-weighed tin cups (6×4 mm, Lüdi Swiss, Switzerland): $\sim$ 10 to 15 for $\delta^{13}C_{ephippia}$ and $\delta^{15}N_{ephippia}$ analysis and 15 to 20 for $\delta^{18}O_{ephippia}$ analysis. Three samples were prepared and measured for each treatment replicate group, except for Treatment 4, which yielded only sufficient numbers of ephippia to measure once per treatment replicate group.

2.5 Assessing the source of oxygen in *Daphnia*

Following Wang et al. (2009), our experimental setup was used to approximate the proportional contribution of oxygen in the *Daphnia* stemming from the environmental water relative to that from the diet, using the following equation:

$$p = \frac{\left(\delta^{18}O_{Daphnia(A)} - \delta^{18}O_{Daphnia(B)}\right)}{\left(\delta^{18}O_{water(A)} - \delta^{18}O_{water(B)}\right)},$$

where p is the proportion of oxygen in *Daphnia* stemming from the water, $\delta^{18}O_{Daphnia(A)}$ and $\delta^{18}O_{water(A)}$ would be the δ^{18}O values of *Daphnia* and the water if *Daphnia* were cultivated in non-manipulated, filtered lake water, and $\delta^{18}O_{Daphnia(B)}$ and $\delta^{18}O_{water(B)}$ would be the δ^{18}O values of *Daphnia* and the water if *Daphnia* were cultivated in the ^{18}O-enriched, filtered lake water.

2.6 Stable isotope mass spectrometry

The δ^{13}C and δ^{15}N values of the algae, *Daphnia* and ephippia were measured on a Costech ESC 4010 elemental analyzer interfaced via a ThermoConflo III with a Thermo Delta V isotope ratio mass spectrometer (IRMS) at the Alaska Stable Isotope Facility (ASIF) at the University of Alaska, Fairbanks. The analytical precisions for δ^{13}C and δ^{15}N values are expressed as 1 SD from the mean based on the results from multiple ($n = 13$) analyses of a laboratory standard (peptone) and were $\pm$ 0.2 ‰ and $\pm$ 0.1 ‰, respectively. The δ^{18}O values of the water samples were measured on an online pyrolysis thermochemical reactor elemental analyzer (TCEA) (Finnigan ThermoQuest) coupled to a continuous flow (Conflo III) IRMS (Finnigan MAT Delta V) at the ASIF. Analytical precision is expressed as 1 SD from the mean based on the results from multiple ($n = 3$) analyses of a laboratory standard (doubly labeled water; $\pm$0.3 ‰). The δ^{18}O values of the algae, *Daphnia* and ephippia were measured using the same techniques and instruments as used for the water samples. Analytical precision based on replicate ($n = 12$) laboratory standard measurements (benzoic acid, Fisher Scientific, Lot No 947459) was $\pm$0.4 ‰ . Stable isotopic compositions are expressed in standard delta (δ) notation in ‰ relative to V-PDB (Vienna Pee Dee Belemnite) for δ^{13}C values, AIR for δ^{15}N values and V-SMOW (Vienna Standard Mean Ocean Water) for δ^{18}O values.

3 Results

3.1 Food and water

The $\delta^{13}C_{algae}$ values from both chemostats showed some variation with time (Fig. 1). On all sampling dates except the first, the algae cultured on ^{13}C-depleted medium had lower $\delta^{13}C_{algae}$ values than the standard algae (Fig. 1). As a consequence, the mean $\delta^{13}C_{algae}$ value for the culture grown using ^{13}C-depleted medium (-20.6 ± 1.84 ‰)

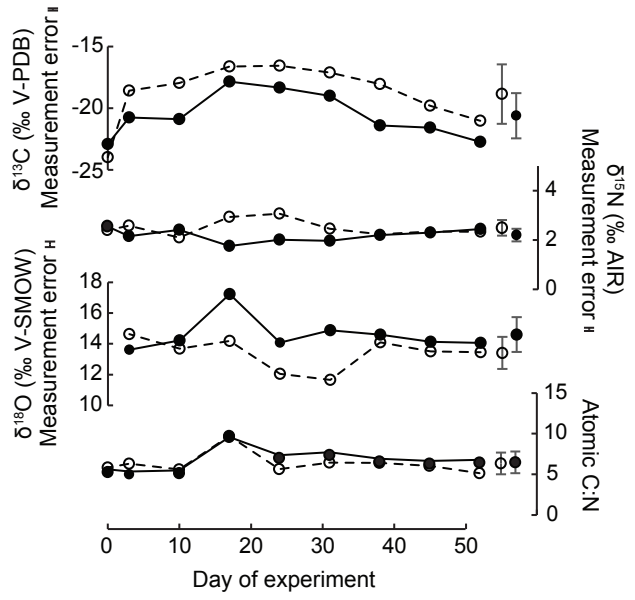

Figure 1. δ^{13}C, δ^{15}N and δ^{18}O values and atomic C : N ratios of the algae harvested from both chemostats during the experiment. Open circles with dashed line represent the standard algae, and the closed circles with solid line represent the algae that were cultured on a medium with the addition of ^{13}C-depleted bicarbonate. The data points and error bars on the right side of the plots indicate average values and 1 SD, respectively.

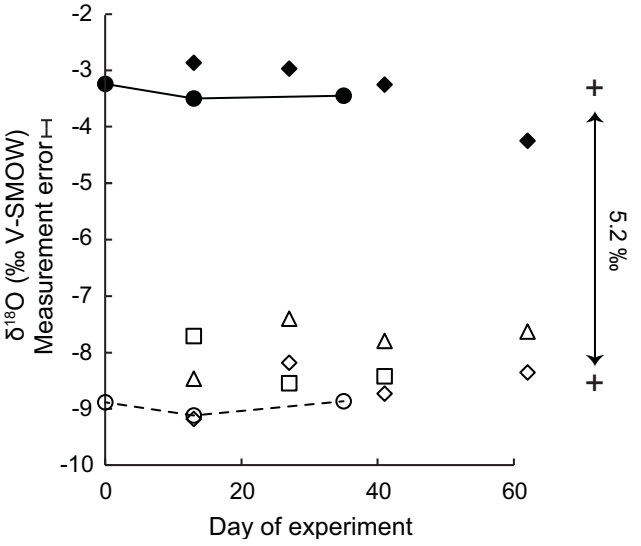

Figure 2. δ^{18}O values of the water in the storage barrels for the standard water (open circles, dashed line) and the artificially ^{18}O-enriched water (closed circles, solid line) sampled on day 0, 13 and 35; and the δ^{18}O values of the water sampled from the experimental jars before water was exchanged for Treatment 1 (open diamonds, control), Treatment 2 (open triangles, ^{13}C-depleted algae), and Treatment 3 (closed diamonds,^{18}O-enriched water) sampled on day 13, 27, 41 and 62; and Treatment 4 (open squares, 20 °C) sampled on day 13, 27 and 41. The plus symbols (+) on the right side indicate the mean of the mean experimental jar values and the mean storage barrel values for the standard water and the ^{18}O-enriched water, respectively.

