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Size-dependent predation of round goby *Neogobius melanostomus* on blue mussels *Mytilus edulis*

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ABSTRACT

Many aquatic ecosystems are invaded by alien species, often with severe implications for native species and associated fisheries. Round goby *Neogobius melanostomus* is of Ponto-Caspian origin and has established large populations in the Baltic Sea. Here, round goby often feed on blue mussel *Mytilus edulis*, which may affect the invaded ecosystems. Experimental data were modelled and showed that round goby up to c. 15 cm of total length (TL) feed on mussels <3 cm. Moreover, logistic regression models revealed significant negative relationships between mussel size and probability of being consumed by round goby. The maximum prey size to gape size ratio r_{max} varied from 1.5 to 2 (mean = 1.75 ± 0.25) between five round goby size groups and was unrelated to fish TL. A mechanistic model is presented that describes maximum prey size as a function of fish TL. The results of this study can be embedded in ecosystem models and used to predict ecosystem effects of invasions by the round goby.

KEYWORDS

Baltic Sea, invasive species, predator-prey interaction, bivalves, trophic interaction, prey-size to gape-size ratio.

One of the most wide-ranging invasive species of fresh- and brackish-water environments is the round goby *Neogobius melanostomus* (Kornis, Mercado-Silva & Vander Zanden, 2012). Originating from the Ponto Caspian region, the round goby is a highly successful invader of novel environments (Behrens, van Deurs & Christensen, 2017; Nurkse, Kotta, Orav-Kotta & Ojaveer, 2016) and has established populations within the North American Great Lakes, the Baltic Sea and many European rivers (Jude, Reider & Smith, 1992; Azour et al., 2015; Buřič, Bláha, Kouba & Drozd , 2015; Kotta, Nurkse, Puntila & Ojaveer, 2016). The round goby feeds heavily on bivalves, both in its native (Skazkina & Kostyuchenko, 1968) and invaded ranges (Raby, Gutowsky & Fox, 2010; Järv, Kotta, Kotta & Raid, 2012). In the Baltic Sea, this predation is a novel pressure on mussel populations, which are rarely preyed upon by native fish species (Kautsky, 1981; Fenchel, Bendtsen & Sand-Jensen, 2006). In the North American Great Lakes and in invaded European rivers, round goby mainly consume zebra *Dreissena polymorpha* and quagga mussels *Dreissena bugensis*, whereas *Mytilus* species are the main bivalves preyed upon in the Baltic Sea (Kornis et al., 2012). Mussels are ecosystem engineers (Chowdhury, Zieritz & Aldridge, 2016), providing habitat for diverse fauna and flora (Koivisto & Westerbom, 2010; Donadi et al., 2015), and mitigating the negative effects of eutrophication through filter feeding (Petersen, Saurel, Nielsen & Timmermann, 2016). In addition, mussels often support substantial regional fisheries, e.g. the annual profit of Danish blue mussel fisheries exceeded €7,5 million in 2016 (Yearbook of Fishery Statistics 2016, 2017) . There is consequently a need for the development of environmental impact models that incorporate predation of invasive round goby on mussel beds.

The aim of the present study was to describe the relationship between round goby size and the maximum size of blue mussels (*Mytilus edulis*) consumed. To describe the relationship between fish total length (measured from snout tip to end of caudal fin, TL) and the maximum prey size, a model was formulated based on the notion that gape size determines the maximum prey size (Nilsson & Brönmark, 2000). Given that the relationship between gape size and predator TL is linear (Ray & Corkum, 1997):

$$\frac{[prey\ size]}{[gape\ size]} = \frac{[prey\ size]}{\{a*[predator\ length]+b\}}$$

After rearrangement, this renders the following simple mechanistic model formulation (Eq. 1):

$$P_{max} = r_{max}\alpha L + r_{max}\beta$$

where P_{max} is the maximum prey size, r_{max} is the maximum prey size to gape size ratio (i.e. prey size divided by gape size), L is predator TL, and α and β are the slope and intercept of the relationship between predator TL and gape size. Empirical data on round goby and blue mussels were used to estimate the parameters of the model.

