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The importance of rip-rap for round goby invasion success – a field habitat manipulation experiment

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Abstract. In a recent study, we showed how local-scale climate change impacts (increased temperature, reduced rainfall, shifts in peak rainfall) affected the hydrology of a channelised lowland European river (reduced flow, reduction in flood events, increased siltation, macrophyte growth), allowing native fish species to recolonise the bankside zone and reduce the density of invasive round goby *Neogobius melanostomus* by effectively removing its preferred habitat, rip-rap bank stabilisation. Here, we report on a follow-on study whereby stretches of the newly vegetated bank were stripped back to clean rip-rap to assess whether presence/absence of rip-rap was the major factor affecting non-gobiid, tubenose goby *Proterorhinus semilunaris* and round goby abundance. Our results confirmed rip-rap as a major factor increasing round goby abundance, and hence invasion success, on European rivers, while vegetated banks saw an increase in the abundance and diversity of non-gobiid species. While tubenose gobies showed no preference for habitat type, their numbers were significantly reduced in rip-rap colonised by larger and more aggressive round gobies. We discuss our results in light of recent artificial bank restoration measures undertaken on the Danube and Rhine and the potential role of round goby as a flagship species for cost-effective, large scale river bank restoration projects with multiple ecosystem benefits.

Key words: bank stabilisation, habitat preference, habitat restoration, invasive fish species, mitigation, potamalisation

Introduction

European rivers have been severely altered by anthropogenic activities over the last two hundred years (Dudgeon et al. 2006), with channelisation and replacement of natural shores with rip-rap bank stabilisation leading to a general decline in rheophilic species and an increase in eurytopic species (Ramler & Keckeis 2019). Further, rip-rap bank stabilisation has been directly implicated in the spread of some non-native invasive species, especially Ponto-Caspian gobiids such as the western tubenose goby

Proterorhinus semilunaris and round goby *Neogobius melanostomus* (Ray & Corkum 2001, Erős et al. 2005, Young et al. 2010, Janáč et al. 2012, 2018, Roche et al. 2013). While sub-optimal for many native European fish species, rip-rap represents optimal habitat for speleophilic species such as round goby, which use the interstitial spaces as shelter and spawning sites (Ray & Corkum 2001, Belanger & Corkum 2003, Young et al. 2010, Didenko 2013). These nest/shelter sites are then guarded aggressively by the male round goby, forcing other, less competitive, species away (Kornis et al. 2012).

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Ponto-Caspian gobiid species have greatly increased their ranges since the 1980s, with round gobies in particular now established in most major European rivers, e.g. the Rhine (Borcherding et al. 2011), Danube (Wiesner et al. 2000, Jurajda et al. 2005, Paintner & Seifert 2006, Roche et al. 2013) and Vistula (Grabowska et al. 2010). Round gobies have also been established in the Laurentian Great Lakes of North America since the 1990s, where their larger size and aggressive nest-guarding behaviour has had a significant impact on native benthic species, such as cottiids (Janssen & Jude 2001), through dietary/habitat competition and predation (Marsden & Jude 1995). While some detrimental impacts have been observed in some places (e.g. Barton et al. 2005, van Kessel et al. 2016, Jůza et al. 2018, Janáč et al. 2019), a number of studies have indicated that the effects of such impacts may be relatively mild or only temporary (e.g. Kornis et al. 2013, Janáč et al. 2016, 2018, Jůza et al. 2021), suggesting that round goby life-history traits and impacts cannot be generalised.

Until the late 1960s, the River Dyje (a side tributary of the River Morava (Czech Republic), a main tributary of the River Danube); was a slow-flowing lowland floodplain river with backwaters, meanders and associated standing waterbodies. The river was channelised between 1968 and 1982, during which the river banks up to the Nové Mlýny reservoir complex were stabilised with 30–80 cm rip-rap boulders. At this time, sediment was regularly flushed away by heavy rain and regular high spring discharges following snow melt, which kept the rip-rap and main channel largely clear of silt and vegetation. The channelisation process led to a loss of heterogeneous habitat (e.g. vegetation, riffles, slack water), floodplain connectivity and specialised breeding habitats (Roche et al. 2020) and, by the mid-2000s, rheophilic species had all but disappeared from the bankside community, to be replaced by low numbers of juvenile and small eurytopic and limnophilic species, with two widely established non-native species dominant, i.e. topmouth gudgeon *Pseudorasbora parva* and tubenose goby (Prášek & Jurajda 2005, Valová et al. 2006, Šlapanský et al. 2017).