was 1.8 ± 1.2 ‰ ($n = 9$) lower than the mean $\delta^{13}C_{algae}$ of the standard algae (-18.8 ± 2.4 ‰), and this difference was statistically significant (LME, $F_{(1,8)}$ 18.04, $p < 0.005$). There was no statistically significant difference between the algae cultures in terms of δ^{15}N values (standard algae 2.5 ± 0.3 ‰, ^{13}C-depleted algae 2.2 ± 0.3 ‰; $F_{(1,8)}$ 4.58, $p > 0.05$), δ^{18}O values (standard algae 13.4 ± 1.0 ‰, ^{13}C-depleted algae 14.6 ± 1.1 ‰; $F_{(1,7)}$ 5.43, $p > 0.05$) or atomic C : N ratios (standard algae 6.4 ± 1.3, ^{13}C-depleted algae 6.5 ± 1.3; $F_{(1,8)}$ 0.18, $p > 0.05$) (Fig. 1).

The addition of ^{18}O-enriched water led to an increase in $\delta^{18}O_{water}$ values in the storage barrels by 5.6 ‰ (δ^{18}O value of -3.4 ± 0.1 ‰ , $n = 3$) relative to the non-labeled water (δ^{18}O value of -9.0 ± 0.1 ‰ $n = 3$) (Fig. 2). The $\delta^{18}O_{water}$ values from the experimental jars in Treatment 1, 2 and 4 were not significantly different (one-way ANOVA, $F_{(2,2)}$ 30.1, $p > 0.05$) between the three treatments throughout the experiment, and the mean was -8.2 ± 0.5 ‰ ($n = 11$). Water from experimental jars from Treatment 3 had a mean $\delta^{18}O_{water}$ value of -3.3 ± 0.6 ‰ ($n = 4$). The mean $\delta^{18}O_{water}$ values in the storage barrels and the mean $\delta^{18}O_{water}$ values in the experimental jars after 1 week were used to approximate the baseline $\delta^{18}O_{water}$ values during cultivation for resolving Eq. (1) by taking the mean of the two values. This resulted in estimates of -8.6 ‰ for the cultures in non-manipulated lake water at 12 °C (Treatment 1 and 2) and -3.4 ‰ for the cultures in Treatment 3 with ^{18}O-enriched water.

3.2 *Daphnia* stable isotope ratios

Mean stable isotope values for *Daphnia* are based on 9 measurements (three measurements for each of the three replicates per treatment). The mean $\delta^{13}C_{Daphnia}$ value in Treatment 2 (where *Daphnia* were offered ^{13}C-depleted algae) was lower (-20.2 ± 0.1 ‰) than in Treatment 1 (-18.7 ± 0.1 ‰) and 3 (-17.9 ± 0.1 ‰) (Fig. 3). For treatments at 12 °C (1–3), the mean $\delta^{13}C_{Daphnia}$ value was 0.5 ± 0.3 ‰ higher than the mean $\delta^{13}C_{algae}$ value that *Daphnia* were cultured on. The mean $\delta^{13}C_{Daphnia}$ value in Treatment 4 (20 °C; -19.0 ± 0.1 ‰) was 0.2 ± 0.1 ‰ lower than the mean $\delta^{13}C_{algae}$ value. The results from all treatments in terms of $\delta^{13}C_{Daphnia}$ values were significantly different from each other (one-way ANOVA and Tukey post hoc test; Table 1)

Mean $\delta^{15}N_{Daphnia}$ values at 12 °C were 5.5 ± 0.1 ‰ (Treatment 1), 5.7 ± 0.1 ‰ (Treatment 2) and 6.2 ± 0.1 ‰ (Treatment 3), and they were 3.4 ± 0.3 ‰ higher than the mean $\delta^{15}N_{algae}$ value (Fig. 3). At 20 °C (Treatment 4), the mean $\delta^{15}N_{Daphnia}$ value (6.5 ± 0.2 ‰) was 4.0 ± 0.2 ‰ higher than the mean $\delta^{15}N_{algae}$ value. All treatments, except for Treatments 1 and 2 and Treatments 3 and 4, were signif-

Table 1. Results of the tests for statistical differences between the four (1–4) treatments (one-way ANOVA) and between pairs of treatments (Tukey test) for $\delta^{13}C_{Daphnia}$, $\delta^{15}N_{Daphnia}$ and $\delta^{18}O_{Daphnia}$ values. The results of the Tukey test are presented below the F and p values for the one-way ANOVA, showing Q values (lower left part of matrix) and p values after Bonferroni correction (upper right).

	Daphniaδ^{13}C values					*Daphnia*δ^{15}N values					*Daphnia*δ^{18}O values			
	$F_{(2.3)}$ 303.8 $p < 1 \times 10^{-8}$					$F_{(2.3)}$ 52.1 $p < 1 \times 10^{-5}$					$F_{(2.3)}$ 255.3 $p < 1 \times 10^{-8}$			
	1	2	3	4		1	2	3	4		1	2	3	4
1		< 0.002	< 0.002	< 0.05	1		> 0.9	< 0.005	< 0.002	1		> 0.1	< 0.002	< 0.005
2	28.16		< 0.002	< 0.002	2	1.686		< 0.01	< 0.002	2	5.646		< 0.002	> 0.05
3	13.62	41.78		< 0.002	3	10.16	8.476		> 0.1	3	24.6	30.25		< 0.002
4	6.968	21.19	20.58		4	15.32	13.63	5.154		4	11.88	6.234	36.48	

icantly different from each other with regard to $\delta^{15}N_{Daphnia}$ values (one-way ANOVA and Tukey post hoc test; Table 1).

Treatments 1 and 2 were both performed at 12 °C and with similar water in terms of $\delta^{18}O$ values. The mean $\delta^{18}O_{Daphnia}$ values in these treatments were 11.7 ± 0.1 ‰ and 11.0 ± 0.2 ‰ (Fig. 3). In Treatment 3, where the mean $\delta^{18}O_{water}$ value was 5.2 ‰ higher than in the other treatments, the mean $\delta^{18}O_{Daphnia}$ value was 14.6 ± 0.3 ‰ , which was 2.9 and 3.6 ‰ higher than in Treatment 1 and 2, respectively. In Treatment 4, with $\delta^{18}O_{water}$ as in Treatment 1 and 2 but run at a higher temperature (20 °C), the mean $\delta^{18}O_{Daphnia}$ value (10.2 ± 0.2 ‰) was 1.5 and 0.8 ‰ lower than in Treatment 1 and 2, respectively. A significant difference in $\delta^{18}O_{Daphnia}$ values was found between all treatments, except for Treatments 1 and 2 and Treatments 2 and 4 (one-way ANOVA and Tukey post hoc test; Table 1).

