



Seasonal nutritional status in Norway lobsters, *Nephrops norvegicus* (L.): Are females nutritionally compromised over the winter?

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1 **Seasonal nutritional status in Norway lobsters, *Nephrops norvegicus* (L.): Are females**
2 **nutritionally compromised over the winter?**

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18
19 **Running head**

20 Seasonal nutritional status in lobster *N. norvegicus*

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26 **Abstract**

27 Norway lobsters, *Nephrops norvegicus*, are sediment-dwelling decapod crustaceans that
28 excavate burrows from which they make short excursions to feed by predation and
29 scavenging. The females of this species are known to reside within their burrows for an
30 extended period of time over the winter while brooding their eggs. The aim of this study was
31 to assess the likelihood of these females being able to feed during this brooding period.
32 Biophysical and biochemical measurements that had previously been shown to change with
33 starvation under laboratory conditions in male *N. norvegicus* were taken for female *N.*
34 *norvegicus* under similar conditions. These measurements were also compared in both
35 sexes obtained from monthly trawl samples from the Clyde Sea Area, Scotland, UK, together
36 with trawl composition data. The laboratory study showed that the hepatosomatic index, and
37 the copper, lipid and water content of the hepatopancreas can be used as indicators of the
38 state of starvation in females, as in males. In the wild, both sexes have reduced nutritional
39 status during the winter, but not to the degree seen in animals starved for 20 weeks in
40 aquarium trials. This study does not support the hypothesis that females cease feeding over
41 winter, during their brooding period. Firstly, some females were unable to sustain ovary
42 development during starvation under controlled conditions, contrary to field observations.
43 Secondly, field data suggests that there is no sex-specific reduction in nutritional status.

44

45 **Key words**

46 *Nephrops norvegicus*, Norway lobster, nutritional state, starvation, brooding

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49 **Introduction**

50 Norway lobsters, *Nephrops norvegicus* (Linnaeus, 1758), are carnivores that emerge from
51 their burrows to feed. Periods of burrow emergence vary in relation to ambient light
52 conditions, sex and season (Bell et al. 2006). The nutritional status of a wild animal depends
53 on a variety of factors, such as abundance and quality of food, search and capture ability,
54 conspecific and interspecific competition, predator avoidance and periodical physiological
55 changes (Macleod et al. 2008) Animals have developed coping mechanisms to deal with
56 periods of food shortage, which range from reducing their metabolic rate to varying the
57 extent to which tissue reserves are utilised to obtain energy (Roots 2006). Norway lobsters
58 experience a number of these limiting nutritional conditions throughout their life.

59 Norway lobsters have been shown to be opportunistic predators and scavengers (Thomas &
60 Davidson 1962) with stomach contents reflecting prey abundance rather than feeding
61 preference (Bell et al. 2006). Fluctuations in primary production will influence the abundance
62 of the benthic organisms on which they feed and may result in a reduction in food availability
63 in the winter (Stephens et al. 1967). The nutritional status of a population of *N. norvegicus* in
64 a particular area is also driven by density-dependent factors. In high density areas
65 competition for food may limit scope for growth. Moreover, increased aggressive social
66 behaviour in high density areas could drive up the metabolic rate and thus energy
67 requirements (Chapman & Bailey 1987; Tuck et al. 1997b; Parslow-Williams 1998; Tuck et
68 al. 1999; Bell et al. 2006; Campbell et al. 2009).

69 The reproductive cycle of female *N. norvegicus* shows latitudinal differences in the times of
70 spawning, incubation, egg hatching and mating (Bell et al. 2006). Those in the Clyde Sea
71 Area contain both annual and biennial spawners (Bailey 1984). Females become
72 reproductively mature at around 3 years of age (Bell et al. 2006). As age is not easy to
73 determine, due to the fact that there are no morphological structures that change in an age-
74 related manner and are retained across successive moults, the size of the female is most
75 often used to determine the stage at which it becomes reproductively active. This is known
76 as the 'Size at Onset Maturity' or SOM, which has been defined by Bailey (1984) and Tuck
77 et al. (1997a) as the size at which 50% of females (L_{50}) have ovaries in a reproductively-
78 active condition - an indicator of 'physiological maturity'. As an alternative indicator of SOM,
79 both Bailey (1984) and Tuck et al. (1997a) have also used the size of the smallest ovigerous
80 female as an indicator of 'functional maturity' and found no significant difference between
81 these two methods.

82 Farmer (1974), Rotllant et al. (2005) and Mente et al. (2009) described in detail the
83 development of the ovary maturation cycle. Immature females and those between

84 reproductive events have cream coloured ovaries. As they develop, the ovaries are coloured
85 by a green vitellogen protein (Avarre et al. 2003). Ovary development commences during
86 the winter, only reaching pale green coincident with emergence in spring. Most development
87 takes place as a result of active feeding after spawning, moulting and mating (Farmer 1974).
88 They mature through the spring and summer when animals are actively feeding, with egg
89 laying occurring in late summer and autumn, after which females retreat to their burrows
90 (Bell et al. 2006).