Round gobies first appeared in the Slovak-Austrian stretch of the River Morava in 2006, and in the River Dyje in 2008 (Lusk et al. 2008), and aspects of invasive goby biology have been monitored annually on both the Morava and Dyje since that time (see Šlapanský et al. 2017). Soon after their

arrival, round goby numbers increased rapidly until they were the dominant species along the banks (Šlapanský et al. 2017). At the same time, tubenose goby (and topmouth gudgeon) numbers declined, most likely due to competition and predation. Numbers of predatory fish visiting the bankside increased markedly over this same period as they adapted to foraging on the now dominant round goby (Mikl et al. 2017, Všeticková et al. 2018, Ramler & Keckeis 2019). From 2014 onward, however, round goby numbers appeared to decline rapidly, while tubenose goby numbers increased markedly (Roche et al. 2020). Roche et al. (2020) were able to demonstrate that local-scale climate change impacts (increased temperature, reduced rainfall and shifts in peak rainfall) had affected the hydrology of the River Dyje (reduced flow, reduction in flood events and increased siltation, resulting in extensive macrophyte growth), allowing eurytopic, phytophilic and limnophilic fish species, including tubenose goby, to recolonise the bankside zone. At the same time, the density of invasive round goby declined due to the effective loss of its preferred rip-rap habitat.

These findings strongly suggest that a) habitat preference, and specifically presence of rip-rap, plays a major role in the invasion success of round goby in European channelised rivers, and b) that loss of habitat and shelter played a stronger role in native species decline along this channelised stretch than invasion of round goby. In an effort to confirm these findings, we undertook a follow-on study based on controlled bank habitat manipulation to test the hypothesis that removal of siltation and vegetative growth (i.e. reestablishment of rip-rap) would reverse this process (i.e. increase round goby and reduce non-gobiid density), thereby confirming a strong preference or avoidance of rip-rap by the different fish groups, i.e. round goby, tubenose goby and non-gobiid species. This could also provide strong support for river bank naturalisation along channelised stretches as a means of i) mitigating against the invasion of round goby, and ii) increasing the density and abundance of native eurytopic, phytophilic and limnophilic fish species.

Material and Methods

Study area

Following its channelisation between 1968 and 1982, the River Dyje had a channel width of 40 m, a depth of 0.5–1.0 m and an annual mean discharge

rate over the study stretch of $41.7 \text{ m}^3 \cdot \text{s}^{-1}$ (Czech Hydrometeorological institute; <http://portal.chmi.cz>). The bottom substrate comprised sand, gravel and pebbles, with occasional woody debris and pools and riffles occurring rarely. While current velocity along the banks rarely exceeded $0.4 \text{ m} \cdot \text{s}^{-1}$, sediment was regularly flushed away by flooding and high spring flows, ensuring the main course and rip-rap banks remained virtually clear of vegetation year round.

Since 2014, a series of exceptionally dry years and a shift in peak rainfall has affected the river's hydrological regime, resulting in lowered water levels, reduced flow rates and a lack of flood events. A subsequent increase in siltation along the banks covered the rip-rap, which quickly became overgrown with filamentous algae and aquatic and riparian vegetation, especially reed canary



Fig. 1. Illustration of a vegetated stretch (left) and cleared stretch (right) of rip-rap bank stabilisation along the River Dyje (Czech Republic), used for testing preference or avoidance of rip-rap by three fish groups, i.e. round goby, tubenose goby and non-gobiid species.

Table 1. Fish assemblages (ind./100 m and relative frequency (RF%)) for the River Dyje (Břeclav) i) at peak round goby density (2013), and ii) four years after bankside potamalisation began (2017). * Occurs infrequently over the study period. Dominant species (> 10% RF) in bold. Table adapted from Roche et al. 2020.