3.3 Ephippia stable isotope ratios

In all treatments ephippia production started between day 27 and day 34 of the experiment. Until day 48 of the experiment, ephippia production was low (on average 1 to 1.5 ephippia per jar per week), after which production increased to 4.5 to 6 ephippia per jar per week in Treatments 1, 2 and 3, whereas production in Treatment 4 remained low. Across the replicate treatments (A–C), the production of ephippia was similar with, on average, 12 to 13 ephippia per jar at the end of the experiment. The majority of the ephippia were produced by clone LC PUL 99 (55 %), whereas LC PUL 101 and 53 were responsible for 23 and 22 % of the ephippia production, respectively.

The measurements that we performed on untreated ephippia did not reveal a detectable effect of the KOH treatment on the $\delta^{13}C_{ephippia}$, $\delta^{15}N_{ephippia}$ and $\delta^{18}O_{ephippia}$ values (t tests: $\delta^{13}C$ $t = 0.41$, $p > 0.05$; $\delta^{15}N$ $t = 2.20$, $p > 0.05$; $\delta^{18}O$ $t = 0.03$, $p > 0.05$). The mean $\delta^{13}C_{ephippia}$ value was, on average, 0.2 ± 0.8 ‰ lower than the mean $\delta^{13}C_{Daphnia}$ value, but this difference was not statistically significant (paired t test: $t = 0.83$, $p > 0.05$; Fig. 4). However, this value was strongly affected by the results from Treatment 4 (20 °C), which yielded unexpected values that will be discussed below. In the three treatments at 12 °C, $\delta^{13}C_{ephippia}$ values were, on average, 0.2 ± 0.4 ‰ higher than $\delta^{13}C_{Daphnia}$, although this difference was again not significant (paired t test: $t = 1.50$, $p > 0.05$). Over all four treatments, $\delta^{15}N_{ephippia}$ values were, on average, 1.6 ± 0.4 ‰ lower than $\delta^{15}N_{Daphnia}$ values (paired t test: $t = 14.01$, $p < 5 \times 10^{-8}$), and $\delta^{18}O_{ephippia}$ values were, on average, 0.9 ± 0.4 ‰ lower than $\delta^{18}O_{Daphnia}$ values (paired t test: $t = 5.58$, $p < 5 \times 10^{-5}$).

4 Discussion

Statistically significant differences were found between nearly all treatments for all investigated *Daphnia* stable isotope ratios, even in cases where we expected no differences based on the manipulations. For example, Treatment 1 and 3 were identical in terms of $\delta^{13}C$ values of the food source and temperature and only differed in the $\delta^{18}O$ values of the water, and Treatment 1, 2 and 3 were identical in terms of $\delta^{15}N$ values of the food source and temperature. However, the unexpected differences between these treatments were generally small and of the same order of magnitude as the analytical precisions associated with each element (Fig. 3). They may represent the inherent variability associated with stable isotope ratios in organisms (Schimmelmann, 2011). Alternatively, since the stable isotope ratios of the algae showed some variability over the course of the experiment (Fig. 1), a slight difference in timing in the buildup of biomass may have led to small differences in *Daphnia* stable isotope ratios. In previous experiments, $\delta^{13}C_{Daphnia}$ and $\delta^{15}N_{Daphnia}$ values have been found to differ as much as 1 ‰ between identical treatments (Power et al., 2003). The differences in *Daphnia* stable isotope ratios were much larger when comparing treatments with manipulated $\delta^{13}C_{algae}$ and $\delta^{18}O_{water}$ values to those with non-manipulated algae and water.

4.1 The food experiment: changing $\delta^{13}C_{algae}$

Offering *Daphnia* algae with, on average, 1.8 ‰ lower $\delta^{13}C_{algae}$ values resulted in 1.5 to 2.1 ‰ lower $\delta^{13}C_{Daphnia}$ values. Since the $\delta^{13}C_{algae}$ values were variable over time, we cannot reconstruct the exact $\delta^{13}C$ value of the carbon that

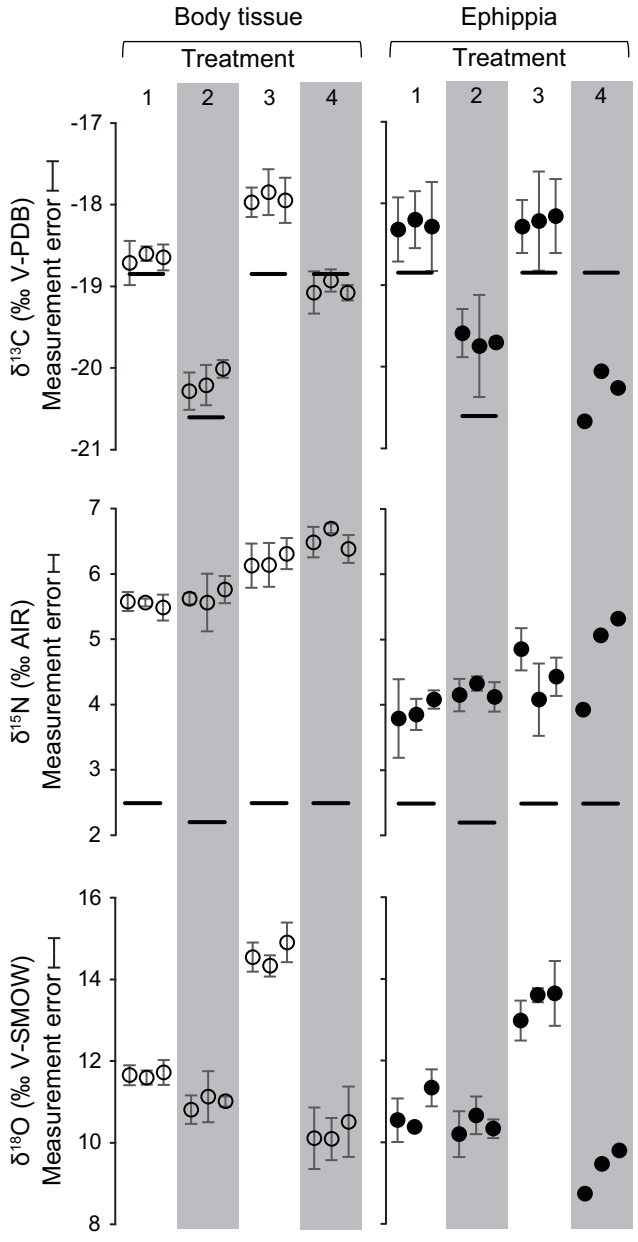

Figure 3. δ^{13}C, δ^{15}N and δ^{18}O values of *Daphnia* body tissue (left, open circles) and ephippia (right, closed circles) for Treatment 1 (control), 2 (^{13}C-depleted algae), 3 (^{18}O-enriched water) and 4 (elevated temperature). Each data point represents one of the treatment replicate groups and consists of three measurements, of which the standard deviation is indicated by the error bars (only one measurement per replicate treatment group was available for ephippia in Treatment 4). The black horizontal lines in the δ^{13}C and δ^{15}N plots represent the average value of the algae used in that treatment.