Round goby were captured in Karrebæk Fjord and Guldborgsund (Western Baltic Sea) in April 2017 and September 2018 and transported to the National Institute of Aquatic Resources, Technical University of Denmark. Fish were kept in recirculating tanks at 10°C and 8–10 psu and fed with high-nutrition, 3-mm fish pellets (Primo). Preliminary experiments revealed that the fish were more likely to feed when kept in groups, hence experiments were carried out with five different batches of round gobies, representing five distinct size groups, ranging from 10.3 to 15.5 cm in TL. Depending on availability of fish, each size-group contained between 10 and 32 individuals. Since the aim was to identify the maximum prey size, the mean TL of the 10 largest individuals within each group was used to define the size groups (Table 1).

Each size group of fish was acclimated to laboratory conditions for one month, and subsequently conditioned to feed on live blue mussels (0.5–1.5 cm in shell height) for 10–20 days. Shell height of mussels was measured from umbo to rear (i.e. the longest dimension of the mussel). A series of repeated feeding trials were used to determine maximum mussel size vulnerable to predation in each goby size group. Each trial started by fasting fish for 48–72 h, where after live blue mussels from different 0.5 cm size classes, ranging from 0.5 to 3.0 cm in shell height, were presented to the gobies. To avoid that fish satiated on smaller mussels, the number of mussels was lower or equal to the number of fish in each experiment. When feeding activity ended, the remaining mussels were counted and measured. The trial protocol was repeated five times for each round goby size group to get repeated measurements and thereby reducing the observation error. If no feeding activity had taken place after 3 h, then observations were not included in the analysis (this happened in four out of 25 trials). Gape size (measured as the gape width in units of cm with 1 mm accuracy using a standard straight edge ruler) was measured on 63 fish, ranging from 10.0 to 16.0 cm in TL. All experiments were performed according to the national guidelines by the Danish Animal Ethics Committee for the care and use of laboratory animals.

The final dataset consisted of 365 observations, one for each mussel presented to the gobies. Each observation was dichotomous, i.e. ‘0’ if the mussel was eaten and ‘1’ if it was still there after feeding activity had ceased. Logistic mixed-effect models were fitted to data (five models in total, one for each round goby size group) to estimate the relationship between mussel size and the consumption probability. Trial number was treated as a random effect in the models and the models were created using the free statistical software R (The R Foundation, R 3.5, Vienna, Austria).
All logistic regression models revealed significant effects of mussel size (Table 1) on the probability of being consumed (see Fig. 1a). There was a significant positive relationship between the mean fish TLs (that represented the five size groups) and the estimated maximum sizes of mussels consumed (Linear regression-1: $F_{1,3} = 21.04$, $r^2 = 0.83$, $p = 0.02$). The relationship between fish TL and gape size (derived from 63 individual measurements) was also positive and significant (linear regression-2: gape size = 0.17 × fish length – 1, $F_{1,61} = 395.6$, $r^2 = 0.86$, $p < 0.001$).

Using the relationship between fish TL and gape size (regression-2), gape size for each of the five fish size groups was calculated (Table 1). The estimated maximum size of mussels consumed was then divided by the gape size to derive the prey size to gape size ratio, $r_{\max}$, which varied from 1.5 to 2 between the five round goby size groups (mean = 1.75 ± 0.25) (Table 1). Fish TL and $\mathrm{r}_{\max}$ were unrelated (linear regression-3: $F_{1,3} = 0.56$, $r^2 = -0.13$, $p = 0.51$). By inserting slope α (0.17) and intercept β (–1) from regression-2, and mean r_{max} (1.75) into Eq. 1, the relationship between predator length and $P_{\max}$ was modelled (Fig. 1b). Note that the intercept of the gape size vs. fish TL relationship was <0, indicating a different relationship may apply in early ontogenetic stages. Hence, the current model may only apply to adult round goby.

The present study is the first to provide a quantitative model of the maximum size of blue mussels likely to be consumed by round goby, $P_{\max}$. Furthermore, as has been shown in recent studies (including both zebra and quagga mussels: Nilsson & Brönmark, 2000; Naddafi & Rudstam, 2014; Schrandt, Stone, Klimek, Makelin, Heck, Mattila & Herlevi, 2016), the results also points to the conclusion that round goby has a preference for bivalves that are considerably smaller than $P_{\max}$ (i.e. see the probability curves in Fig. 1) .

