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Does resource availability influence the vital rates of the tropical copepod *Apocyclops royi* (Lindberg, 1940) under changing salinities?

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ABSTRACT

Functioning of invertebrates inhabiting coastal ecosystems is challenged by strong temporal fluctuations in salinity. We investigate how food availability influences vital rates in the tropical cyclopoid copepod *Apocyclops royi* under different salinities (5-32 PSU). We hypothesized that i) mortality decreases and egg production rate increases with food availability, ii) that under suboptimal salinity mortality increases and the egg production rate is reduced and iii) the threshold concentration for egg production (lowest food concentration where egg production is initiated) shifts to higher food concentrations when challenged by salinity. Surprisingly, *A. royi* survived, ~~fed~~ingested food, and produced eggs at all tested salinities. Mortality rate was however dependent on salinity level, but not on food availability. Mortality increased (~12 % h^{-1}) during short-term (1 h) salinity acclimatization to 5 PSU and during the following 24 h incubations (~5 % d^{-1}) compared to higher salinities. Feeding- and egg production rates increased with food availability up to an optimum at all salinity levels, with no effect of salinity on the lowest food concentration initiating egg production. This reveals a high salinity tolerance by *A. royi* and may partly explain why this particular copepod is so successful compared to its congeners in occupying extreme habitats.

INTRODUCTION

Living as ~~a~~ zooplankton in near shore environments such as estuaries, lagoons or intertidal areas can be considered a challenge because of regular or rapid salinity oscillations (Mcallen *et al.*, 1998; Rivera-ingraham and Lignot, 2017). How spatiotemporal variation in salinity affect zooplankton depends on their physiology and functioning under fluctuating salinity. Therefore salinity is a shaping environmental factor for distribution of species inhabiting these environments and the overall near shore ecosystem structure and functioning (Peterson and Ross, 1991; Henry *et al.*, 2002; Hauton, 2016).

Dominant zooplankton in these physically rapidly changing environments are species of copepods, often below mm-sized euryhaline crustaceans. There is substantial evidence that most copepods inhabiting these environments do not strictly conform to the external salinity but have osmoregulatory capacities to various degrees. In adult species of all the dominant orders of free living copepods, Calanoida, Cyclopoida and Harpacticoida hypo- and hyperregulation of the internal osmotic pressure and ion balance (Battaglia and Bryan, 1964; Bayly, 1969; Farmer, 1980; Roddie *et al*., 1984; Mcallen *et al*., 1998) or body density (Svetlichny and Hubareva, 2014), non-isometric to the external conditions, has been observed~~, non-isometric to the external conditions~~. This indicates the process of active ion regulation.

Different from osmoconformation, osmoregulation is an energetically expensive process as ion-transport is particularly ATP consuming (Hand and Hardewig, 1996; Bradly, 2009). Furthermore, elevated aerobic metabolism (mitochondrial activity) associated with exposure to salinity changes may cause oxidative stress by compromising cell functionality and it requires energy to restore the cellular redox balance (reviewed in Rivera-Ingraham and Lignot, 2017). Thus adjusting to osmotic stress infers increased energy expenditure and hence, less energy availability for other basic physiological functions of the copepod e.g. reproduction (Chen *et al.*, 2006).

It is therefore not surprising that studies investigating the effect of salinity changes on the vital rates of copepods reveal increased respiration rates (Miliou and Moraitou-Apostolopoulou, 1991; Dutz and Christensen, 2018), decreased reproductive output and even increased mortality under sub-optimal salinities (Lance, 1963; Cervetto *et al*., 1999; Lee *et al*., 2005; Chen *et al*., 2006; Svetlichny and Hubareva, 2014). However, the osmotic dependence of these rates, or ´salinity tolerance´, varies greatly among species (Gaudy *et al.*, 1982; Bergmans and Janssens, 1988; Lee *et al.*, 2005).

The constant energy requirement for osmoregulation in some copepods infers that their osmoregulatory capacity may be restricted under food-limited conditions and can be compensated when resources are available. This is supported by Rippingale and Hodgkin (1977), who showed that longevity of the calanoid copepod *Sulcanus conflictus* increases at hyperosmotic salinities when food was available. Similarly Hammock *et al.* (2016) showed that survival of the calanoid copepod *Eurytemora affinis* increases at hypo- or hyperosmotic salinities when resource levels are high. Further, they measured a relatively high food consumption rate at sub-optimal salinities when resources were abundant, possibly to compensate for the elevated metabolic cost due to osmoregulation. Thus, the few studies available on the effect of food presence on the copepods vital rates under hypo- or hyperosmotic salinities suggest that ~~saturated~~ increased resource availability increases ~~their~~ tolerance to sub-optimal salinities. In the present study, we experimentally investigate if and how food availability influences the vital rates of the cyclopoid copepod *Apocyclops royi* at a range of salinities, expected to cover from sub-optimal to optimal salinities.

This small, euryhaline copepod inhabits tropical and sub-tropical estuaries (Muthupriya and Altaff, 2009; Su *et al.*, 2005) and coastal saline ponds (Blanda *et al.*, 2015; Dhanker and Whang, 2013). Salinity is an important environmental variable here, as ~~in~~ the coastal waters of (sub)tropical regions~~, which~~ are characterized by dilution due to heavy rainfall and by evaporation dominated incidents (Muthupriya and Altaff, 2009).

A. royi is regularly exposed to abrupt and extreme salinity changes and presumably also to fluctuating food abundance due to heavy rainfall (Blanda *et al.*, 2015). Although previous studies on *A. royi* have shown ~~-~~it tolerates and reproduces over a wide range in salinity (0-35 PSU) (Muthupriya and Altaff, 2009; Pan *et al.*, 2016), no data is available on the effect of food concentration on other vital rates of this species as a function of ~~differences in~~ salinit~~ies~~y. Here we test the hypothesis that due to presumed energetic expenses for osmoregulation and oxidative stress at sub-optimal salinities vital rates are affected. Specifically we hypothesize that under sub-optimal salinities i) the mortality rate increases and maximum egg production rate ~~are~~is reduced; ii) mortality decreases and egg production rate increases with food availability; and iii) that the threshold concentration for egg production (lowest food concentration where egg production is initiated) shifts to higher food concentrations when challenged by salinity. This is the first study describing the mortality, feeding and egg production responses for *A. royi* as a function of a wide span of food concentrations at different salinities. Our results are highly relevant for understanding

how ~~euryhaline copepod~~ the vital rates of a euryhaline copepod respond to salinity changes under food-limited ~~and~~ or eutrophicated conditions.

METHOD

Experimental organisms

Apocyclops royi was originally obtained from Tungkang Biotechnology Research Center, Taiwan, but was received from culturing facilities at the LOG-Marine Station of Wimereux, France (Pan *et al.*, 2016). The copepods were kept in continuous cultures at Roskilde University (Roskilde, Denmark) at 25 °C in 0.2 µm filtered seawater (FSW) and acclimated from 20 PSU to 32 PSU in at least 111 days (~10 generations). *A. royi* was kept in 70 L buckets, gently aerated and fed daily atd libitum with the marine cryptophyte algae *Rhodomonas salina* (strain code K-1487). *R. salina* was kept in culture at 18 °C in 20 L plastic bags in 0.2 µm FSW at 32 PSU in exponential growth by daily dilution with FSW amended with a modified 0.1 % F/2 medium deprived for cobalt chloride (Guillard, 1975; Thoisen *et al.*, 2018). *R. salina* proved to have a suitable cell size (~7 µm, Table 1) for feeding all developmental stages of *A. royi* and to be sufficiently nutritious to use as sole food source for maintaining the copepod cultures. Further, *R. salina* has a high salinity tolerance, with growth rates close to 1 d^{-1} at salinities between 5 – 50 PSU (Jepsen *et al.*, 2018).

Experimental procedure of incubation experiments

We determined the mortality rates, feeding rates and ovigerous rates by initiating experiments with non-egg carrying females at four salinity levels (5, 10, 20 and 32 PSU), each at 7 different food concentrations (Table 1, exp. 1-4) using bottle incubations (Frost, 1972; Kiørboe *et al.*, 1985). Food concentrations were chosen to ensure reaching a tendency to saturation of the ingestion rate of the copepods according to other studies (e.g. Almeda *et al.*, 2017) and trial experiments. Due to unexplainable cell degradation of *R. salina* during the incubation experiment at 10 PSU, we were not able to determine cell concentrations and feeding rates at this salinity level, thus only data on mortality rate at that particular salinity was further analyzed.