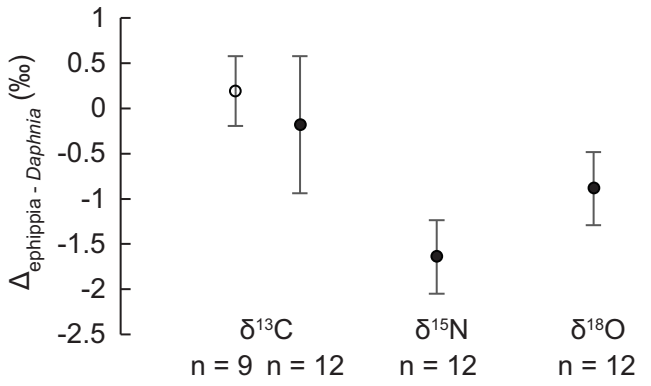

Figure 4. The difference in δ^{13}C, δ^{15}N and δ^{18}O values between ephippia and *Daphnia* for all four treatments (closed circles). The open circle gives the offset for the three treatments at 12 °C excluding Treatment 4 (20 °C), which yielded unexpected results for δ^{13}C (see text). Error bars indicate standard deviations.

Daphnia in our different treatments assimilated, and therefore we cannot calculate a precise estimate of Δ^{13}C. Based on the mean $\delta^{13}C_{algae}$ value over the duration of the experiment, however, Δ^{13}C between *Daphnia* and algae is estimated to be $+0.5 \pm 0.3$ ‰ at 12 °C. This is in agreement with commonly found Δ^{13}C values of 0 to +1 ‰ for a range of animals, including invertebrates (DeNiro and Epstein, 1978; McCutchan et al., 2003). *D. magna* has been reported to have a Δ^{13}C value of +1.7 ‰ at 12 °C on a diet of aquarium food (Power et al., 2003). However, in this study a lipid correction was applied to infer δ^{13}C values based on C : N ratios following a model by McConnaughey and McRoy (1979). This leads to relatively higher δ^{13}C values, and the procedure has been criticized, since it potentially provides biased estimates when comparing isotopic ratios of different organisms and tissues (Mintenbeck et al., 2008). Power et al. (2003) did not report the C : N of the food and *Daphnia*, so we cannot back-calculate the δ^{13}C values they measured prior to lipid correction.

$\delta^{13}C_{ephippia}$ values also reflected the difference in $\delta^{13}C_{algae}$ values between the treatments. At 12 °C, they were not significantly different from the $\delta^{13}C_{Daphnia}$ values (although they were consistently lower at 20 °C; see below). This is in line with the findings by Perga (2011), who found that the δ^{13}C value of ephippia collected in the field was slightly, but not significantly, higher than the δ^{13}C value of *Daphnia* collected in the same net trawls. This suggests that $\delta^{13}C_{ephippia}$ values are a reliable indicator of changes in $\delta^{13}C_{Daphnia}$ values, and consequently of variations in δ^{13}C values of *Daphnia* diet: at 12 °C, $\delta^{13}C_{ephippia}$ was 0.7 ± 0.2 ‰ higher than the mean $\delta^{13}C_{algae}$. The absence of a clear offset in δ^{13}C values between whole *Daphnia* and *Daphnia* ephippia at 12 °C is in contrast to the difference found between whole *Daphnia* and *Daphnia* exoskeletons (0.8 ‰; Perga, 2010) and between chironomid body tissue and chironomid head capsules (∼ 1 ‰; Heiri et al., 2012; Frossard et al., 2013).

4.2 δ^{15} N values of *Daphnia* and ephippia

At 12 °C, the observed Δ^{15}N was $+3.4 \pm 0.3$ ‰, which agrees well with Δ^{15}N values referred to in the literature ($+3$ to $+4$ ‰; DeNiro and Epstein, 1981; Minagawa and Wada, 1984). A range of Δ^{15}N values for *Daphnia* have been reported. *D. pulicaria* reared on a diet of frozen algae pellets had a Δ^{15}N of $+1.4$ ‰ (Matthews and Mazumder, 2008). This is lower than the Δ^{15}N we found. According to Matthews and Mazumder (2008), the low Δ^{15}N they observed may be explained by the observation that a diet consisting of detritus (dead algae) is associated with considerably (~ 2.5 ‰) lower Δ^{15}N values than one consisting of living plant matter (Vanderklift and Ponsard, 2003). Our observed Δ^{15}N for *D. pulicaria* is within the range of reported *D. magna* Δ^{15}N values ($+1$ to $+6$ ‰; Adams and Sterner, 2000; Power et al., 2003).

$\delta^{15}N_{ephippia}$ values were lower (1.6 ± 0.4 ‰) than $\delta^{15}N_{Daphnia}$ values. In contrast, Perga (2011) found $\delta^{15}N_{ephippia}$ values to be slightly, but not significantly, lower than $\delta^{15}N_{Daphnia}$ values in the field. Together with the results of Perga (2011), our data provide an indication that $\delta^{15}N_{ephippia}$ values are indicative of δ^{15}N values of *Daphnia* and their diet, with only relatively minor offsets between food, *Daphnia* and ephippia. For chironomids, differences of similar magnitude between whole-body δ^{15}N values and head capsule δ^{15}N values (-1 to $+1$ ‰) were observed over a large range of δ^{15}N values (2.5 to 15 ‰; Heiri et al., 2012). Therefore, it seems likely that differences between *Daphnia* and ephippia δ^{15}N values may also be similar across this δ^{15}N range.