91 *Nephrops norvegicus* need to balance their food-searching behaviour with the need to avoid
92 predators. These trade-offs are resolved by the animals staying in close proximity to their
93 burrows during feeding excursions (Chapman & Rice 1971). Many of these limiting factors
94 could be experienced by both sexes of *N. norvegicus*, but some will particularly affect
95 ovigerous (so-called 'berried') females as they are known to reside within their burrows over
96 winter while brooding their eggs, presumably in order to reduce their predation risk (Aguzzi
97 et al. 2007). Newland (1985) showed that abdominal tail flipping (the method of escape
98 swimming) is suppressed in egg-bearing *N. norvegicus* and that any flexions performed
99 involve only the tail fan (uropods and telson) which does not carry eggs. Therefore there
100 would be a greater predation risk for females in leaving their burrows to feed. Aguzzi et al.
101 (2007) suggested that females can be attracted out of their burrows when food is available,
102 as indicated by catching ovigerous females in creels, but then stay within close proximity to
103 a burrow opening. With this limited foraging range, it is entirely possible that females reduce
104 their feeding rate, or completely cease feeding. Aguzzi et al. (2007) showed that the
105 percentage of ovigerous females with empty stomachs was significantly higher (60%) than
106 that of non-ovigerous females (50%). Also, Oakley (1978) showed that ovigerous females
107 were less likely to react to chemical food stimuli than either males or non-ovigerous females.
108 Female *N. norvegicus* possibly enter a period of torpor while incubating their eggs in
109 burrows, although there remains a requirement for them to ventilate and clean the eggs
110 (Waddy et al. 1995). Such studies hypothesised that ovigerous females have a reduced
111 nutritional state. It has been suggested that suspension feeding may provide an additional
112 food source (Loo et al. 1993; Bell et al. 2006) but this is unlikely to be of benefit during the
113 winter, though suspended matter derived from phytoplankton blooms may be available in
114 late autumn and early spring, near the beginning and end of the period of burrow residence.

115 We have recently established that male *N. norvegicus* can survive for over 6 months without
116 feeding (Watts et al. 2014), and since this is a similar length of time to the burrow residence
117 time for female *N. norvegicus* it is entirely possible that they can also survive for this
118 duration without feeding.

Comment [a1]: Comment1: addition

Comment [a2]: Comment2: deletion

119 Determining biomarkers of starvation that could be used reliably with specimens sampled in
120 the field would help to show whether the females have a reduced nutritional status through
121 the winter. Females are inaccessible for such assessments while they remain within their
122 burrows (they are difficult to sample), but due to their relatively synchronised emergence
123 from burrows post-brooding (Milligan et al. 2009), meaningful data can be obtained by
124 targeting newly-emerged females.

125 Watts et al. (2014) identified appropriate measures for establishing the nutritional status of
126 male *N. norvegicus* when they had not fed for 20 weeks. These were, the hepatosomatic
127 index (HSI) and the water, lipid and copper content of the hepatopancreas and the carbon:
128 nitrogen ratio of the abdominal tail muscle.

129 A reduction of whole body weight due to a reduced nutritional status does not occur within *N.*
130 *norvegicus* since when reserves such as lipids become depleted in the hepatopancreatic
131 tissue there is a corresponding increase in water content (Comoglio et al. 2005). In Male *N.*
132 *norvegicus* lipid content decreased from an initial percentage of 15.22 ± 2.78 to 2.58 ± 1.32
133 (wet weight), with a corresponding increase of water content from $68.05 \pm 2.22\%$ to $75.62 \pm$
134 2.39% (Watts et al 2014). This was also seen by Karapanagiotidis et al. (2015) where crude
135 lipids from the hepatopancreas (measured as dry weight) were $50.22 \pm 1.28 \%$ in well fed *N.*
136 *norvegicus* and $13.35 \pm 1.19\%$ in *N. norvegicus* starved over similar time scales as Watts et
137 al (2014). As a result, the combined weight of lipid and water held within the hepatopancreas
138 did not significantly vary over time, remaining at approximately 80% of the tissue weight. The
139 hepatopancreas itself however has also been shown to decrease in size with starvation.
140 Therefore HSI (the proportion compared to whole body weight) can be an effective indicator
141 of starvation in male *N. norvegicus*. Copper content of the hepatopancreas was shown in
142 Watts et al. (2014) to increase with the level of starvation, from an initial $153.53 \pm 42.17 \mu\text{g}$
143 g^{-1} to $423.37 \pm 158.88 \mu\text{g g}^{-1}$ by week 12. This was also noted by Baden et al. (1994) with
144 a drop in copper concentration in the haemolymph being accompanied by an increase in the
145 hepatopancreas. Starvation showed very few effects on the constituents of the tail muscle:
146 its water content did not vary significantly, perhaps due to the fact that it contains only ca.
147 2% lipid. A decrease in lipid content was not directly recorded, although the carbon:nitrogen
148 ratio, which is known to be a proxy indicator of lipid metabolism did decrease.

149 The aims of the present study were therefore to establish whether these measures of
150 starvation effects in males were also appropriate for assessing the nutritional status of
151 female *N. norvegicus* by performing a laboratory fasting experiment, and if so, to use such
152 measures on newly emerged field-caught females to determine if they are in a reduced
153 nutritional state (compared to males) having been confined to their burrows through the
154 winter.

Comment [a3]: Comment3: addition

155 **Material and Methods**

156 The study comprised an aquarium investigation of the effect of food deprivation on the
157 biophysical dimensions and biochemical reserves of female *N. norvegicus* over a period of
158 approximately 6 months. Biophysical and biochemical measurements were taken from field-
159 caught individuals, and then compared with those from the aquarium study to assess the
160 likelihood of food deprivation in the wild and thus the nutritional status for both males and
161 females. Data presented in Watts et al. (2014) were used to compare the nutritional status of
162 males in the field.

163 *Aquarium study: physiological effects of long-term starvation*

164 *Nephrops norvegicus* were collected (Oct 2010) by trawling from the Clyde Sea Area (CSA),
165 Scotland, UK along an established transect north of the Isle of Cumbrae (55°51.35'N
166 4°54.42'W to 55°48.97'N 4°54.05'W) (Beevers et al. 2012; Watts et al. 2014). Females with a
167 mean (\pm SD) carapace length of 33.2 mm \pm 5.1 mm were selected randomly (n=62) and
168 transferred to a recirculating natural sea water aquarium (12h:12h light: dark photoperiod, at
169 9.4 °C \pm 0.6 °C SD) in the University of Glasgow for two weeks. All animals were fed with ca
170 1g squid mantle three times a week (the 'standard food ration') for an initial 2-week period,
171 until the trial started on 26 October 2010.