Prior to each bottle incubation experiment a mix of males and females were gently separated from the stock culture with a 200 µm mesh and starved in 0.2 µm FSW (32 PSU) for 19 h to ensure complete gut evacuation and to evoke fertilization of the females. One hour prior to the start of the incubation period of each tested food concentration, copepods were gradually acclimated to the experimental salinity to avoid an acute salinity shock (Pan *et al.,* 2016). Briefly, copepods were gradually (~ -1.7% min^{-1} of final PSU) acclimated during 1 h from 32 PSU to 5, 10, 20 PSU or 32

PSU, respectively. To reach the desired salinity, temperature acclimated deionized water (0 PSU) was increasingly added and culture water was removed from the animals using a programmable peristaltic pump (Jebao® DP-4). Previously, dilution of seawater with deionized water ~~have~~has shown not to cause reduced physiological performances by the calanoid copepod *Acartia tonsa* (Jepsen *et al.*, 2018). *R. salina* was acclimated to the desired experimental salinity with steps of ± 5 PSU per day ~~also~~ by addition of deionized water, similar to ~~like in~~ Jepsen *et al.* (2018), and to the experimental temperature in 2 h prior to start of the experiments. Hence, there are reasons to believe that neither of our experimental organisms suffered from e.g. low calcium ion concentration.

Food suspensions were prepared by successive dilution of the highest food concentration with 0.2 µm FSW and amended with 3.5 mL L^{-1} modified F/2 algal growth medium to avoid differential growth of *R. salina* between treatments due to nutrient excretion by the copepods. For each food concentration 12 Pyrex glass bottles (300 mL) were filled with the suspension. Three bottles were used to measure the initial concentration, three bottles to measure algal growth during the incubation (controls) and three bottles, with copepods added, served as experimental treatments (experimental bottles). From the acclimated copepods only live, non-egg bearing females were selected under a dissection microscope and distributed over the experimental bottles (35-50 females per bottle, Table 1). The number of copepods added per bottle varied depending on food concentration, to assure an approximately 30 % reduction of *R. salina* at the end of the incubation. The control and experimental bottles were sealed with a screw cap and placed on a slowly rotating plankton wheel (0.6 rpm) in dark for 24 h at 25 °C. At the end of the experiment, the content of each bottle was filtered through a 100 µm mesh to retrieve all copepods, which were consequently checked for mortality and egg-sac production.

Food concentrations (cells mL^{-1}) of the initial, control and experimental bottles were determined using a Beckman Coulter Multisizer 4e. The salinity of the food suspension was measured at the start of each experiment with a~~n~~ Atago S/Mill-E hand-held refractometer with a resolution of 0.5 units. Prosome length (Table 1) of live copepods (n = 25, immobilized by cooling) were measured at termination of each experiment from digital images taken with a Nikon SMZ 18 stereomicroscope mounted with a Nikon DS-Fi2 camera, using the imaging processing software NIS-Elements ~~Imaging Software~~.

Experimental procedure of short-term salinity acclimatization experiment

To investigate copepod resilience to the short-term salinity acclimatization prior to the start of the previous described incubation experiments, we conducted an additional experiment (Table 1, exp. 5) where we determined copepod mortality after a 1 h acclimatization period. Briefly, a mix of males and females were separated from the stock culture with a 200 µm mesh and starved in 0.2 µm FSW (32 PSU) for 19 h. Prior to the salinity acclimatization three replicates of 50 non-egg carrying females were prepared per treatment. The procedure for salinity acclimatization was similar as described previously for experiment 1-4. Copepod mortality (copepods were considered dead when a response to mechanical stimuli was absent) was determined 30 minutes after the acclimatization period with a dissection microscope.

Mortality rate

Mortality rate (M, % t^{-1}) of *A. royi* after short-term salinity acclimatization and after the 24 h incubation experiments was calculated as

$$M = \frac{n\,alive_{start} - n\,alive_{end}}{n\,alive_{start} * 0.01} * t^{-1} \qquad (1)$$

, where t is the incubation period in hours or days.

Functional feeding response

The ingestion rate, clearance rate and average food concentration during the incubation experiments were calculated according to Frost (1972). The sigmoidal shape of the observed feeding response suggested the presence of a feeding threshold, below which the copepod reduces its feeding rate. Therefore, a Holling type III functional response model was fitted to the measured ingestion and clearance rates (Table 2). This is similar to Schultz and Kiørboe (2009) and van Someren Gréve *et al.* (2017), where model parameter β is the maximum clearance rate (mL d^{-1}), C ~~is~~ the prey concentration (cells mL^{-1}) and α ~~is~~ the prey concentration at the maximum clearance rate. The maximum ingestion rate, I_{max}, was calculated as $\alpha\beta e^{1}$ (cells cop^{-1} d^{-1}).

Carbon content of the prey item (*R. salina*) was determined by CHN elemental analysis. Briefly, triplicates of ca. 10^7 cells were filtered onto 12 mm diameter pre-combusted GF/C filters (Whatman), dried at 60 °C for 24 h and analyzed by a Thermo Fisher Scientific FLASH 2000

Organic Elemental Analyzer. A methionine standard curve was used to obtain concentrations of C and N.

Ovigerous rate

Directly after termination of each feeding experiment, the presence of egg sacs was determined under a dissection microscope. Similar to Rayner *et al.* (2017) we calculated the female ovigerous rate (G, % of ovigerous females d^{-1}) for each replicate by

$$G = \frac{ovigerous\ copepods_{end}}{copepods\ alive_{end} * 0.01} * t^{-1} \qquad (2)$$

The dependence of the ovigerous rate on the food concentration was described by ~~the~~a model similar to Kiørboe *et al.* (1982) (see Table 2), where G_{max} equals the maximum ovigerous rate (% of ovigerous females d^{-1}), C the food concentration (cells mL^{-1}) and b a constant.

Gross efficiency of egg production

The gross efficiency of egg production was calculated from the functional response and ovigerous rate observations according to Peterson (1988):

$$E = \frac{C_{eggs}\ cop^{-1} d^{-1}}{C_{ingested}\ cop^{-1} d^{-1}} \qquad (3)$$

, where egg carbon produced per copepod (µg C cop^{-1} d^{-1}) was calculated by multiplying the measured average clutch size (n eggs cop^{-1}) by the ovigerous rate G (%) and egg carbon content (µg C egg^{-1}). The egg carbon content was calculated from measured egg diameter (n = 20 per experiment) and the egg diameter to carbon equation for copepods derived by Uye and Sano (1995).

Further, the maximum weight-specific fecundity (µg C_{eggs} µg $C_{copepod}^{-1}$ d^{-1}) was calculated from the maximum total egg carbon produced per copepod and measured copepod sizes (n = 25 per experiment, Table 1), using the length-dry weight relationship for *A. royi* by Chang and Lei (1993) and dry weight-carbon relationship for copepods according to Kiørboe and Sabatini (1995).

Statistics

We conducted an analysis of variance (ANOVA and Tukey post-hoc test) to determine the significance level ($p < 0.05$) of differences in mortality between salinity levels using the software SPSS Statistics 20. All models (Table 2) were fitted to the observational data using the software Sigmaplot 14.0. To compare differences in the vital rates (ingestion rate, clearance rate, maximum ovigerous rate, gross efficiency of egg production) between salinities for non-linear models fitted to the experimental data, we calculated the Wald confidence intervals (95 %) for each model parameter.

RESULTS

The ~~M~~mortality rate of *A. royi* during short-term (1 h) salinity acclimatization after a 19 h starvation period was highest at 5 PSU (12.6±2.1 % mortality h^{-1}) compared to 10, 20 and 32 PSU (4.6±1.4, 3.6±0.7, 3.7±0.5 % mortality h^{-1} respectively, Fig 1). During the following 24 h incubation, with or without food, the average mortality showed a similar salinity dependent trend, with highest measured mortality rates at 5 PSU (6.8±0.9 % mortality d^{-1}) and lowest mortality at 32 PSU (1.8±0.4 % mortality d^{-1}, Fig 2d). Both during the short-term (1 h) acclimatization and following incubation a significantly higher mortality was observed at PSU 5 compared to 10, 20 and 32 PSU ($p < 0.05$). No significant differences in mortality were observed between 10, 20 and 32 PSU though. Food availability did not appear to influence the mortality of *A. royi* during the incubations (Fig 2a-c).

The cumulative mortality of *A. royi* during the experiment (mortality during 1 h salinity acclimatization + 24 h incubation with/without food) was consequently highest and statistically significantly different at 5 PSU (19.4±2.3 %, $p < 0.05$) and lowest at 32 PSU, with no significant differences in mortality between 10, 20 and 32 PSU (8.4±1.7, 5.7±0.8, 5.5±0.6 % respectively, Fig 3).

The feeding rate of *A. royi* varied depending on food concentration at all tested salinities (Fig 4a-c, e-f). The ingestion rate increased with food concentration towards saturation. The estimated maximum ingestion rates (I_{max}) did not differ (overlapping 95 % CL) between the tested salinities (44.459±9.157, 36.377±21.627 and 48.783±10.939 cells cop^{-1} d^{-1} at 5, 20 and 32 PSU respectively, Fig 4d). The observed clearance rate was very low at the lowest tested food concentrations and increased with food concentration up to an optimum (β, Table 2) followed by a decrease with increasing food availability, indicating *A. royi* exhibited a typical Holling type III functional feeding response (Fig 4e-g). The estimated maximum clearance rate did not differ (95 % confidence intervals overlap) between salinities, (Fig 4h). Model parameters of the fitted functional response model to the observations are shown in Table 2.