4.3 The water experiment: changing $\delta^{18}O_{water}$ values

$\delta^{18}O_{water}$ values were 5.2 ‰ higher in Treatment 3 than in Treatment 1 and 2, and the mean $\delta^{18}O_{Daphnia}$ values in Treatment 3 were 2.9 ‰ higher than in Treatment 1 and 3.6 ‰ higher than in Treatment 2. This implies that, as expected, differences in $\delta^{18}O_{Daphnia}$ values reflect differences in $\delta^{18}O_{water}$, yet that, as in other invertebrates, only part of the oxygen incorporated by the *Daphnia* originated from the water. Wang et al. (2009) reported that 69 % of the oxygen in chironomid larvae stemmed from the water in their environment. Soto et al. (2013) estimated that 84 % of the oxygen in protein isolated from chironomids came from the water in their environment, and Nielson and Bowen (2010) reported that 69 % of the oxygen in chitin from brine shrimp came from water in their environment. Based on Eq. (1), we estimate that in our experiment 56 to 69 % of the oxygen in *Daphnia* came from the water, based on Treatment 1 and 2, respectively. These estimates are similar to the values reported by Wang et al. (2009) and Nielson and Bowen (2010).

$\delta^{18}O_{ephippia}$ values closely reflected differences in $\delta^{18}O_{Daphnia}$: they were, on average, 0.9 ± 0.4 ‰ lower than $\delta^{18}O_{Daphnia}$ values. This suggests that $\delta^{18}O_{ephippia}$ may be used as an indicator of $\delta^{18}O_{Daphnia}$, which in turn can be expected to be related to lake water δ^{18}O values. This is in agreement with the correlation between surface sediment $\delta^{18}O_{ephippia}$ values and lake water δ^{18}O values found in a field survey of a number of European lakes (Verbruggen et al., 2011).

4.4 The temperature experiment

Power et al. (2003) reported an increase of 0.1 ‰ in Δ^{13}C values for *D. magna* with a temperature increase from 12 to 20 °C (and $+1.4$ ‰ when temperature increased from 12 to 26 °C). Therefore, we expected Δ^{13}C values for *Daphnia* in Treatment 4 (20 °C) to be similar to or slightly higher than in the other treatments (12 °C). Δ^{13}C values were clearly lower, however, in Treatment 4 (-0.2 ± 0.1 ‰) than in the other treatments ($+0.5 \pm 0.3$ ‰). While we cannot exclude a negative relation between temperature and Δ^{13}C values for *Daphnia*, we choose to treat this result with caution due to the discrepancy with the positive Δ^{13}C values as reported in other studies (DeNiro and Epstein, 1978; McCutchan et al., 2003; Power et al., 2003). A higher lipid content of *Daphnia* may potentially lead to lower $\delta^{13}C_{Daphnia}$ values (McCutchan et al., 2003). However, the C : N ratios of *Daphnia* in Treatment 4 were slightly lower (but not significantly different; t test: $t = 1.18$ $p > 0.05$) than those of *Daphnia* in Treatment 1, which does not agree with a higher lipid content in *Daphnia* from Treatment 4 (Smyntek et al., 2007). Alternatively, ^{13}C depletion of algal biomass during dark respiration may have affected the $\delta^{13}C_{algae}$ in Treatment 4 disproportionately due to the higher temperature. Degens et al. (1968) found that δ^{13}C values of the alga *Dunaliella tertiolecta* were 4 ‰ lower after 3 days in darkness. The rate of respiration by algae depends on temperature and can be 2 to 4 times higher at 20 °C than at 12 °C (e.g., Vona et al., 2004). Microbial activity in the experimental jars could have been affected by temperature and could have also influenced our results. Additionally, if *Daphnia* in Treatment 4 had a different timing of growth compared to Treatment 1, as might be expected, they may have been assimilating carbon from algae with different $\delta^{13}C_{algae}$ values during the main phase of their growth compared to the other treatments, since $\delta^{13}C_{algae}$ values were relatively low in the beginning and at the end of the experiment (Fig. 1). $\delta^{13}C_{ephippia}$ values were also lower in Treatment 4, and 1.3 ± 0.3 ‰ lower than $\delta^{13}C_{Daphnia}$ values. For the same reasons as outlined above, it remains unclear whether this observation is the consequence of a fundamental change in the offset between $\delta^{13}C_{Daphnia}$ and $\delta^{13}C_{ephippia}$ with temperature or whether it is affected by variations in $\delta^{13}C_{algae}$ and algal respiration rates or differences in *Daphnia* growth rates between our treatments. Controlled experiments over a range of temperature values analyzing not only $\delta^{13}C_{Daphnia}$ and $\delta^{13}C_{ephippia}$ values, but also δ^{13}C values of respired CO_2 and microbial biomass would be desirable to further explore this issue. Although the results of Treatment 4 indicate that the

difference between $\delta^{13}C_{ephippia}$ and $\delta^{13}C_{Daphnia}$ values may be more variable than suggested by the cultivations at 12 °C, the offset is still relatively small compared to the variation in $\delta^{13}C_{ephippia}$ values in lake sediment records (up to 10 ‰; e.g., Wooller et al., 2012).

$\Delta^{15}N$ between *Daphnia* and algae was $+4.0 \pm 0.2$ ‰ at 20 °C, 0.6 ‰ higher than at 12 °C. A small increase (0.4 ‰) in $\Delta^{15}N$ in this temperature range has also been reported for *D. magna* (Power et al., 2003). Power et al. (2003) found a decrease of 2.7 ‰ in $\Delta^{15}N$ values for *D. magna* between 20 and 26 °C, however, and Barnes et al. (2007) found a decrease of 0.6 ‰ in $\Delta^{15}N$ values for sea bass with a temperature increase from 11 to 16 °C. Previously observed $\Delta^{15}N$ values in field studies of aquatic food webs (Vander Zanden and Rasmussen, 2001), and specifically in experimental studies of *Daphnia* (Adams and Sterner, 2000; Matthews and Mazumder, 2008), are, in some cases, lower than +3 to +4 ‰. A potential effect of temperature on $\Delta^{15}N$ values for *Daphnia* which, based on presently available observations, may amount to 2.7 ‰ at temperatures above 20 °C (Power et al., 2003) therefore deserves future attention. The offset between $\delta^{15}N_{Daphnia}$ and $\delta^{15}N_{ephippia}$ in our experiment was, however, not significantly different (*t* test: $t = 0.26$ $p > 0.05$) between Treatment 1 (control, 12 °C) and 4 (20 °C).