Because of the constraints imposed by the experimental design, it is important to note that $P_{\max}$ applies only to situations with a wide range of mussel sizes available to the fish. Thus, if only larger mussels are available, and for prolonged periods without alternative prey, then $P_{\max}$ could potentially be higher. Alternatively, if large quantities of smaller mussels are present, then larger mussels are probably not selected even if they could technically be eaten. $P_{\max}$ may also be influenced by other factors than merely mussel size, e.g. shell morphology (varying amongst species) or shell thickness. Two studies using wild zebra mussels (having a more triangular shape as compared to blue mussels) from the Great Lakes found that round gobies of 10 cm in standard length (SL), consumed mussels up to 1.3 cm (Ghedotti, Smihula & Smith, 1995; Ray & Corkum, 1997). For round goby, 10 cm SL equals 12 cm TL (based on data used in Copp et al. 2008). Hence, the prediction made for a similar sized round goby in the present study (using Eq. 1) suggests that $P_{\max}$ is as much as 1.8 cm (using Eq. 1), thus demonstrating the potential effect of mussel morphology.

Round goby can grow substantially larger than the specimens tested in the present study, up to 20–25 cm TL (Azour et al. 2015). Thus, assuming $L = 20$ cm and $r_{\max} = 1.75$, blue mussels up to 4.2 cm may be at risk of predation by round goby (Eq 1.). Blue mussels rarely exceed lengths of 5 cm in the Baltic Sea and have a lower growth rate compared to in the North Sea (Riisgård, Lüskow, Pleissner, Lundgreen & López, 2013; Kautsky, Johannesson & Tedengren, 1990). This suggests that mussels in the Baltic Sea may be at risk of being preyed upon throughout most of their lifespan, although if smaller mussels are in plenty, this would substantially reduce the risk that the largest mussels are being consumed by round goby. Incorporating the present model into ecosystem models may enable estimations of trophic interactions between blue mussels and round goby and predict whether round goby populations can control, reduce, or alter the size composition of local blue mussel populations.

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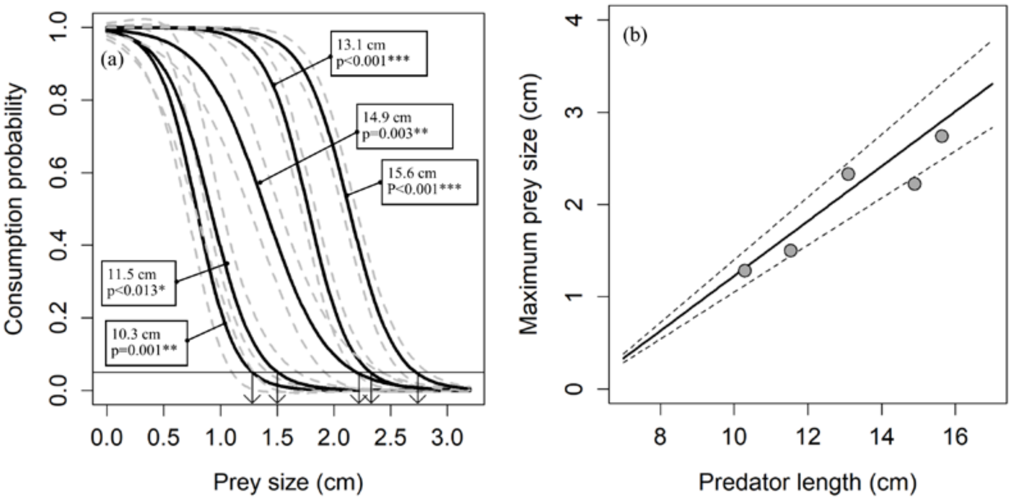

FIGURE 1. (a) The probability that a prey of a given size will be consumed. The prey is blue mussel *Mytilus edulis* and the predator is round goby *Neogobius melanostomus*. The five probability curves represent five fish size groups (mean total length [TL] of the size group and *p* values for each fit are indicated in boxes in the plot window). Prey size is the shell height of the blue mussel (measured from umbo to rear in cm). Arrows point to the maximum size of mussels consumed defined by the 5% probability cutoff. (b) Predicted maximum prey size (P_{max}) as a function of predator TL from the following model: $P_{max} = r_{max}\alpha L + r_{max}\beta$ (Eq. 1), where r_{max} is 1.75 (± 0.25) (black solid and dashed lines) and α and β are 0.17 and –1, respectively. Observed P_{max} are superimposed (grey points) to allow visual comparison between model predictions and empirical observations.