The ovigerous rate of *A. royi* (% of ovigerous females d^{-1}) varied with food concentration in a similar fashion as the observed feeding rate (Fig 5a-c). Generally, the percentage of egg carrying females increased with increasing food availability towards a maximum. No differences in maximum ovigerous rates were observed between salinities (61.5-61.9 %, Fig 5a-c), neither in the

estimated maximum ovigerous rates (Fig 5d, Table 2). The observed maximum weight-specific fecundity was equal to 0.176 µg C_{eggs} µg $C_{copepod}^{-1}$ d^{-1}, regardless the treatment.

Egg production was completely absent when no food was present, but was initiated at all tested salinities at the lowest food concentrations offered (Fig 5a-c). Contrary to the ovigerous rate, the clutch size was largely independent of food availability (Fig 5h) and only decreased at the lower end of the tested concentrations. There did not appear to be a correlation between food concentration and the gross efficiency of egg production (Fig 5e-f). However, egg production was positively correlated to ingestion rate (Fig 6), showing a gross efficiency of egg production of *A. royi* ranging between 10-12 %, with no significant differences between salinities (parameter *a*, Table 2). Model parameters of the fitted models to the observations for ovigerous rate, clutch size and gross efficiency of egg production are shown in Table 2.

Overall, our observations suggest that during and after a short-term acclimatization (1 h) to low saline water, mortality of *A. royi* increased compared to ~~when~~ exposure~~ed~~ to 32 PSU. However, short-term acclimatization did not compromise the ability to feed and produce eggs within the following 24 h incubations. Further, food availability did not influence the mortality rate, but strongly influence~~s~~d feeding rate and egg production in a sigmoidal fashion.

DISCUSSION

The physiological cost of regulating body osmolarity and ion balance in coastal copepods has been investigated and quantified extensively during the past decades. This has been conducted by monitoring end-points at different levels e.g. in terms of mortality, growth rate, reproduction rate and metabolic rate. These studies indicate that increased energy allocation due to osmoregulation significantly compromise energy investment in growth and reproduction and the overall viability of embryonic, naupliar~~,~~ and adult life stages (e.g. Devreker *et al.*, 2007; Dutz and Christensen, 2018). However., ~~T~~the presence of an adequate food source may, in part, cover the increased energetic needs imposed by osmoregulation and thereby dampen the negative physiological response by copepods (Rippingale and Hodgkin, 1977), but ~~. However,~~ multiple stressor experiments on salinity tolerance, taking into account the effect of resource availability are rare, particularly for copepods. This is surprising as estuarine species often reside in environments with strong temporal variations in both abiotic and biotic factors (Devassy and Goes, 1988; Madhu *et al.*, 2007; Martinez *et al.*, 2011). In the present study, we investigated the physiological response to different salinities of the small, tropical copepod *A. royi* exposed to different food concentrations. ~~*A. royi* exhibit a relatively short generation time of approximately 10 d under the present cultivation conditions with food in excess. We showed that salinity affects the mortality rate of *A. royi*, during short term (1 h) salinity acclimatization and a following 24 h incubation period, but not the ovigerous rate. Moreover, food availability did not influence the osmotic dependence of mortality, feeding rate or ovigerous rate of this species.~~

The effect of salinity and food availability on mortality

Acclimatization or plasticity and adaption to different abiotic factors in marine copepods are poorly understood (Lee and Petersen, 2003). It varies greatly between species (Calliari *et al.*, 2008) and within species and may depend on acclimatization period and biotic factors, such as food availability (Dutz and Christensen, 2018; Lindley *et al.*, 2011). We observed the highest mortality of *A. royi* directly after each short-term salinity acclimatisation (Fig. 1) and somewhat lower mortality during the following 24 h incubation, regardless the absense or presence of food (Fig. 2a-d). Overall, mortality of *A. royi* in our study was highest when exposed to the lowest tested salinity (5 PSU, Fig 1, 2d and 3) as hypothesized. In our experiments, we acclimatized *A. royi* by changing from 32 PSU during 1 h to either 20, 10 or 5 PSU. We used a similar acclimation method as

described in Pan *et al.* (2016). As a result, Pan *et al.* (2016) found a sigmoidal survival curve as a function of salinities ranging from 0 to 35 PSU, with an optimum of 20 PSU. Muthupriya and Altaff (2009) however, showed a mortality of *A. royi* lowest at 12 PSU and highest at 32 PSU. In the present study, we observed an elevated mortality after acclimatization in 5 PSU but did not see any difference between 10 and 32 PSU (Fig 1 and 2). We consider this is an effect of that our *A. royi* strain has been reared at 32 PSU for several generations and therefore may have adapted to this condition, but still has kept the ability to perform well at 20 PSU. This suggests that within species, salinity tolerance is population specific or even may be related to pre-experimental rearing conditions.

Excess f~~F~~ood availably has previously shown to reduce mortality of copepods exposed to hypersaline environments (Rippingale and Hodgkin, 1977; Hammock *et al.* 2016). This elevated salinity tolerance is supported by ~~A~~a study by Lindley *et al.* (2011) on the species *Apocyclops panamensis*, a close relative to *A. royi*~~,~~. They investigated the effect of short-term (3 h) acclimatization to a hypersaline environment, from 6.6 PSU to 30 PSU ~~(Lindley *et al.*, 2011).~~ ~~They~~and showed a significant increase of the intracellular free amino acid (FAA) pool in the animals and an even higher increase when the copepods were offered additional FAAs (Lindley *et al.*, 2011). FAAs, such as proline, alanine, glycine and taurine have been shown to be major osmolytes in marine invertebrates (Helland *et al.*, 2000). The~~ir~~ observed built up of FAAs in *A. panamensis* could be dedicated to protein catabolism, but increase of intracellular FAAs also depends on food intake (amino acids) presumably accounting for their observed larger FAA pool when the copepods were enriched with FAAs (Farmer and Reeve, 1978). ~~The effect of food availability on mortality of copepods in hypersaline environments has been demonstrated by Hammock *et al.* (2016), who observed increased mortality of the euryhaline copepod *Eurytemora affinis* with increasing salinity at low food availability, compared to high food availability.~~

Contrary to our hypothesis, food availability did not influence the osmotic dependence of mortality of *A. royi* (Fig 2a-c). This may be partly explained by the fact that ~~I~~in our study ~~on the other hand~~, the copepods were exposed to hyposaline environments. Adjusting the internal osmolarity to a lowered external salinity requires down-regulation of the intracellular FAA pool (Farmer and Reeve, 1978). Protein synthesis and enhanced excretion account for the decrease of the FAA pool and this mechanism is even active in the absence of food (Farmer and Reeve, 1978). ~~This may partly explain, contrary to our hypothesis, the absence of an effect of food availability on mortality~~

of *A. royi* in response to lower salinity (Fig 2a-c). In order toTo understand the underlying mechanism of osmoregulation in *A. royi*, it would therefore be interesting to investigate in future studies changes in FAA concentrations in *A. royi* as an effect of decreasing external salinity and functional feeding response.

Another possible explanation of the absence of an effect of food availability on mortality could be a decrease in energetic expenses related to foraging activity at low food concentrations, allowing energy allocation to energy demanding osmoregulatory processes, such as ion transport (Hand and Hardewig, 1996; Bradly, 2009) and restoring the cellular redox balance (reviewed in Rivera-Ingraham and Lignot, 2017). The observed functional response of *A. royi* follows a Holling type III response (Fig 4) suggesting that feeding activity ceases when food availability is limited. Optimal foraging theory predict such a response for actively foraging zooplankton (Kiørboe *et al.*, 2018) in order to reduce the energetic cost for searching for food at low food conditions. In fact, for various marine copepod species such a behavioral response has been observed, which can be dedicated to reduced swimming activity at low food concentrations (Kiørboe, 2016). However, no direct observational studies exist on *A. royi* foraging tactics and the effect of food availability on foraging behavior verifying such a behavioral response.

The effect of salinity and food availability on feeding rate

The effect of salinity on the feeding rate of copepods has been scarcely studied. Feeding rate may be increased under iso-osmotic conditions in order tototo compensate for the increased metabolic demand imposed by osmoregulation (Gaudy *et al*. 2000). On the other hand, exposure to extreme iso-osmotic conditions may reduce the predatory capabilities of an animal, thereby reducing the animals´ feeding rate (Hammock *et al.*, 2016; Rivera-Ingraham and Lignot, 2017).