The effect of temperature on oxygen isotope fractionation during the formation of chitin by aquatic organisms has not been examined previously in experimental studies. Schimmelmann and DeNiro (1986) analyzed the $\delta^{18}O$ values of the chitin of marine crustaceans collected along a temperature gradient of 10 °C and van Hardenbroek et al. (2012) studied the $\delta^{18}O$ values of aquatic beetles in museum specimens selected to represent a temperature gradient across North America. Both studies concluded that the temperature effect on oxygen isotope fractionation during chitin formation (if any) was smaller than the variability due to minor differences in local environmental conditions. In this study we kept close control over the environmental conditions and source water $\delta^{18}O$ values, and we found that $\delta^{18}O_{Daphnia}$ was slightly (0.8 to 1.5 ‰) lower with an increase of temperature by 8 °C but otherwise similar conditions. This may indicate an effect of temperature on oxygen isotope fractionation by *Daphnia*. We do note, however, that the potential temperature effect on oxygen isotope fractionation by *Daphnia* observed in our experiment was relatively small and resulted from a large difference in temperature. Therefore, $\delta^{18}O_{Daphnia}$values most likely primarily reflect environmental water $\delta^{18}O$ values. The offset between $\delta^{18}O_{ephippia}$ and $\delta^{18}O_{Daphnia}$ in Treatment 4 (20 °C) was not significantly different, however (*t* test: $t = 0.09$, $p > 0.05$), from that in Treatment 1 (control, 12 °C). This suggests that, in contrast to the difference between $\delta^{18}O_{water}$ and $\delta^{18}O_{Daphnia}$, this offset is not affected by temperature in the investigated temperature range (12 to 20 °C). Verbruggen et al. (2011) measured the $\delta^{18}O$ values of recently deposited ephippia from surface sediments in lakes along a geographical gradient in Europe. They found a strong correlation between $\delta^{18}O_{ephippia}$ values and lake water $\delta^{18}O$ values. In their data set, the $\delta^{18}O$ values of lake water increased by ∼ 4.8 ‰ with a temperature increase of 8 °C, whereas $\delta^{18}O_{ephippia}$ values increased by only ∼ 3 ‰ over this temperature gradient, a difference of ∼ 1.8 ‰. This difference is of a similar order of magnitude as the 0.8 to 1.5 ‰ lower $\delta^{18}O_{Daphnia}$ values we found with an 8 °C temperature rise. The data of Verbruggen et al. (2011) and our experimental data would therefore be in agreement with a slight temperature effect on the fractionation of ^{18}O between lake water and *Daphnia* biomass. However, other mechanisms, such as a change in timing of *Daphnia* ephippia production with temperature and variations in $\delta^{18}O$ values of food across the examined temperature gradient could also explain varying offsets between $\delta^{18}O_{water}$ and $\delta^{18}O_{Daphnia}$ at different temperatures in the study of Verbruggen et al. (2011). Moreover, differences in air temperature at lakes, which Verbruggen et al. (2011) reported, do not necessarily lead to similar differences in lake water temperatures.

4.5 Implications for palaeoecological studies

In general, we found that the stable isotopic composition of ephippia closely reflected the stable isotopic composition of *Daphnia*. The offsets were consistent within treatments and between most treatments (Fig. 4), and the ephippia stable isotope ratios responded to the manipulations in $\delta^{13}C_{algae}$ and $\delta^{18}O_{water}$ that we performed. Studies investigating the $\delta^{13}C$ and $\delta^{15}N$ values of fossil *Daphnia* ephippia have recorded shifts of up to 5 to 10 ‰ in $\delta^{13}C$ values (Wooller et al., 2012; Frossard et al., 2014) and 3 ‰ in $\delta^{15}N$ values (Griffiths et al., 2010). Shifts of 2 to 3 ‰ in $\delta^{18}O$ values have been reported for fossil chironomid head capsules (Wooller et al., 2004; Verbruggen et al., 2010b). In our experiment, the standard deviation of the offset between *Daphnia* and ephippia stable isotope ratios was much smaller than the reported shifts in stable isotope ratios of fossil remains: ±0.4 ‰ for $\delta^{13}C$, $\delta^{15}N$ and $\delta^{18}O$ (±0.8 ‰ for $\delta^{13}C$ when including Treatment 4 at 20 °C). If our findings are representative of the offset in stable isotope ratios between *Daphnia* and their ephippia in nature, they indicate that reported shifts in stable isotope ratios of fossil ephippia can reliably be interpreted as indicating past variations in *Daphnia* stable isotope ratios. These in turn can be expected to reflect past changes in isotopic composition of *Daphnia* diet and/or the $\delta^{18}O$ of the water they lived in. While experiments offer the possibility to closely control the food sources and growth conditions for *Daphnia*, they cannot cover the full range of environments and interactions found in nature. Further studies in the field, in the fossil record and in an experimental setting are therefore needed to confirm the findings that we present here and to improve our understanding of the relationship between the stable isotopic composition of food, ambient water and chitinous fossilizing structures produced by *Daphnia* and other invertebrates. Although we only cultured *Daphnia* at two different temper-

atures, we found indications that temperature may have affected $\Delta^{13}C$ and $\Delta^{15}N$ on the one hand and the relationship between $\delta^{18}O_{water}$ and $\delta^{18}O_{Daphnia}$ values on the other in an experimental setting. Future efforts focused on constraining the effect of temperature on these offsets and relationships are therefore particularly necessary.

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References

Adams, T. S. and Sterner, R. W.: The effect of dietary nitrogen content on trophic level ^{15}N enrichment, Limnol. Oceanogr., 45, 601–607, 2000.

Barnes, C., Sweeting, C. J., Jennings, S., Barry, J. T., and Polunin, N. V. C.: Effect of temperature and ration size on carbon and nitrogen stable isotope trophic fractionation, Funct. Ecol., 21, 356–362, 2007.

Belle, S., Parent, C., Frossard, V., Verneaux, V., Millet, L., Chronopoulou, P-M., Sabatier, P., and Magny, M.: Temporal changes in the contribution of methane-oxidizing bacteria to the biomass of chironomid larvae determined using stable carbon isotopes and ancient DNA, J. Paleolimnol., 52, 215–228, doi:10.1007/s10933-014-9789-z, 2014.

Cáceres, C. E. and Tessier, A. J.: Incidence of diapause varies among populations of *Daphnia pulicaria*, Oecologia, 141, 425–31, doi:10.1007/s00442-004-1657-5, 2004.

Degens, E. T., Guillard, R. R. L., Sackett, W. M., and Hellebust, J. A.: Metabolic fractionation of carbon isotopes in marine plankton – I. Temperature and respiration experiments, Deep-Sea Res., 15, 1–9, 1968.

DeNiro, M. and Epstein, S.: Influence of diet on the distribution of nitrogen isotopes in animals, Geochim. Cosmochim. Ac., 45, 341–351, 1981.

DeNiro, M. J. and Epstein, S.: Influence of diet on the distribution of carbon isotopes in animals, Geochim. Cosmochim. Ac., 42, 495–506, 1978.