172 Animals were assigned randomly to one of 14 numbered tanks. The animals in two tanks
173 had the standard food ration ('fed' group), and food was removed from the tanks after 20 h.
174 Those in the other ~~ten~~ 12 tanks were starved ('unfed' group). One unfed animal was
175 removed from each even-numbered tank at weeks 0, 8 and 16, and one unfed animal was
176 removed from each odd-numbered tank at weeks 4, 12 and 20. As there were no major
177 changes in nutritional status over the course of the trial in the male fed group (Watts et al.
178 2014), the fed group of females was sampled once at week 20.

179 Animals were put on ice for 20 minutes prior to measurements of carapace length (with dial
180 callipers) and weight without claws (to avoid differences due to claw loss during trawling and
181 post-capture handling). The hepatopancreas and ovary were then removed from the
182 cephalothorax (noting the colour and weight of the organs), and all muscle tissue was
183 removed from the abdomen. These three tissues were frozen in liquid nitrogen and then
184 stored at -80°C prior to further analysis.

185 The biophysical measure of hepatosomatic index and the biochemical measures of
186 hepatopancreas water, lipid and copper content, along with abdominal tail muscle protein,
187 water, the stable isotopes of $\delta^{15}\text{N}$, $\delta^{13}\text{C}$ and the carbon-nitrogen ratio (C:N), were made on
188 each animal, using methods described by Watts et al. (2014).

Comment [a4]: Comment4: correction

189 *Field study*

190 Starting in January 2009, *Nephrops norvegicus* were collected monthly (January-December)
191 by trawling along the established transect in the CSA mentioned above. Three research
192 vessels from University Marine Biological Station Millport were used throughout the sampling
193 period (RV Aora, RV Aplysia and RV Actinia), each equipped with an otter trawl with a mesh
194 size of 70 mm at the cod-end. Trawls lasted for 1 h, at a mean depth of $78.5 \text{ m} \pm 1.1 \text{ m SD}$.

195 *Assessment of reproductive state*

196 A sub-sample of *Nephrops norvegicus* was taken non-selectively from each catch before any
197 other animals were removed for other purposes. A random sample of the catch was placed
198 into a fishing basket. The bycatch was then removed and discarded, leaving approximately
199 200 *N. norvegicus* (depending on the size of the catch). When the catch had fewer than 200
200 animals the entire catch was recorded. The sample was placed in a polystyrene box and
201 covered with ice and transported to the University of Glasgow. This sample was measured
202 within 24h of the catch, when not measured the same night the animals were refrigerated
203 overnight (5°C).

204 The carapace length, weight without chelipeds, and sex of all *N. norvegicus* were recorded.
205 The colour and weight of the hepatopancreas, and the colour and weight of the ovaries in
206 females, were also recorded in a randomly selected sample of 25 of each sex.

207 *Assessment of nutritional state*

208 An additional 15 *Nephrops norvegicus* of each sex were sampled from the remainder of the
209 catch from each haul. Their moult stage, according to carapace hardness, was determined
210 as pre/post moult (soft), immediate post-moult ('jelly') or intermoult (hard) (Milligan et al.
211 2009). Intermoult animals were taken preferentially, and postmoult animals were used only
212 when low numbers of animals were caught. Animals were put on ice and taken ashore were
213 processed within 4h. The carapace length, body weight, hepatopancreas colour and weight,
214 and gonad colour, stage and weight were recorded. Samples of abdominal tail muscle and
215 hepatopancreas were taken, frozen in liquid nitrogen and transported to the University of
216 Glasgow where they were stored at -80°C until all samples were collected and processed
217 further. Biophysical and biochemical measures were then taken for each animal and
218 assessed against the biophysical and biochemical measurements (see Section 2.1).

219 *Statistics*

220 Variation in biophysical or biochemical measurements over time and in relation to nutritional
221 status were tested with general linear models (GLM, computed in the statistical program
222 Minitab). For unfed animals in the aquarium study the factor 'time' was represented by

223 weeks since last fed as a categorical variable. Differences between fed and unfed animals
224 were tested in *Nephrops norvegicus* sampled at week 20. For the field study the factor 'date'
225 was represented by the months caught, with males and females assessed separately.
226 Normality of residuals and homogeneity of variances were assessed visually. A significant
227 result was determined when $p < 0.05$ and the Tukey multiple comparison procedure was
228 followed for both studies.

229

230 Results

231 Aquarium study

232 The results obtained from the fed and unfed groups of female *Nephrops norvegicus* during
233 the 20 week experimental period are presented in Figure 1 (means + SE). Values of fed and
234 unfed females at week 20 are shown in Table SI (supplementary material).

235 The concentration of copper in the hepatopancreas in unfed females increased significantly
236 between week 0 and week 20 ($F_{5,35}=3.45$, $p=0.014$) (Figure 1A). There was also a significant
237 difference in the copper concentration in the hepatopancreas between fed and unfed
238 animals at week 20 ($F_{1,10}=10.25$, $p=0.011$).

239 The HSI in unfed females decreased significantly between week 0 and week 4 and then
240 remained relatively constant throughout the rest of the trial ($F_{5,35}=5.60$, $p=0.001$) (Figure 1B).
241 At week 20, fed females had a significantly higher HSI than unfed animals ($F_{1,10}=12.61$,
242 $p=0.006$).

243 The lipid concentration in the hepatopancreas in unfed females initially increased between
244 week 0 and weeks 8–16 and then decreased to lower than the initial value ($F_{5,28}=4.89$,
245 $p=0.003$) (Figure 1C). Hepatopancreas lipid content was significantly lower in unfed female
246 *N. norvegicus* at week 20 ($F_{1,9}=10.45$, $p=0.012$).