Calliari *et al*. (2008) investigated the effect of instantaneous salinity reduction on the feeding rate of *A. tonsa* and *A. clausi* and showed a substantial decrease in both ingestion rate and clearance rate of both species when salinity was lowered from 32 PSU to 14 and 4 PSU, respectively. Their results indicate that sudden lowering of salinity significantly decreases the feeding rate by these species and thereby potentially influence the plankton dynamics in the coastal system these species reside. The euryhaline species *Eurytemora affinis* on the other hand, showed an opposing response and considerably increased its consumption rate when exposed to increased salinity. However, when

exposed to increased salinity under low food levels, *E. affinis* did not increase its feeding rate and their growth was reduced (Hammock *et al*., 2016).

We did not observe a significant decrease or increase in either ingestion or clearance rate with decreasing salinity (Fig 4), which may be together with the relatively low observed mortality rates an indicator for the overall high salinity tolerance of *A. royi* exposed to lower salinities. In comparison, the mortality rates observed for *A. tonsa* and *A. clausi* which lowered their feeding rate in hyposaline environments (Calliari *et al*., 2008) were much higher (31.3 and 20 %, respectively) than observed for *A. royi* (from 1.8 to 6.8 %) (Fig 1 and 2).

A possible reason for the absence of increased feeding rates in *A. royi* exposed to hyposaline conditions could be differences in osmotic regulation mechanisms, where . Ddown-regulation of the FAAs may be independent of feeding, contrary to up-regulation (synthesis) of FAAs as in *E. affinis* exposed to hypersaline environments, which requires food uptake (Farmer and Reeve, 1978; Hammock *et al*., 2016).

The effect of salinity and food availability on egg production

Exposure to hypo- or hypersaline environments may reduce egg production rates in copepods due to increased energy allocation to osmoregulation (Gaudy *et al*., 2000). It is therefore not surprising that reduced egg production rates have been observed in various species when subjected to hyposaline environments (Dutz and Christensen, 2018; Calliari *et al*., 2006). .In the present study, we investigated the ovigerous rate of *A. royi* at different salinities over a gradient in food availability. Whereas the food availability dependent egg production of *A. royi* has not been previously described, s Salinity dependent egg production has been scarcely studied in a few cases for this *Apocyclops royi*species. Muthupriya and Altaff (2009) and Pan *et al.* (2016) tested the long-term egg production rate of aclimated *A. royi* in the presence of food and showed, similar to our observations (Fig 5), that *A. royi* is capable of maintaining egg production at a wide range of salinities (0-35 PSU) with optimal conditions varying between 12-20 PSU. Salinity above 35 PSU appeared to be unfavorable in terms of egg production (Muthupriya and Altaff, 2009). Hatching success and postembryonic development as maxima for nauplii production were observed between 10-20 PSU (Lee *et al.*, 2005; Pan *et al.*, 2016) and maximum culture densities were reached at 20 PSU (Pan *et al.*, 2016). In the present study the maximum ovigerous rate of *A. royi* was not significantly affected by salinity (Fig 5d), contrary to our hypothesis.

Further, we did not observe an affect of salinity on the threshold concentration for egg production, thus rejecting our hypothesis that the threshold concentration for egg production would shifts to higher food concentrations when exposed to sub-optimal salinities. Egg production was, regardless salinity treatment, initiated at the lowest food concentrations offered (Fig 5a-c) and showed, as hypothesized a food density dependency in reproductive output principally similar to its congeners (e.g. Berggreen *et al.*, 1988; Sabatini and Kiørboe, 1994). The maximum weight-specific fecundity of *A. royi* measured here also did not vary between salinities (0.18±0.0 µg C_{eggs} μg^{-1} $C_{copepod}$ d^{-1}) and is relatively high compared to similar sized egg sac carrying copepods, but low compared to broadcast spawners (Kiørboe and Sabatini, 1995).

Gaudy *et al*. (1982) observed a similar absence of response in egg production over a wide range in salinity. They did not observe variation in ovigerous rate of the exceptionally euryhaline harpacticoid copepod species *Tisbe holothuriae*. However, the majority of copepod species tolerate a much narrower salinity range before egg production is reduced (e.g. Hall and Burns, 2002; Holste and Peck, 2006; Dutz and Christensen, 2018). We did not measure egg hatching success or larval development to assess the salinty effect on the full life-cycle and population dynamics of *A. royi*. From the few studies that exist these are more salinity dependent than egg production and may vary greatly depending on the copepod strain used (Lee *et al.*, 2005; Pan *et al.*, 2016).

~~Ecological implications~~Success of *A. royi* in an extreme habitat

~~Th~~e *Apocyclops royi* strain used in the present study was isolated from artificial aquaculture ponds in Taiwan. These ponds we consider representing an extreme habitat. Each of the ponds cover an area ~0.7 ~~ha and is 1 m deep~~ha, is 1 m deep, and filled with coastal water from the nearby South China Sea. Hence, it is reasonable to assume that the copepods are not native to these ponds, but originate from the South China Sea (Blanda *et al.*, 2015). Brackish water systems generally show strong temporal fluctuations in environmental conditions, and the ponds *A. royi* is isolated from are documented to fluctuate in biotic and abiotic conditions on a seasonal and even daily basis (Blanda *et al.*, 2015, 2017). For example, oxygen levels in these ponds reach hypoxic conditions on a daily basis and severe hypoxia on a weekly basis, with *A. royi* still thriving in these ponds (Blanda *et al.*, 2015). Salinity is variable over the season, but more interestingly, short-term drops in salinity of 6 PSU are observed due to heavy monsoon rain events. Hence, *A. royi* is exposed to abrupt salinity changes in its natural environment and ~~is able to~~can successfully maintain its population. This

414 correlates well with our results where decreasing salinities resulted in only minor increase in
415 mortality rates and no effect on ovigerous rate (Fig 1, 2 and 5). Moreover, *A. royi* is able to upgrade
416 their fatty acid pool to become richer in long chained fatty acids (Rayner *et al.,* 2017; Nielsen *et al.*,
417 2019). These traits, combined with a low osmotic dependency of the vital rates of *A. royi* as shown
418 in the present study, most likely contribute to the fact that *A. royi* can survive and is one of the
419 predominant copepod species in Taiwanese aquaculture ponds (Blanda et *al*., 2015; Rayner et *al*.,
420 2015).

421 ~~**Salinity tolerance of *A. royi***~~

422 ~~Here we tested the hypothesis that due to presumed energetic expenses for osmoregulation and~~
423 ~~oxidative stress at sub-optimal salinities vital rates of *A. royi* are affected. Firstly, we hypothesized~~
424 ~~that under sub-optimal salinities the mortality rate increases, and maximum egg production rate are~~
425 ~~reduced. This hypothesis was partly rejected as mortality rate increased when exposed to a lowered~~
426 ~~salinity during salinity acclimatization and incubation period (Fig 1, 2 and 3), but egg production~~
427 ~~was not reduced (Fig 5).~~

428 ~~Second, we hypothesized that mortality decreases, and egg production rate increases with food~~
429 ~~availability. Egg production increased with increasing food availability (Fig 4) as expected from~~
430 ~~previous research on food dependency of egg production. However, we did not observe a decrease~~
431 ~~in mortality rate with increasing food availability (Fig 2).~~

432 ~~Lastly, we hypothesized that the threshold concentration for egg production (lowest food~~
433 ~~concentration where egg production is initiated) shifts to higher food concentrations when~~
434 ~~challenged by salinity. This hypothesis was rejected as at all tested salinities egg production was~~
435 ~~absent when no food was present, but was initiated at the lowest food concentrations offered (Fig~~
436 ~~5a-c).~~

437 **CONCLUSIONS**

438 In the present study we experimentally investigated the physiological response of the tropical
439 copepod *Apocyclops royi* to different salinities under varying food availability. We showed that ~~the~~
440 ~~tropical copepod *A. pocyclops*~~ *royi* is a euryhaline species. Its mortality rate increased during and
441 after short-term (1 h) acclimatization to low salinity (5 PSU), whereas the individual feeding- and

ovigerous rate was not affected at all during our 24 h exposure experiments. Food availability directly influenced the ovigerous rate and feeding rate of *A. royi* in a sigmoidal manner, but did not influence the threshold concentration for egg production or the mortality rate of this species when exposed to sub-optimal salinities.

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DATA ARCHIVING

No supplementary data related to this article is archived.

REFERENCES

Almeda, R., van Someren Gréve, H. and Kiørboe, T. (2018) Prey perception mechanism determines maximum clearance rates of planktonic copepods. *Limnol. Oceanogr.*, **63**, 2695-2707.

Battaglia, B. and Bryan, G. (1964) Some aspects of ionic and osmotic regulation in *Tisbe* (Copepoda, Harpacticoida) in relation to polymorphism and geographical distribution. *J. Mar. Biol. Assoc. U. K*, **44**, 17-31.

Bayly, I. A. E. (1969) The body fluids of some centropagid copepods: Total concentration and amounts of sodium and magnesium. *Comp. Biochem. Physiol.*, **28**, 1403-1409.

Berggreen, U., Hansen, B. and Kiørboe, T. (1988) Food size spectra, ingestion and growth of the copepod *Acartia tonsa* during development: implications for determination of copepod production. *Mar. Biol.*, **99**, 341-352.