Frossard, V., Belle, S., Verneaux, V., Millet, L., and Magny, M.: A study of the $\delta^{13}C$ offset between chironomid larvae and their exuvial head capsules: implications for palaeoecology, J. Paleolimnol., 50, 379–386, doi:10.1007/s10933-013-9732-8, 2013.

Frossard, V., Verneaux, V., Millet, L., Jenny, J.-P., Arnaud, F., Magny, M., and Perga, M.-E.: Reconstructing long-term changes (150 years) in the carbon cycle of a clear-water lake based on the stable carbon isotope composition ($\delta^{13}C$) of chironomid and cladoceran subfossil remains, Freshwater Biol., 59, 789–802, doi:10.1111/fwb.12304, 2014.

Gannon, J. E.: Two counting cells for the enumeration of zooplankton micro-crustacea, Trans. Am. Microsc. Soc., 90, 486–490, 1971.

Geller, W. and Müller, H.: The filtration apparatus of Cladocera: Filter mesh-sizes and their implications on food selectivity, Oecologia, 49, 316–321, 1981.

Goedkoop, W., Åkerblom, N., and Demandt, M. H.: Trophic fractionation of carbon and nitrogen stable isotopes in *Chironomus riparius* reared on food of aquatic and terrestrial origin, Freshwater Biol., 51, 878–886, doi:10.1111/j.1365-2427.2006.01539.x, 2006.

Gophen, M. and Geller, W.: Filter mesh size and food particle uptake by *Daphnia*, Oecologia, 64, 408–412, 1984.

Griffiths, K., Michelutti, N., Blais, J. M., Kimpe, L. E., and Smol, J. P.: Comparing nitrogen isotopic signals between bulk sediments and invertebrate remains in High Arctic seabird-influenced ponds, J. Paleolimnol., 44, 405–412, doi:10.1007/s10933-009-9354-3, 2010.

Guillard, R. L.: Cultures of phytoplankton for feeding of marine invertebrates, in: Culture of marine invertebrate animals conference, edited by: Smith, W. L. and Chanley, M. H., Plenum Press, New York, p. 338, 1975.

Hammer, Ø., Harper, D. A. T., and Ryan, P. D.: PAST: paleontological Statistics software package for education and data analysis, Paleontol. Electron., 4, 9 pp., 2001.

He, X. and Wang, W.-X.: Releases of ingested phytoplankton carbon by *Daphnia magna*, Freshwater Biol., 51, 649–665, doi:10.1111/j.1365-2427.2006.01519.x, 2006.

Heiri, O., Schilder, J., and Hardenbroek, M. van: Stable isotopic analysis of fossil chironomids as an approach to environmental reconstruction: state of development and future challenges, Fauna Nor., 31, 7–18, doi:10.5324/fn.v31i0.1436, 2012.

Hobson, K. A.: Applying Isotopic Methods to Tracking Animal Movements, in: Tracking animal migration with stable isotopes, vol. 7961, edited by: Hobson, K. A. and Wassenaar, L. I., Academic Press, Waltham, 45–78, 2008.

Hobson, K. A. and Cherel, Y.: Isotopic reconstruction of marine food webs using cephalopod beaks: new insight from captively raised *Sepia officinalis*, Can. J. Zoolog., 84, 766–770, doi:10.1139/Z06-049, 2006.

Kamjunke, N., Benndorf, A., Wilbert, C., Opitz, M., Kranich, J., Bollenbach, M., and Benndorf, J.: Bacteria ingestion by *Daphnia galeata* in a biomanipulated reservoir: a mechanism stabilizing biomanipulation?, Hydrobiologia, 403, 109–121, doi:10.1023/A:1003722318598, 1999.

Kleiven, O. T., Larsson, P., and Hobæk, A.: Sexual reproduction in *Daphnia magna* requires three stimuli, Oikos, 65, 197–206, 1992.

Lampert, W.: *Daphnia*: Development of a model organism, in: Excellence in ecology, p. 250, International ecology institute, Oldendorf/Luhe, 2011.

Leng, M. J. and Henderson A. C. G.: Recent advances in isotopes as palaeolimnological proxies, J. Paleolimnol., 49, 481–496, 2013.

Martínez del Rio, C., Wolf, N., Carleton, S. A., and Gannes, L. Z.: Isotopic ecology ten years after a call for more laboratory experi-

ments, Biol. Rev. Camb. Philos., 84, 91–111, doi:10.1111/j.1469-185X.2008.00064.x, 2009.

Matthews, B. and Mazumder, A.: Detecting trophic-level variation in consumer assemblages, Freshwater Biol., 53, 1942–1953, doi:10.1111/j.1365-2427.2008.02018.x, 2008.

McConnaughey, T. and McRoy, C. P.: Food-Web structure and the fractionation of Carbon isotopes in the bering sea, Mar. Biol., 53, 257–262, doi:10.1007/BF00952434, 1979.

McCutchan, J. H., Lewis, W. M., Kendall, C., and Mcgrath, C. C.: Variation in trophic shift for stable isotope ratios of carbon, nitrogen, and sulfur, Oikos, 102, 378–390, 2003.

Miller, R. F., Voss-Foucart, M.-F., Toussaint, C., and Jeuniaux, C.: Chitin preservation in quaternary Coleoptera: preliminary results, Palaeogeogr. Palaeocl., 103, 133–140, 1993.

Minagawa, M. and Wada, E.: Stepwise enrichment of ^{15}N along food chains: Further evidence and the relation between δ^{15}N and animal age, Geochim. Cosmochim. Ac., 48, 1135–1140, 1984.

Mintenbeck, K., Brey, T., Jacob, U., Knust, R., and Struck, U.: How to account for the lipid effect on carbon stable-isotope ratio (δ^{13}C): sample treatment effects and model bias, J. Fish Biol., 72, 815–830, doi:10.1111/j.1095-8649.2007.01754.x, 2008.

Möst, M.: Environmental change and its impact on hybridising *Daphnia* species complexes, PhD thesis, ETH, Zurich, 139 pp., doi:10.3929/ethz-a-010076219, 2013.

Nielson, K. E. and Bowen, G. J.: Hydrogen and oxygen in brine shrimp chitin reflect environmental water and dietary isotopic composition, Geochim. Cosmochim. Ac., 74, 1812–1822, doi:10.1016/j.gca.2009.12.025, 2010.

Perga, M.-E.: Potential of δ^{13}C and δ^{15}N of cladoceran subfossil exoskeletons for paleo-ecological studies, J. Paleolimnol., 44, 387–395, doi:10.1007/s10933-009-9340-9, 2010.

Perga, M.-E.: Taphonomic and early diagenetic effects on the C and N stable isotope composition of cladoceran remains: implications for paleoecological studies, J. Paleolimnol., 46, 203–213, doi:10.1007/s10933-011-9532-y, 2011.