247 The water content in the hepatopancreas in unfed females did not increase significantly
248 between week 0 and week 20 ($F_{5,35}=2.29$, $p=0.071$) (Figure 1D). However, there was a
249 significant difference in the water content of the hepatopancreas between fed and unfed
250 female *N. norvegicus* at week 20, being higher in unfed females ($F_{1,8}=10.13$, $p=0.015$).

251 For female *N. norvegicus* there was no significant variation among weeks or between fed
252 and unfed groups in the measurements of abdominal tail muscle water ($F_{5,35}=0.86$, $p=0.518$;
253 $F_{1,8}=3.31$, $p=0.112$), abdominal tail muscle $\delta^{13}\text{C}$ ($F_{5,35}=2.03$, $p=0.103$; $F_{1,8}=1.63$, $p=0.243$),
254 abdominal tail muscle $\delta^{15}\text{N}$ ($F_{5,35}=0.54$, $p=0.745$; $F_{1,8}=1.38$, $p=0.279$) or the abdominal tail
255 muscle C:N ratio ($F_{5,35}=0.69$, $p=0.635$; $F_{1,8}=1.02$, $p=0.347$) (Supplementary Material Table
256 SI).

257 The proportion of each ovary stage at each time period is shown in Figure 2. Within the first
 258 4 weeks four out of six females reabsorbed their ovaries. From the females that were fed
 259 throughout the trial, two of them displayed white gonads and one had cream gonads,
 260 showing no utilisation of ovaries as reserves in these individuals during the trial. Ovary
 261 development did not occur within half of the unfed individuals, but rather there was an
 262 increasing amount of reabsorption.

263 *Field studies*

264 *Nutritional Status*

265 *Females*

266 Only one female was collected in the whole catch in January, therefore this month was
 267 removed from all further analyses. Only mature females (<26mm) were used for nutritional
 268 status measurements. [Average sizes of male and females each month can be seen in](#)
 269 [TableSII.](#)

270 When female *Nephrops norvegicus* were measured monthly throughout 2009 there was
 271 significant seasonal variation in hepatopancreas copper concentration ($F_{10,115}=3.98$,
 272 $p<0.001$) ([Figure 3A](#)), [water content \(\$F_{9,133}=9.90\$, \$p<0.001\$ \) and lipid content \(\$F_{9,67}=5.29\$,](#)
 273 [\$p<0.001\$ \) \(\[Figure 3E\]\(#\)\), and \[water content \\(\\$F_{9,133}=9.90\\$, \\$p<0.001\\$ \\) \\(\\[Figure 3G\\]\\(#\\)\\)\]\(#\) However there
 274 was no significant variation in HSI \(\$F_{7,107}=1.76\$, \$p=0.104\$ \) \(\[Figure 3C\]\(#\)\). Females caught in
 275 February had an elevated copper concentration in the hepatopancreas, as found in males
 276 but to a smaller extent. The water content of the hepatopancreas was high in the months
 277 February–June and lipid content of the female hepatopancreas was 14–24% throughout the
 278 year and only exceeded 30% \(\$30.5 \pm 3.47\%\$ \) in December. \(Table \[SIII4A\]\(#\)\).](#)

279 *Males*

280 In males, there was significant seasonal variation in hepatopancreas copper concentration
 281 ($F_{10,129}=15.22$, $p<0.001$) ([Figure 3B](#)), HSI ($F_{7,112}=5.17$, $p<0.001$) ([Figure 3D](#)), [hepatopancreas](#)
 282 [lipid content \(\$F_{9,63}=4.34\$, \$p<0.001\$ \) \(\[Figure 3F\]\(#\)\) and hepatopancreas water content](#)
 283 [\(\$F_{10,140}=7.72\$, \$p<0.001\$ \) \(\[Figure 3H\]\(#\)\), and \[hepatopancreas lipid content \\(\\$F_{9,63}=4.34\\$, \\$p<0.001\\$ \\).\]\(#\)](#)

284 The hepatopancreas copper values in males collected from the field in February were
 285 $420.34 \pm 69.81 \mu\text{g}\cdot\text{g}^{-1}$. Males caught between February and April also had values of
 286 hepatopancreas water and lipid content comparable to the values observed in unfed
 287 individuals (Table [SIII-4B](#)). Later in the year (September) all parameters measured indicated
 288 that males were well fed with values closer to the fed group (aquarium trial).

289 *Female reproductive state*

290 The seasonal pattern in the proportion of all females caught in the trawl catches along the
 291 sampled transect is shown in Figure [3A4A](#). The main features for females were low numbers

Comment [a5]: Comment 5: addition of figure references

Comment [a6]: Comment 5: addition of figure references

Comment [a7]: Comment 6: correction, along with two other occurrences below

292 during the winter months, an increasing proportion in the spring, peak abundance in the
293 summer, a declining proportion in the autumn and a return to low numbers in the winter.

294 The seasonal pattern in the proportion of females in each stage of ovary maturation is shown
295 in Figure ~~3B4B~~. The females caught in the winter months had less-well developed ovaries
296 than those in the summer ~~(although as shown in Figure 4A some of these may be~~
297 ~~immature)~~. A progression in the maturation cycle can be seen within the first half of the year
298 (January–July). In April 50% females had green ovaries, and were therefore mature and
299 ready to mate. This increased to 87.8% in July as all females sampled had ovaries
300 developed to stage 3 or beyond. In the second half of the year an increased proportion of
301 females caught had spent ovaries, indicating that they had spawned recently.

Comment [a8]: Comment7: Addition to clarify

302 The seasonal pattern in the proportion of females with eggs is shown in Figure ~~3C4C~~.
303 Ovigerous females were caught in highest numbers in September with 37% of all females
304 being berried prior to their winter burrow period. Only 1% and 4% of the newly emerged
305 females in April and May respectively were ovigerous suggesting that they have released the
306 eggs prior to the collection.