Bergmans, M. and Janssens, P. P. M. (1988) Competition between the sibling species *Tisbe holothuriae* and *T. battagliai* (Harpacticoida). *Hydrobiologia*, **167**, 455-462.

Blanda, E., Drillet, G., Huang, C.-C., Hwang, J.-S., Jakobsen, H. H., Rayner, T. A., Su, H.-M., Wu, C.-H. and Hansen, B.W. (2015) Trophic interactions and productivity of copepods as live feed from tropical Taiwanese outdoor aquaculture ponds. *Aquaculture*, **445**, 11–21.

Blanda, E., Drillet, E., Huang, C.-C., Hwang, J.-S., Højgaard, J. K., Jakobsen, H. H., Rayner, T. A., Su, H.-M. and Hansen, B. W. (2017) An analysis of how to improve production of copepods as live feed from tropical Taiwanese outdoor aquaculture ponds. *Aquaculture*, **479**, 432-441.

Bradly, T. (2009) *Animal Osmoregulation (Oxford Animal Biology Series)*. Oxford University Press, New York. 184 pp. ISBN 13: 978-0198569961.

Calliari, D., Andersen, C. M., Thor, P., Gorokhova, E. and Tiselius, P. (2006) Salinity modulates the energy balance and reproductive success of co-occurring copepods *Acartia tonsa* and *A. clausi* in different ways. *Mar. Ecol. Prog. Ser.*, **312**, 177–188.

Calliari, D., Andersen B. M. C., Thor, P., Gorokhova, E. and Tiselius, P. (2008) Instantaneous salinity reductions affect the survival and feeding rates of the co-occurring copepods *Acartia tonsa*

Dana and *A. clausi* Giesbrecht differently. *J. Exp. Mar. Biol. Ecol.*, **362**, 18–25.

Cervetto, G., Gaudy, R. and Pagano, M. (1999) Influence of salinity on the distribution of *Acartia tonsa* (Copepoda, Calanoida). *J. Exp. Mar. Biol. Ecol.*, **239**, 33-45.

Chang, W.-B. and Lei, C.-H. (1993) Development and energy content of a brackish-water copepod, *Apocyclops royi* (Lindberg) reared in a laboratory. *Bull. Inst. Zool., Academia Sinica*, **32**, 62-81.

Chen, Q., Sheng, J., Lin, Q., Gao, Y. and Lv, J. (2006) Effect of salinity on reproduction and survival of the copepod *Pseudodiaptomus annandalei* Sewell, 1919. *Aquaculture*, **258**, 575–582.

Devassy, V. P. and Goes, J. I. (1988) Phytoplankton community structure and succession in a tropical estuarine complex (central west coast of India). *Estuar. Coast. Shelf Sci.*, **27**, 671-685.

Devreker, D., Souissi, S., Forget-Leray, J. and Leboulenger, F. (2007) Effects of salinity and temperature on the post-embryonic development of *Eurytemora affinis* (Copepoda; Calanoida) from the Seine estuary: a laboratory study. *J. Exp. Mar. Biol. Ecol.*, **368**, 113–123.

Dhanker R. and Whang, J.-S. (2013) Predation by *Apocyclops royi* (Cyclopoid: Copepod) on ciliates and rotifers. *J. Mar. Sci. Technol.*, **21**, 246-251.

Dutz, J. and Christensen, A. M. (2018) Broad plasticity in the salinity tolerance of a marine copepod species, *Acartia longiremis*, in the Baltic Sea. *J. Plankton. Res.*, **40**, 342–355.

Farmer, L. (1980) Evidence for hyporegulation in the calanoid copepod, *Acartia tonsa*. *Comp. Biochem. Physiol.*, **65A**, 359-362.

Farmer, L. and Reeve, M.R. (1978) Role of the free amino acid pool of the copepod *Acartia tonsa* in adjustment to salinity change. *Mar. Biol.*, **48**, 311–316.

Frost, B. W. (1972) Effects of size and concentration of food particles on the feeding behavior of the marine planktonic copepod *Calanus pacificus*. *Limnol. Oceanogr.*, **17**, 805–815.

Gaudy, R. and Guerin, J. P. (1982) Population dynamics of *Tisbe holothuriae* (Copepoda; Harpacticoida) in exploited mass cultures. *Neth. J. Sea Res.*, **16**, 208-216.

506 Gaudy, R., Cervetto, G. and Pagano, M. (2000) Comparison of the metabolism of *Acartia clausi*
507 and *A. tonsa*: influence of temperature and salinity. *J. Exp. Mar. Biol. Ecol.*, **247**, 51–65.

508 Guillard, R. R. L. (1975) *Culture of phytoplankton for feeding marine invertebrates*. In *Culture of*
509 *marine invertebrate animals* (ed. Smith, W. L and Chanley, H. M.), pp 26-60. Springer, Boston,
510 MA. ISBN 978-1-4615-8714-9.

511 Hall, C. J. and Burns, C. W. (2002) Effects of temperature and salinity on the survival and egg
512 production of *Gladioferens pectinatus* Brady (Copepoda: Calanoida). *Estuar. Coast. Shelf Sci.*, **55**,
513 557–564.

514 Hammock, B. G., Lesmeister, S., Flores, I., Bradburd, G. S. and Hammock, F. H. (2016) Low food
515 availability narrows the tolerance of the copepod *Eurytemora affinis* to salinity, but not to
516 temperature. *Estuaries Coast.*, **39**, 189-200.

517 Hand, S. C. and Hardewig, I. (1996) Downregulation of cellular metabolism during environmental
518 stress: Mechanisms and implications. *Annu. Rev. Physiol.*, **58**, 539-63.

519 Hauton, C. (2016) *Effects of salinity as a stressor to aquatic invertebrates*. In *Stressors in the*
520 *Marine Environment. Physiological and ecological responses; societal implications* (ed. Solan, M.
521 and Whitley, N. M.), pp. 3-24. Oxford University Press, Oxford, United Kingdom. ISBN: 978-0-19-
522 871882-6.

523 Helland, S., Triantaphyllidis, G. V., Fyhn, H. J., Evjen, M. S., Lavens, P. and Sorgeloos, P. (2000)
524 Modulation of the free amino acid pool and protein content in populations of the brine shrimp
525 *Artemia* spp. *Mar. Biol.*, **137**, 1005-1016.

526 Henry, R. P., Garrelts, E. E., McCarty, M. M. and Twole, D. W. (2002) Differential induction of
527 branchial carbonic anhydrase and Na+/K+ ATPase activity in the euryhaline crab, *Carcinus*
528 *maenas*, in response to low salinity exposure. *J. Exp. Zool.*, **292**, 595–603.

529 Holste, L. and Peck, M. A. (2006) The effects of temperature and salinity on egg production and
530 hatching success of Baltic *Acartia tonsa* (Copepoda: Calanoida): a laboratory investigation. *Mar.*
531 *Biol.*, **148**, 1061–1070.

532 Jepsen, P. M., Thoisen, C. V., Carron-Cabaret, T., Pinyol-Gallemí, A., Nielsen, S. L. and Hansen,
533 B. W. (2018) Effects of salinity, commercial salts, and water type on cultivation of the cryptophyte
534 microalgae *Rhodomonas salina* and the calanoid copepod *Acartia tonsa*. *J. World Aquacult. Soc.*,

50, 104-118.

Kiørboe, T. (2016) Foraging mode and prey size spectra of suspension-feeding copepods and other zooplankton. *Mar. Ecol. Prog. Ser.*, **558**, 15–20.

Kiørboe, T., Møhlenberg, F. and Hamburger, K. (1985) Bioenergetics of the planktonic copepod *Acartia tonsa*: relation between feeding, egg production and respiration, and composition of specific dynamic action. *Mar. Ecol. Prog. Ser.,* **26**, 85-97.

Kiørboe, T., Møhlenberg, F. and Nicolajsen, H. (1982) Ingestion rate and gut clearance in the planktonic copepod *Centropages hamatus* (Lilljeborg) in relation to food concentration and temperature. *Ophelia*, **21**, 181–194.

Kiørboe, T. and Sabatini, M. (1995) Scaling of fecundity, growth and development in marine planktonic copepods. *Mar. Ecol. Prog. Ser.*, **120**, 285-298.

Kiørboe T., Saiz E., Tiselius P. and Andersen K. H. (2018) Adaptive feeding behavior and functional responses in zooplankton. *Limnol. Oceanogr.*, **63**, 308–321.

Lance, J. (1963) The salinity tolerance of some estuarine planktonic copepods. *Limnol. Oceanogr.,* **8**, 440–449.

Lee, K.-W., Kwon, O.-N. and Park, H.-G. (2005) Effects of temperature, salinity and diet on the productivity of the cyclopoid copepod, *Apocyclops royi*. *J. of Aquaculture*, **18**, 52-59.