Pinnegar, J. K. and Polunin, N. V. C.: Differential fractionation of δ^{13}C and δ^{15}N among fish tissues: implications for the study of trophic interactions, Funct. Ecol., 13, 225–231, doi:10.1046/j.1365-2435.1999.00301.x, 1999.

Power, M., Guiguer, K. R. R. A., and Barton, D. R.: Effects of temperature on isotopic enrichment in *Daphnia magna*: implications for aquatic food-web studies., Rapid Commun. Mass Sp., 17, 1619–1625, doi:10.1002/rcm.1094, 2003.

R Core Team: R: A language and environment for statistical computing, R Foundation for Statistical Computing, Vienna, Austria, 2013.

Rubenstein, D. R. and Hobson, K. A.: From birds to butterflies: animal movement patterns and stable isotopes, Trends Ecol. Evol., 19, 256–263, doi:10.1016/j.tree.2004.03.017, 2004.

Schilder, J. Bastviken, D., van Hardenbroek, M., Leuenberger, M., Rinta, P., Stötter, T., and Heiri, O.: The stable carbon isotopic composition of *Daphnia* ephippia in small, temperate lakes reflects in-lake methane availability, Limnol. Oceanogr., 60, 1064–1075, doi:10.1002/lno.10079, 2015.

Schimmelmann, A.: Carbon, nitrogen and oxygen stable isotope ratios in chitin, in: Chitin: formation and diagenesis, edited by: Gupta, N. S., Springer, New York, 81–103, 2011.

Schimmelmann, A. and DeNiro, M. J.: Stable isotopic studies on chitin. III. The D/H and ^{18}O/^{16}O ratios in arthropod chitin, Geochim. Cosmochim. Ac., 50, 1485–1496, 1986.

Smyntek, P. M., Teece, M. A., Schulz, K. L., and Thackeray, S. J.: A standard protocol for stable isotope analysis of zooplankton in aquatic food web research using mass balance correction models, Limnol. Oceanogr., 52, 2135–2146, doi:10.4319/lo.2007.52.5.2135, 2007.

Soto, D. X., Wassenaar, L. I., and Hobson, K. A.: Stable hydrogen and oxygen isotopes in aquatic food webs are tracers of diet and provenance, edited by: Raubenheimer, D., Funct. Ecol., 27, 535–543, doi:10.1111/1365-2435.12054, 2013.

Szeroczyńska, K. and Sarmaja-Korjonen, K.: Atlas of subfossil cladocera from central and northern Europe, Friends of the Lower Vistula society, Świecie., 2007.

Vanderklift, M. A. and Ponsard, S.: Sources of variation in consumer-diet δ^{15}N enrichment: a meta-analysis, Oecologia, 136, 169–82, doi:10.1007/s00442-003-1270-z, 2003.

Vander Zanden, M. J. and Rasmussen, J. B.: Primary consumer δ^{13}C and δ^{15}N and the trophic position of aquatic consumers, Ecology, 80, 1395–1404, 1999.

Vander Zanden, M. J. and Rasmussen, J. B.: Variation in δ^{15}N and δ^{13}C trophic fractionation: Implications for aquatic food web studies, Limnol. Oceanogr., 46, 2061–2066, 2001.

Van Hardenbroek, M., Gröcke, D. R., Sauer, P. E., and Elias, S. A.: North American transect of stable hydrogen and oxygen isotopes in water beetles from a museum collection, J. Paleolimnol., 48, 461–470, doi:10.1007/s10933-012-9623-4, 2012.

Van Hardenbroek, M., Heiri, O., Parmentier, F. J. W., Bastviken, D., Ilyashuk, B. P., Wiklund, J. A., Hall, R. I., and Lotter, A. F.: Evidence for past variations in methane availability in a Siberian thermokarst lake based on δ^{13}C of chitinous invertebrate remains, Quaternary Sci. Rev., 66, 74–84, doi:10.1016/j.quascirev.2012.04.009, 2013.

Van Hardenbroek, M., Lotter, A. F., Bastviken, D., Andersen, T. J., and Heiri, O.: Taxon-specific δ^{13}C analysis of chitinous invertebrate remains in sediments from Strandsjön, Sweden, J. Paleolimnol., 52, 95–105, doi:10.1007/s10933-014-9780-8, 2014.

Verbruggen, F., Heiri, O., Reichart, G.-J., De Leeuw, J. W., Nierop, K. G. J., and Lotter, A. F.: Effects of chemical pretreatments on δ^{18}O measurements, chemical composition, and morphology of chironomid head capsules, J. Paleolimnol., 43, 857–872, 2010a.

Verbruggen, F., Heiri, O., Reichart, G.-J., and Lotter, A. F.: Chironomid δ^{18}O as a proxy for past lake water δ^{18}O: a Lateglacial record from Rotsee (Switzerland), Quaternary Sci. Rev., 29, 2271–2279, doi:10.1016/j.quascirev.2010.05.030, 2010b.

Verbruggen, F., Heiri, O., Reichart, G. J., Blaga, C., and Lotter, A. F.: Stable oxygen isotopes in chironomid and cladoceran remains as indicators for lake-water δ^{18}O, Limnol. Oceanogr., 56, 2071–2079, doi:10.4319/lo.2011.56.6.2071, 2011.

Vona, V., Di Martino Rigano, V., Lobosco, O., Carfagna, S., Esposito, S., and Rigano, C.: Temperature responses of growth, photosynthesis, respiration and NADH: nitrate reductase in cryophilic and mesophilic algae, New Phytol., 163, 325–331, doi:10.1111/j.1469-8137.2004.01098.x, 2004.

Wang, Y. V., O'Brien, D. M., Jenson, J., Francis, D., and Wooller, M. J.: The influence of diet and water on the stable oxygen and hydrogen isotope composition of Chironomidae (Diptera)

with paleoecological implications, Oecologia, 160, 225–233, doi:10.1007/s00442-009-1303-3, 2009.

Wooller, M. J., Francis, D., Fogel, M. L., Miller, G. H., Walker, I. R., and Wolfe, A. P.: Quantitative paleotemperature estimates from ^{18}O of chironomid head capsules preserved in arctic lake sediments, J. Paleolimnol., 31, 267–274, 2004.

Wooller, M. J., Pohlman, J. W., Gaglioti, B. V., Langdon, P., Jones, M., Walter Anthony, K. M., Becker, K. W., Hinrichs, K.-U., and Elvert, M.: Reconstruction of past methane availability in an Arctic Alaska wetland indicates climate influenced methane release during the past ∼ 12,000 years, J. Paleolimnol., 48, 27–42, doi:10.1007/s10933-012-9591-8, 2012.