307 Expressing the sizes of both sexes according to size categories (10–19.9, 20–29.9, 30–39.9,
308 40–49.9, and 50+ mm CL) a distinct sex difference was found in the seasonal fluctuation of
309 body size of the animals in the random sample (Figure ~~45A Females, Figure 3B-5B Males~~).

Comment [a9]: Comment 8: correction

310 The size distribution of the males fluctuated throughout the year. Females caught in the
311 winter were mainly less than 30 mm CL, while in the summer there was a greater proportion
312 in the 30–39.9 mm CL category. The dotted line indicates the division between mature
313 (above) and immature (below) female *Nephrops norvegicus*. This shows that a higher
314 proportion of female *N. norvegicus* caught in the months of February, November and
315 December were immature.

316

317 Discussion

318 The aim of this study was to determine if the burrow-bound behaviour of female *Nephrops*
319 *norvegicus* through the winter months, which is related to their annual reproductive cycle,
320 leads to a reduced nutritional state compared to males.

321 To do this, biochemical and biophysical measurements that have been shown to indicate the
322 nutritional state of male *N. norvegicus* (Watts et al. 2014) were determined in females both
323 under controlled conditions and from the wild. In males, the HSI, hepatopancreas copper
324 concentration, lipid and water content all changed significantly during starvation under
325 controlled conditions (Watts et al., 2014). HSI and lipid content decreased as the

326 hepatopancreas decreased in size, whereas the water and copper content of the
327 hepatopancreas increased due to a replacement of lipids with water. In the present study, in
328 starved females (i.e. food deprivation) the HSI, hepatopancreas copper, lipid and water
329 content also changed due to nutritional limitation (as in males). However the C:N ratio of
330 female abdominal tail muscle did not decrease significantly in unfed individuals as it did in
331 males. Also females maintained lipid reserves longer in the hepatopancreas (around 31% ±
332 6.9% remaining at week 16, compared to 13% in males).

333 It is likely therefore that under nutritionally-limited conditions females will utilise lipids stored
334 in the hepatopancreas only as a last resort. Females will still develop ovaries up to stage 2
335 over the 6 months of the burrow dwelling period (Farmer 1974). Tuck et al. (1997c) suggest
336 that starvation could be one reason for ovary reabsorption. In the present study, ovary
337 development did not occur within half of the unfed individuals, but rather there was an
338 increasing amount of reabsorption. Thus, for the population to remain stable females would
339 still have to consume food to gain energy for this development. For reproductive events to
340 take place in the following years it is likely that females will have to eat whilst in their
341 burrows. The sex ratios recorded monthly through the year conformed to the traditional
342 pattern of increasing emergence of females from their burrows during the spring (Oakley
343 1978; Bailey 1984; Briggs 1995; Tuck et al. 1997a; Milligan et al. 2009). Over the winter,
344 females were far less abundant in trawl catches, consistent with them spending much of
345 their time within their burrows. Females in the summer dominated catches rising to 70% of
346 all *N. norvegicus* in the catch; this was also seen in Milligan et al 2009 who sampled the
347 same population in 2005-2006. The reason for this is currently unclear however could relate
348 to an increased exploitation of males over the winter, or females having greater foraging
349 dominance than males at this time. This would be interesting to investigate further.

350 Furthermore, females captured in trawls during the winter months were small (<30mm CL)
351 and in December around 50% were immature. Thomas & Figueiredo (1965) showed that
352 immature females show no seasonal variation in capture abundance. Females caught in
353 April and May therefore include a high proportion of the females emerging from their burrows
354 after egg hatching, and their nutritional status may thus reflect a long period of burrow
355 residence. Consistent with Milligan et al. (2009) the number of females appearing in the May
356 catches was higher than that of males (70% females, 30% males). It is not clear why this is
357 not 50:50.

358 In field-caught *N. norvegicus* there was significant variation in lipid, water and copper content
359 of the hepatopancreas measured in both female and male individuals throughout the year.
360 The results obtained from animals caught from February to June indicated that during this
361 period animals may have a reduced nutritional status compared with that seen in July to

Comment [a10]: Comment 9: addition of suggestion why Females dominant in the catch.

362 December. Copper concentrations in the hepatopancreas were high in February in both
363 males and females. Lipids and water contents of the hepatopancreas were also elevated.
364 These findings suggest that during the winter both male and female *N. norvegicus* have
365 reduced nutritional status, but not to the degree seen after 20 weeks of starvation in the
366 aquarium trials. Temperatures in the aquarium trials were constant with temperatures in the
367 summer, but around 2°C higher than in the winter. Therefore the greater effect seen in the
368 aquarium trial could be due to an increased metabolism in these animals. There is no
369 evidence that females had a lower nutritional status than males when comparing sex specific
370 starvation rates (even though females had higher copper values than males from May to
371 October and lipids from May to September). In September, when the maximum numbers of
372 ovigerous females were found, their nutritional state was consistent with that of fed animals
373 in the aquarium trial. This suggests that females are entering their winter burrowing period in
374 a good nutritional state. This is consistent with the results from quarterly samples of *N.*
375 *norvegicus* taken in 1992–93 (IMBC et al. 1994) and bimonthly samples in 1995–96
376 (Parslow-Williams 1998). Those studies showed that the lowest lipid and highest water in the
377 hepatopancreas occurred in the spring and vice versa for the summer. However, HSI did not
378 vary significantly between these two seasons in this study.