Lee, C. E., and Petersen, C. H. (2003) Effects of developmental acclimation on adult salinity tolerance in the freshwater-invading copepod *Eurytemora affinis*. *Physiol. Biochem. Zool.*, **76**, 296-301.

Lindley, L. C., Phelps, R. P., Davis, D. A. and Cummins, K. A. (2011) Salinity acclimation and free amino acid enrichment of copepod nauplii for first-feeding of larval marine fish. *Aquaculture*, **318**, 402-406.

Madhu, N. V., Jyothibabu, R., Balachandran, K. K., Honey, U. K., Martin, G. D., Vijay, J. G., Shiyas, C. A., Gupta, G. V. M. and Achuthankutty, C. T. (2007) Monsoonal impact on planktonic standing stock and abundance in a tropical estuary (Cochin backwaters – India). *Estuar. Coast. Shelf Sci.*, **73**, 54–64.

562 Martinez, E., Antoine, D., D' Ortenzio, F. and de Boyer Montégut, C. (2011) Phytoplankton spring
563 and fall blooms in the North Atlantic in the 1980s and 2000s. *J. Geophys. Res.*, **116**, C11029.

564 Mcallen, R. J., Taylor, A. C. and Davenport, J. (1998) Osmotic and body density response in the
565 harpacticoid copepod *Tigriopus brevicornis* in supralittoral rock pools. *J. Mar. Biol. Ass. U.K.*, **78**,
566 1143-1153.

567 Miliou, H. and Moraitou-Apostolopoulou, M. (1991) Variations of respiratory rate of *Tisbe*
568 *holothuriae* Humes (copepoda, harpacticoida) in relation to temperature, salinity and food type.
569 *Comp. Biochem. Physiol., Part A: Physiology*, **100**, 169-174.

570 Muthupriya, P. and Altaff, K. (2009) Effect of salinity and temperature on the reproduction of the
571 estuarine copepod *Apocyclops royi* (Lindberg, 1940). *J. Exp. Zoology India*, **12**, 103–106.

572 Nielsen, B. L. H., Gøtterup, L., Jørgensen, T. S., Hansen, B. W., Hansen, L. H., Mortensen, J. and
573 Jepsen, P. M. (2019) n-3 PUFA biosynthesis by the copepod *Apocyclops royi* documented using
574 fatty acid profile analysis and gene expression analysis. *Biol. Open*, **8**, 1-12.

575 Nilsson, B., Jepsen, P. M., Bucklin, A. and Hansen, B. W. (2018) Environmental stress responses
576 and experimental handling artifacts of a model organism, the copepod *Acartia tonsa* (Dana). *Front.*
577 *Mar. Sci.*, **5**, 156.

578 Pan, Y.-J., Souissi, A., Souissi, S. and Hwang, J.-S. (2016) Effects of salinity on the reproductive
579 performance of *Apocyclops royi* (Copepoda, Cyclopoida). *J. Exp. Mar. Biol. Ecol.*, **475**, 108–113.

580 Peterson, W. (1988) Rates of egg production by the copepod *Calanus marshallae* in the laboratory
581 and in the sea off Oregon, USA. *Mar. Ecol. Prog. Ser.*, **47**, 229–237.

582 Peterson, M. S. and Ross S. T. (1991) Dynamics of littoral fishes and decapods along a coastal
583 river-estuarine gradient. *Estuar. Coast. Shelf Sci.*, **33**, 467-483.

584 Rayner, T. A., Højgaard, J. K., Hansen, B. W. and Hwang, J.-S. (2017) Density effect on the
585 ovigerous rate of the calanoid copepod *Pseudodiaptomus annandalei* (Sewell 1919): implications
586 for aquaculture. *Aquac. Res*., **48**, 4573-4577.

587 Rayner, T. A., Jørgensen, N. O. G., Blanda, E., Wu, C.-H., Huang, C.-C., Mortensen, J., Hwang, J.-
588 S. and Hansen, B. W. (2015). Biochemical composition of the promising live feed tropical calanoid
589 copepod *Pseudodiaptomus annandalei* (Sewell 1919) cultured in Taiwanese outdoor aquaculture
590 ponds. *Aquaculture*, **441**, 25-34.

591 Rippingale, R. J. and Hodgkin, E. P. (1977) Food availability and salinity tolerance in a brackish
592 water copepod. *Aust. J. Mar. Freshw. Res.*, **28**, 1-7.

Rivera-Ingraham, G. A. and Lignot, J. H. (2017) Osmoregulation, bioenergetics and oxidative stress in coastal marine invertebrates: raising the questions for future research. *J. Exp. Biol.*, **220**, 1749-1760.

Roddie, B. D., Leakey, R. J. G. and Berry, A.J. (1984) Salinity-temperature tolerance and osmoregulation in *Eurytemora affinis* (Poppe) (Copepoda : Calanoida) in relation to its distribution in the zooplankton of the upper reaches of the Forth estuary. *J. Exp. Mar. Biol. Ecol.*, **79**, 191-211.

Sabatini, M. and Kiørboe, T. (1994) Egg production, growth and development of the cyclopoid copepod *Oithona similis*. *J. Plankton Res.*, **16**, 1329-1351.

Schultz, M. and Kiørboe, T. (2009) Active prey selection in two pelagic copepods feeding on potentially toxic and non-toxic dinoflagellates. *J. Plankton Res.*, **31**, 553–561.

Su, H.-M., Cheng, S.-H., Chen, T.-I., and Su, M.-S. (2005) *Culture of copepods and applications to marine finfish larval rearing in Taiwan*. In *Copepods in Aquaculture* (ed. Lee, C.-S., O'Bryen, P. J. and Marcus, N. H.), pp. 183-194. Blackwell Publishing Ltd , Oxford, United Kingdom. ISBN 13: 978-0-8138-0066-0.

Svetlichny, L. and Hubareva, E. (2014) Salinity tolerance of alien copepods *Acartia tonsa* and *Oithona davisae* in the Black Sea. *J. Exp. Mar. Biol. Ecol.*, **461**, 201–208.

Thoisen, C., Vu, M. T. T., Carron-Cabaret, T., Jepsen, P. M., Nielsen, S. L. and Hansen, B. W. (2018) Small-scale experiments aimed at optimization of large-scale production of the microalga *Rhodomonas salina*. *J. Appl. Phycol.*, **30**, 2193-2202.

Uye, S. and Sano, K. (1995) Seasonal reproductive biology of the small cyclopoid copepod *Oithona davisae* in a temperate eutrophic inlet. *Mar. Ecol. Prog. Ser.*, **118**, 121–128.

van Someren Gréve, H., Almeda, R., Lindegren, M. and Kiørboe, T. (2017) Gender-specific feeding rates in planktonic copepods with different feeding behavior. *J. Plankton Res.*, **39**, 631–644.

TABLE AND FIGURE LEGENDS

Table 1. Overview of the experimental work. Salinity of the final food suspension is given for each experiment. Prey size is the average cell size (n=~30.000) at start and end of the experiment (size generally decreased during incubation). Prey concentrations are the minimum and maximum average concentration during each incubation. All tested prey concentrations for each salinity treatment can be derived from figures 2, 4 and 5. Temperature was monitored with 1-minute intervals using an ONSET HOBO® Pendant temperature logger.

Experiment no.	Salinity	Copepods per 300 mL bottle	Prosome length	Prey size	Prey concentration	Temperature
	‰	n	μm ± SD	μm ESD ± SD	cells mL^{-1}	°C ± SD
1	32	35-50	504±43	6.9±0.8	0-42.388	25.7 ± 1.2
2	20	35-50	501±38	7.4±0.8	0-38.943	26.0 ± 0.9
3	10	35-50	489±38	n.a.	n.a.	26.6 ± 0.5
4	5	40-50	507±28	7.8±1.3	0-36.576	26.9 ± 0.4
5	5, 10, 20, 32	50	495±30	-	0	26.9 ± 0.6

626 Table 2. Model parameters ±SE or 95 % confidence intervals (CI) for all equations fitted to the
627 observational data for mortality rate, feeding rate (ingestion and clearance rate), ovigerous rate, clutch
628 size and egg production as function of ingestion rate for *Apocyclops royi* at different salinities.

629

	Equation	PSU	*a*±SE	*b*±SE	r^2
Mortality rate		5	6.4±1.1	4.9±0.0	0.02
(Fig 2)	$M = a + bC$	20	2.4±0.6	-2.0±0.0	0.01
		32	2.1±0.6	-0.0±0.0	0.02
			β (CI, 95 %)	α (CI, 95 %)	
Ingestion rate		5	2.32 (2.14-2.49)	7056 (6261-7850)	0.99
(Fig 4a-d)	$I = \alpha\beta e^{1 - \frac{a}{C}}$	20	1.87 (1.45-2.29)	7157 (4954-9360)	0.92
		32	1.77 (1.62-1.91)	10156 (8865-11446)	0.99
Clearance rate		5	2.35 (2.02-2.68)	5424 (4294-6553)	0.67
(Fig 4e-h)	$F = \frac{\alpha\beta}{C} e^{1 - \frac{a}{C}}$	20	1.92 (1.62-2.22)	6448 (5133-7762)	0.48
		32	1.80 (1.50-2.10)	8379 (6641-10117)	0.15
			G_{max}(CI, 95 %)	*b* (CI, 95 %)	r^2
Ovigerous rate		5	79.5 (69.0-90.0)	5413 (4020-6806)	0.96
(Fig 5a-d)		20	89.8 (79.7-100.0)	12457 (10422-14492)	0.98
	$G = G_{max} e^{-b/C}$	32	87.0 (72-3-101.7)	11696 (8715-14677)	0.96
Clutch size (Fig 5h)		5,20,32	19.7 (19.1-20.4)	527 (319-733)	0.2
			a±SE	*b*±SE	r^2
Egg prod.-		5	3974±6394	0.114±0.009	0.94
ingestion rate	$SEP = a + bI$	20	-9329±7898	0.120±0.012	0.86
(Fig 6)		32	-4853±4795	0.102±0.006	0.95

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632

Fig 1. Mortality rate during short-term (% h^{-1}) salinity acclimatisation of *Apocyclops royi* as function of salinity. Light dots indicate replicates and black dots are the mean value. Error bars indicate the standard error and different letters indicate statistically significant difference in average mortality between salinities.

Fig 2. Food concentration dependent mortality rate of *Apocyclops royi* at different salinities (panel a-c) and average mortality (% d^{-1}) at each tested salinity (panel d) during 24 h incubations. Light dots indicate replicates and black dots are the mean value. Discontinuous lines (panel a-c) indicate the 95 % confidence intervals for each fitted regression. Regression parameters are shown in Table 2. Error bars (panel d) indicate the standard error and different letters indicate statistically significant difference in average mortality between salinities.

Fig 3. Cumulative mortality rates of *Apocyclops royi* at different salinities during 1h salinity acclimatization and 24 h incubation experiments as a function of time. Dots are the mean value and error bars indicate the standard error. Different letters indicate statistically significant difference in average mortality between salinities.

Fig 4. The functional responses of *Apocyclops royi* feeding on *Rhodomonas salina* at different salinity levels. Copepod ingestion rates (cells cop^{-1} d^{-1}, panel a-c) and clearance rates (mL cop^{-1} d^{-1}, panel e-g) are presented as function of food concentration (cells mL^{-1}). Black solid lines are Holling type III model fits to the experimental observations. Panel d and h show model estimates of the maximum ingestion rate (I_{max}) and maximum clearance rate (β_{max}), respectively as function of salinity; error bars indicate 95 % confidence intervals. All models and parameters are presented in Table 2.

Fig 5. Food concentration dependent egg production rates of *Apocyclops royi* at different salinities. Female ovigerous rates (% of ovigerous females d^{-1}, panel a-c) and gross efficiency of egg production rates (panel e-g) are presented as function of food concentration (cells mL^{-1}). Black solid lines are model fits to the experimental observations. Panel d shows model estimates of the maximum ovigerous rate (G_{max}) and panel h food concentration dependent clutch size, respectively as function of salinity. Error bars indicate 95 % confidence intervals. Models fitted to the observational data and model parameters are presented in Table 2.

662 **Fig 6.** The specific egg production rate (µg C cop^{-1} d^{-1}) is shown as function of the specific
663 ingestion rate (µg C cop^{-1} d^{-1}), where the slopes of the fitted regressions equal the estimated gross
664 efficiency of egg production. Discontinuous lines indicate the 95 % confidence intervals for each
665 fitted regression. Regression parameters are shown in Table 2.

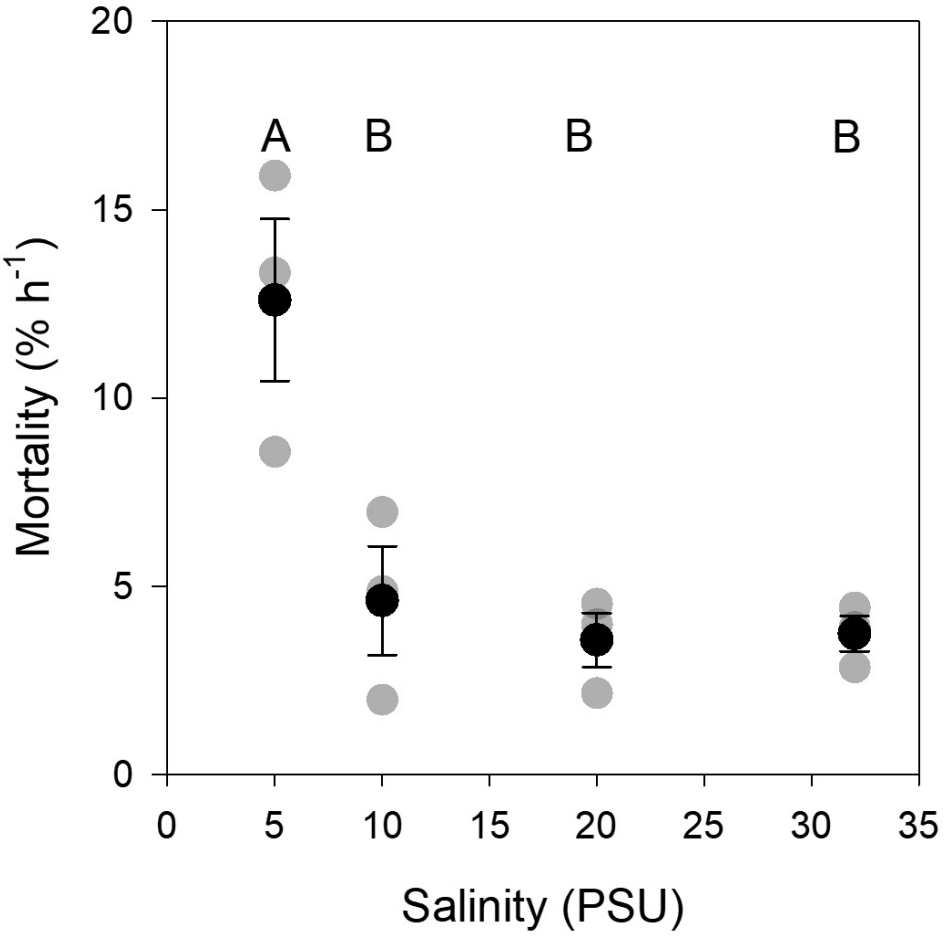

Fig 1. Mortality rate during short-term (% h-1) salinity acclimatisation of Apocyclops royi as function of salinity. Light dots indicate replicates and black dots are the mean value. Error bars indicate the standard error and different letters indicate statistically significant difference in average mortality between salinities.

92x91mm (300 x 300 DPI)

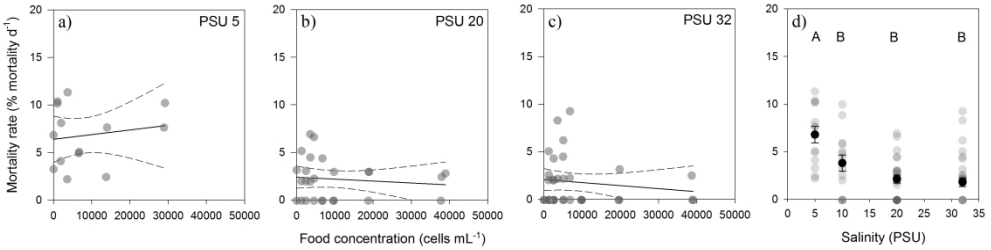

Fig 2. Food concentration dependent mortality rate of Apocyclops royi at different salinities (panel a-c) and average mortality (% d-1) at each tested salinity (panel d) during 24 h incubations. Light dots indicate replicates and black dots are the mean value. Discontinuous lines (panel a-c) indicate the 95% confidence intervals for each fitted regression. Regression parameters are shown in Table 2. Errorbars (panel d) indicate the standard error and different letters indicate statistically significant difference in average mortality between salinities.