379 It is therefore likely that sex specific interactions play a fundamental part in the nutritional
380 status of *N. norvegicus*. Reasons for the reduced nutritional status could include lower food
381 availability, and less consumption of the food that is present. As explained in the
382 introduction, food available to benthic organisms ultimately comes from the water column
383 above, and in the winter months there is a reduction in primary production in the water
384 column and thus the amount being driven down to the benthos. This theory was also
385 suggested by IMBC et al. (1994). Less consumption of any food that is present is also
386 possible during the winter due to a reduced burrow emergence. This might be as a response
387 to lower light levels, or lower temperatures causing *N. norvegicus* to remain in their burrows
388 for more extended periods of time in the winter months (Maynou & Sarda 2001). It is known
389 that spring represents the time of post-brooding burrow emergence of females in the Clyde
390 population of *N. norvegicus* (Milligan et al., 2009), and similarly in our study April was the
391 first month in which the proportion of females in the catch reached 50%. At this time female
392 *N. norvegicus* do seem somewhat limited nutritionally (due to a high hepatopancreas water
393 percentage), but, when considering hepatopancreas copper concentrations, no more so than
394 male *N. norvegicus* and less so than females in March and May. Oakley (1978) observed
395 that in the winter months of a controlled experiment under artificial conditions (November–
396 May) ovigerous females rarely came out beyond 25 cm from the burrow entrance to collect
397 food that had been detected, and carried large food items into their burrow systems for

398 consumption. It is also known that *N. norvegicus* will bury food within their burrows, and
399 females kept for an extended period of time in a mesocosm have shown 'caching' behaviour
400 by burying food items away from the burrow, presumably so as not to attract predators
401 (Atkinson & Eastman 2015). This suggests that females could in fact 'prepare' for the winter
402 months by creating a readily accessible food store.

403 In conclusion, this study does not support the hypothesis that females cease feeding over
404 winter. Firstly, some females were unable to sustain ovary development during starvation
405 under controlled conditions, contrary to field observations. Secondly, field data suggest that
406 there is no sex-specific reduction in nutritional status.

407

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412

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497 Figure 1. Means (\pm SE) of A) copper concentration in the hepatopancreas (in relation to wet
 498 weight); B) hepatosomatic index (HSI); C) lipid content of the hepatopancreas; D) water
 499 content of the hepatopancreas in unfed (black bars) and fed (grey bars) groups of female
 500 *Nephrops norvegicus* during the starvation trial. Letters indicate the results of a Tukey test
 501 on the unfed group. Means that do not share a letter are significantly different ($p < 0.05$).
 502 Asterisks indicate a significant difference between fed and unfed groups at week 20 ($p < 0.05$)
 503 $n=6$.

504 Figure 2. Number of females at various ovary stages sampled during the aquarium trial.
 505 White, Stage 0 (white ovaries); Light grey, Stage 1 (cream ovaries); Grey, Stage 2 (Pale
 506 green ovaries); Black, Stage 3 (dark green ovaries); White with dots, Stage 4 (Dark green
 507 and swollen eggs visible); White with hatching, Stage 5 mottled green reabsorbed) After
 508 Tuck et al.(1997).

509 Figure 3. Means (\pm SE) of A) copper concentration in the hepatopancreas (in relation to
 510 wet weight); B) hepatosomatic index (HSI); C) lipid content of the hepatopancreas; D)
 511 water content of the hepatopancreas in field caught females (left panels) and male (right
 512 panels) *Nephrops norvegicus* in 2009 (circles). With unfed (square with cross) and unfed
 513 (square no cross) means \pm SE shown in each graph as a comparison, values derived from
 514 this study (females) and from Watts et al. (2014) (males) shown.

515 Figure 4 A) Sex composition of the trawl catch from the Clyde Sea Area transect in each
 516 month of 2009. White section of bar represents proportion of the catch which are immature
 517 females and the black bars represent the proportion of the catch which are mature females ;
 518 B) Percentage of females at each ovary maturation stage (see scale in Figure 2 legend). C)
 519 Percentage of females that were *Ovigerousovigerous*.

520 Figure 5. Size distributions (according to carapace length) of (A) female and (B) male
 521 *Nephrops norvegicus* in trawl catch from the Clyde Sea Area transect in each month of
 522 2009. White (10-19.9mm), Light grey (20-29.9mm), Grey (30-39.9mm), Dark grey (40-
 523 49.9mm), Black (50mm+). Black dashed line represents size at onset of maturity of females
 524 (SOM=26 mm CL).

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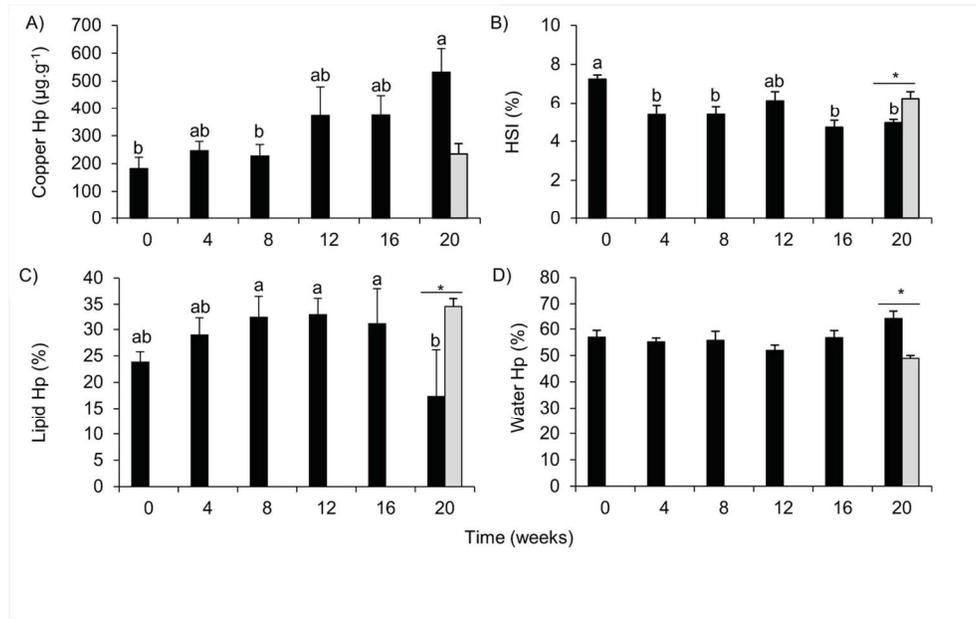


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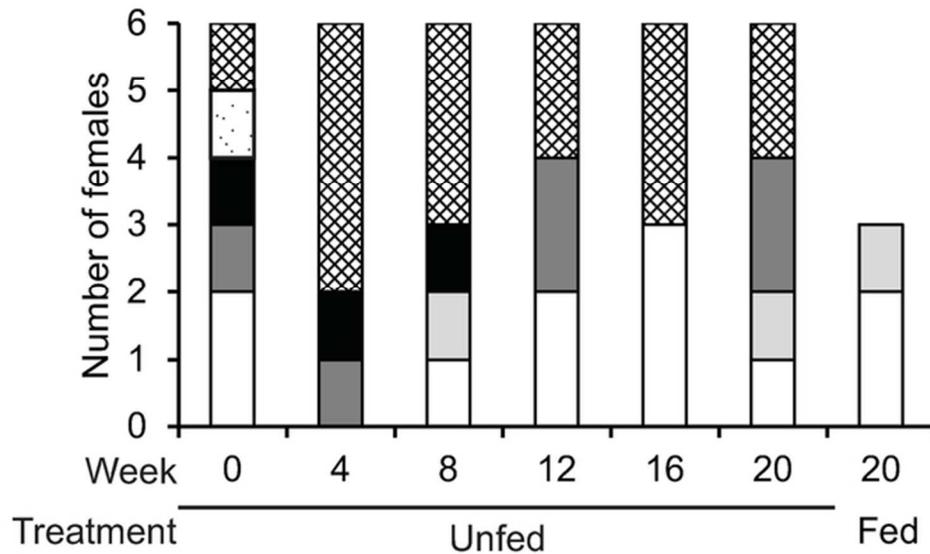


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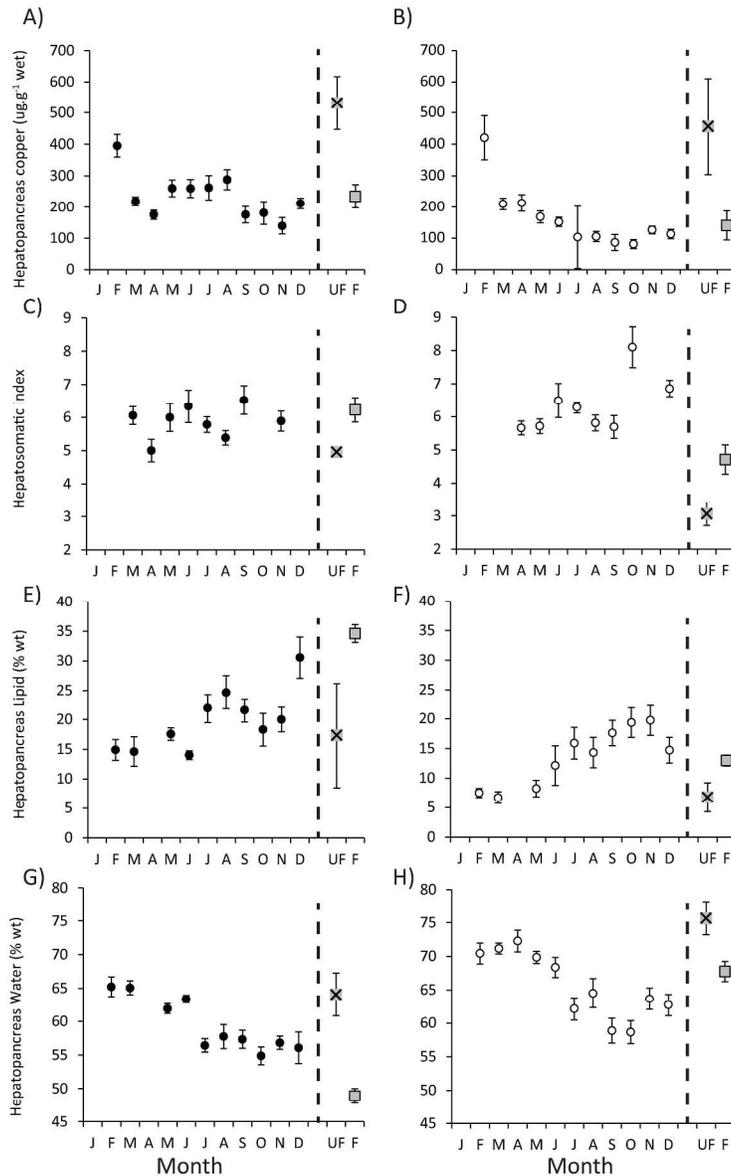