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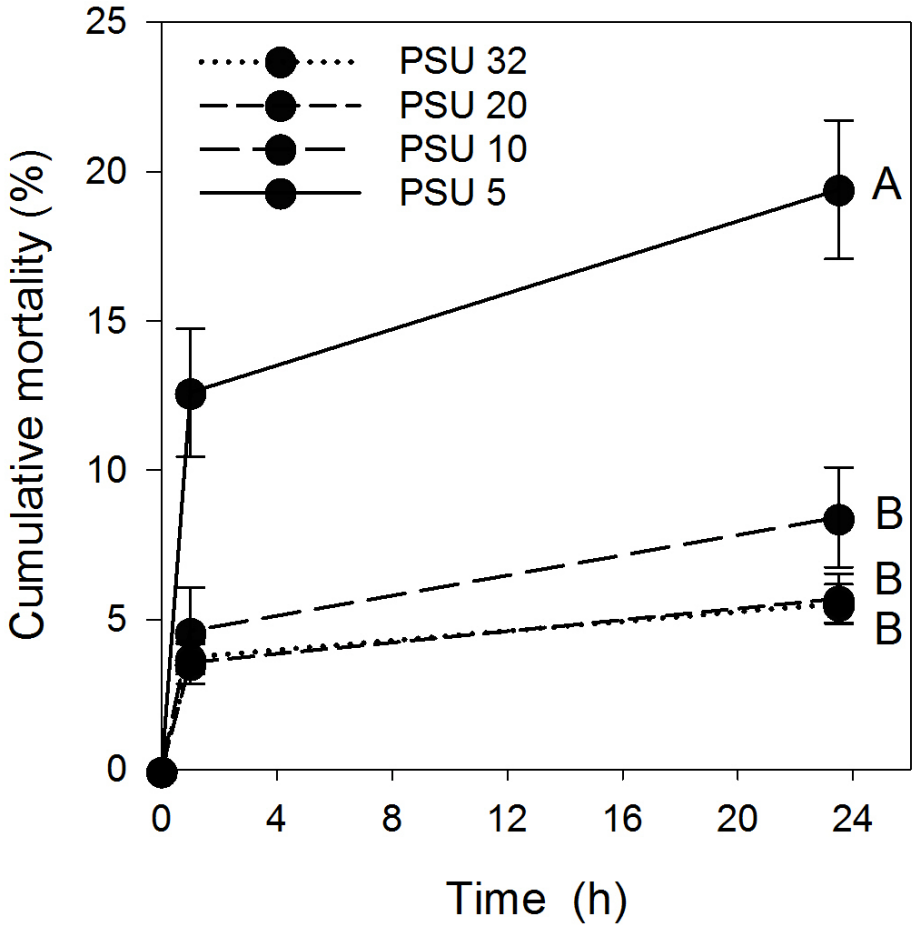

Fig 3. Cumulative mortality rates of Apocyclops royi at different salinities during 1h salinity acclimatization and 24h incubation experiments as a function of time. Dots are the mean value and error bars indicate the standard error. Different letters indicate statistically significant difference in average mortality between salinities.

93x92mm (300 x 300 DPI)

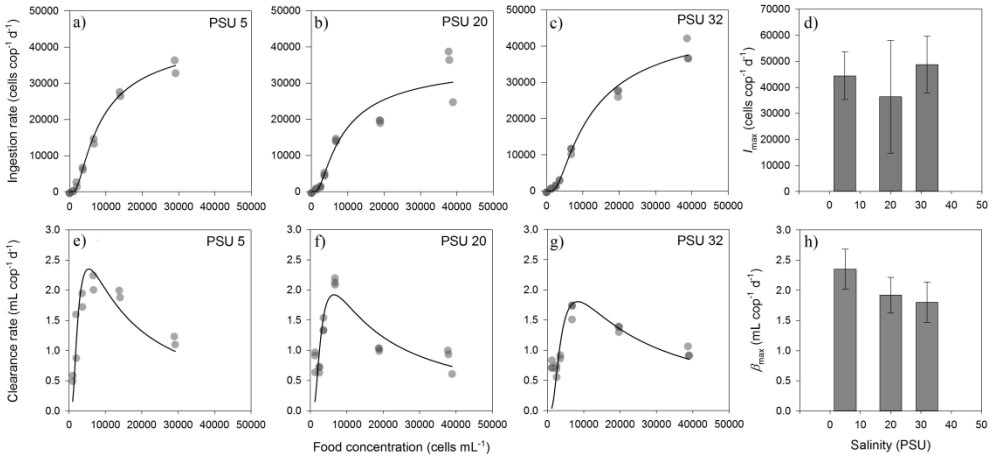

Fig 4. The functional responses of Apocyclops royi feeding on Rhodomonas salina at different salinity levels. Copepod ingestion rates (cells cop-1 d-1, panel a-c) and clearance rates (mL cop-1 d-1, panel e-g) are presented as function of food concentration (cells mL-1). Black solid lines are Holling type III model fits to the experimental observations. Panel d and h show model estimates of the maximum ingestion rate (Imax) and maximum clearance rate (βmax), respectively as function of salinity; error bars indicate 95% confidence intervals. All models and parameters are presented in Table 2.

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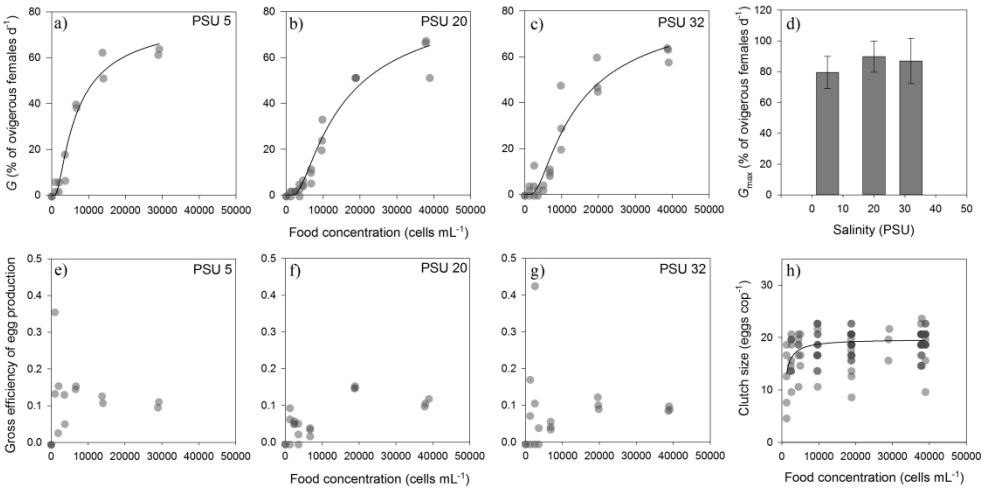

Fig 5. Food concentration dependent egg production rates of Apocyclops royi at different salinities. Female ovigerous rates (% of ovigerous females d-1, panel a-c) and gross efficiency of egg production rates (panel e-g) are presented as function of food concentration (cells mL-1). Black solid lines are model fits (to the experimental observations. Panel d shows model estimates of the maximum ovigerous rate (Gmax) and panel h food concentration dependent clutch size, respectively as function of salinity. Error bars indicate 95% confidence intervals. Models fitted to the observational data and model parameters are presented in Table 2.

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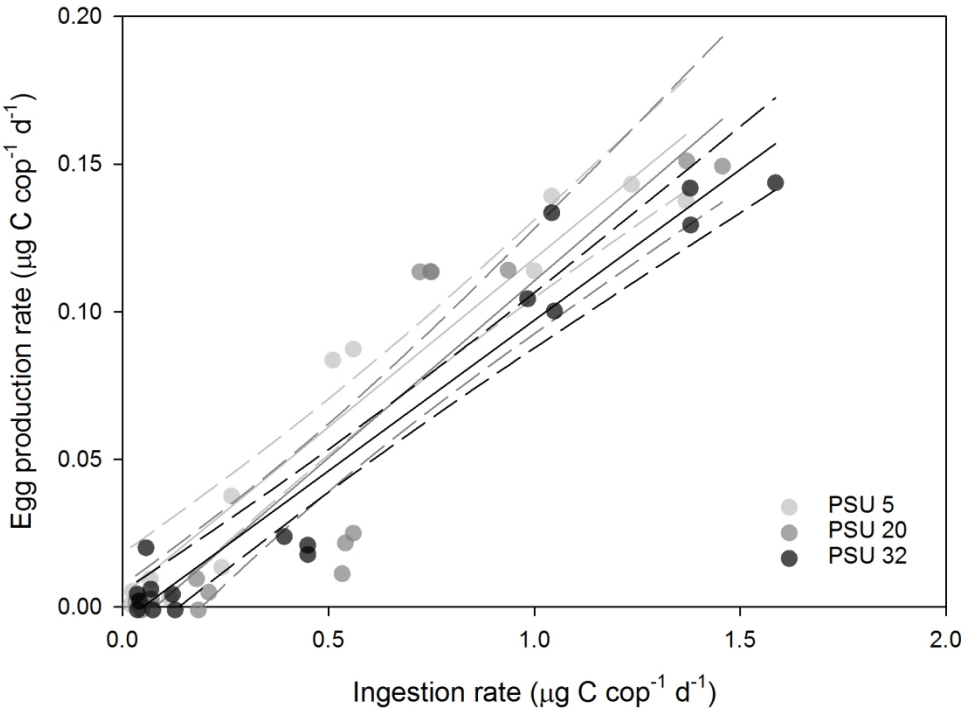

Fig 6. The specific egg production rate (µg C cop-1 d-1) is shown as function of the specific ingestion rate (µg C cop-1 d-1), where the slopes of the fitted regressions equal the estimated gross efficiency of egg production. Discontinuous lines indicate the 95% confidence intervals for each fitted regression. Regression parameters are shown in Table 2.

151x119mm (300 x 300 DPI)