Figure 3. Means (\pm SE) of A) copper concentration in the hepatopancreas (in relation to wet weight); B) hepatopsomatic index (HSI); C) lipid content of the hepatopancreas; D) water content of the hepatopancreas in field caught females (left panels) and male (right panels) *Nephrops norvegicus* in 2009 (circles). With unfed (square with cross) and unfed (square no cross) means \pm SE shown in each graph as a comparison, values derived from this study (females) and from Watts et al. (2014) (males) shown.
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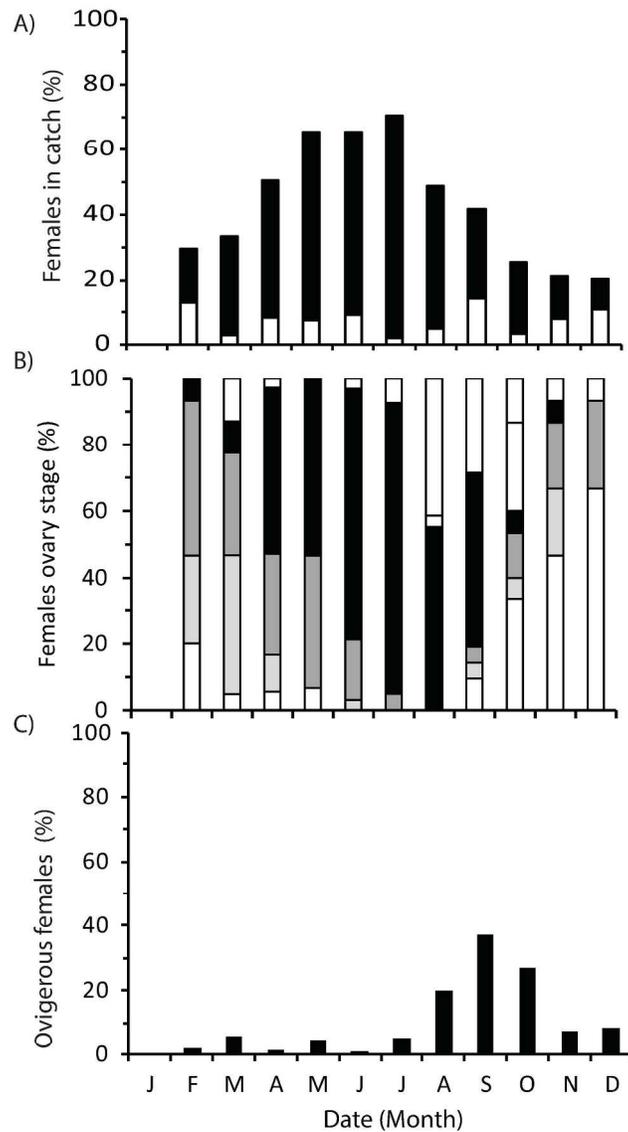


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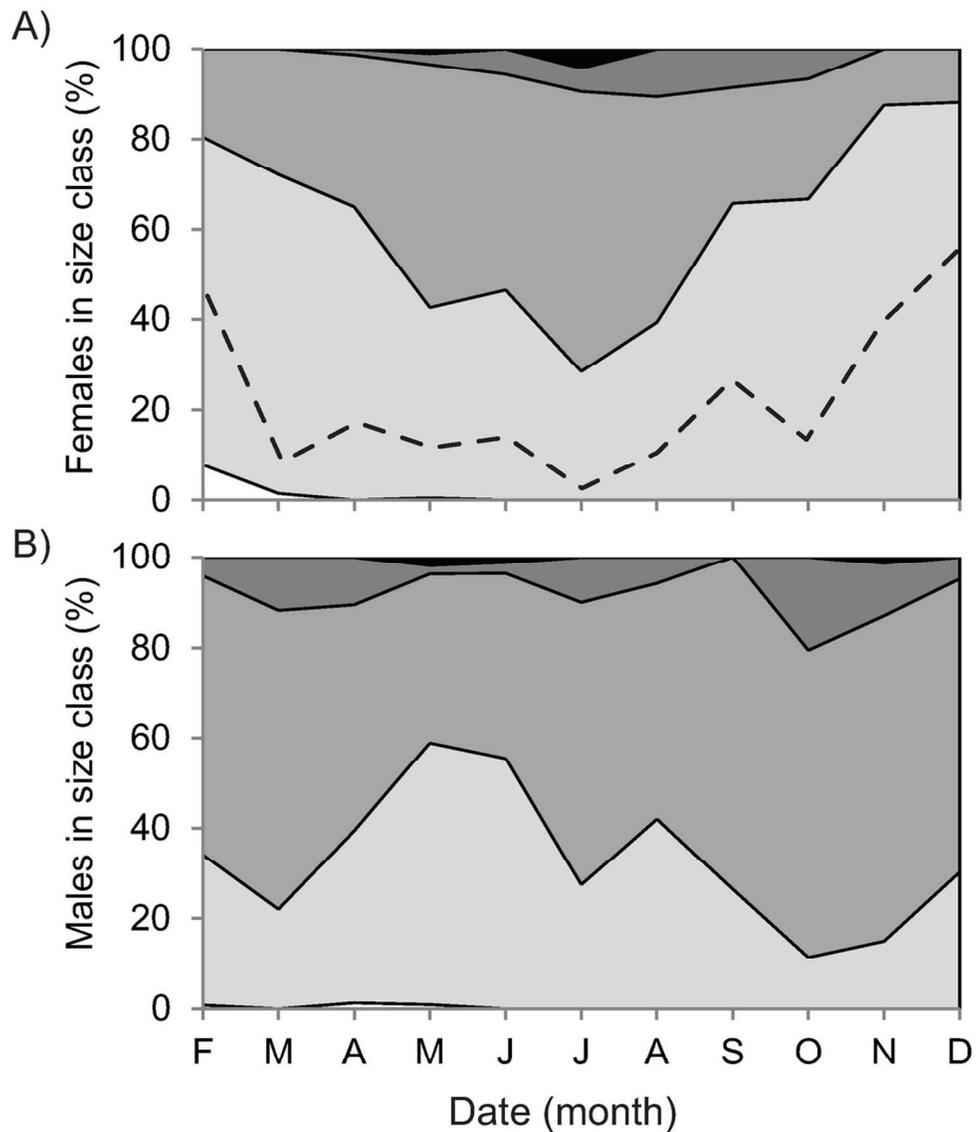


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106x127mm (300 x 300 DPI)