Common name	Latin name	2013		2017	
		Ind./100m	RF%	Ind./100m	RF%
round goby	<i>Neogobius melanostomus</i>	56	59.9	12	5.4
bleak	<i>Alburnus alburnus</i>	2	2.1	99.3	44.7
silver bream	<i>Abramis bjoerkna</i>	1	1.1	1.3	0.6
Prussian carp	<i>Carassius gibelio</i>			18.7	8.4
common carp	<i>Cyprinus carpio</i>			1.3	0.6
perch	<i>Perca fluviatilis</i>	6.5	7.0	1.3	0.6
tubenose goby	<i>Proterorhinus marmoratus</i>	17	18.2	42.7	19.2
topmouth gudgeon	<i>Pseudorasbora parva</i>			0.7	0.3
roach	<i>Rutilus rutilus</i>	3	3.2	2	0.9
European catfish	<i>Silurus glanis</i>	1	1.1	1.3	0.6
pumpkinseed	<i>Lepomis gibbosus</i>			8.7	3.9
bitterling	<i>Rhodeus amarus</i>	5	5.3	6.7	3.0
rudd	<i>Scardinius erythrophthalmus</i>			0.7	0.3
barbel	<i>Barbus barbus</i>			1.3	0.6
white-fin gudgeon	<i>Romanogobio albipinnatus</i>			2	0.9
chub	<i>Squalius cephalus</i>			22	9.9
ide	<i>Leuciscus idus</i>	0.5	0.5		
burbot	<i>Lota lota</i>	1.5	1.6		
spined loach	<i>Cobitis taenia</i>	*			
zingel	<i>Zingel zingel</i>	*		*	
vimba	<i>Vimba vimba</i>	*		*	
Total ind./100 m		94		222	
Total species		10		16	

grass *Phalaris arundinacea* (see Fig. 1; for a more detailed overview of hydrological changes related to climate change on the study stretch, see Roche et al. 2020).

The River Dyje has a relatively diverse fish assemblage, originally dominated by native cyprinid species such as roach *Rutilus rutilus*, chub *Squalius cephalus*, common bream *Abramis brama*, barbel *Barbus barbus*, bleak *Alburnus alburnus*, European bitterling *Rhodeus amarus* and white-finned gudgeon *Romanogobio vladkovi* (Valová et al. 2006). By 2009 (post-channelisation), the bankside community comprised low numbers of juvenile and small eurytopic and limnophilic native species, with two widely established non-native species, topmouth gudgeon and tubenose goby, dominant (Table 1; Prášek & Jurajda 2005, Valová et al. 2006, Šlapanský et al. 2017).

Sample site preparation

The habitat manipulation experiment was undertaken between May 18 and November 9, 2019, with five separate sampling episodes taking place a minimum of three weeks apart (to allow for assemblage recovery) during periods of comparable discharge. The study stretch was chosen to be as homogenous as possible, with depth ranging from 50–80 cm, rip-rap comprising a mixture of 30–80 cm boulders and similar vegetation cover throughout. The study stretch was subsequently divided into 26 × 10 m sections, each section being clearly marked by coloured stakes on the shore to ensure that the same sites could be sampled/cleaned repeatedly. For half of the sections (i.e. 13 of 26 sections;

spaced alternately), the bank and the flooded part of the rip-rap bank were cleansed of vegetation (including all root material and any woody debris or anthropogenic material) using hoes, rakes and spades, after which the exposed rip-rap was thoroughly cleansed of silt and mud using buckets of water (see Fig. 1). The first fish sampling took place 11 days after the initial cleaning, and the rip-rap was washed again to remove silt at least one week before each subsequent fish sampling period ($n = 5$). The remaining 13 vegetated sections were not modified in any way.

Fish sampling and data analysis

Fish were sampled from each alternate test section by electrofishing, using a portable backpack unit (SEN, R. Bednář, Czech Republic; frequency 75–85 Hz; maximum output 225/300 V) fitted with a small elliptical stainless-steel anode (25 × 15 cm) fitted with a 4 mm mesh net (see Janáč et al. 2016 for further details). Based on our own long-term experience, electrofishing by slow wading upstream along the bank has proved to be the most effective method for catching all age-classes of fish inhabiting the littoral riprap. Electrofishing of the nearshore zone is a reliable and commonly used method for sampling not only round goby assemblages (Brandner et al. 2013) but also for describing riverine fish communities in general (FAME Consortium 2004). As the river is relatively shallow (max. depth 0.6 m along sampled sites), we were able to sample the whole nearshore water column covering the whole rip-rap zone in this stretch of the river. Earlier observations (using angling, traps and electrofishing) found

Table 2. Results for GLMM predicting effect of site type (cleaned/vegetated) on four response variables (abundance of round goby, tubenose goby and non-gobiid species and richness of non-gobiid species). Each model was based on 130 observations and used date and site identity as random factors; negative binomial distribution detected for first three models, Poisson for non-gobiid species richness.

Response	Term	Estimate	SE	z value	P
round goby	intercept	2.35	0.40	5.79	< 0.001
	type	−1.05	0.14	−7.43	< 0.001
tubenose goby	intercept	2.57	0.40	6.35	< 0.001
	type	−0.02	0.10	−0.203	0.839
non-gobiids	intercept	1.99	0.15	13.23	< 0.001
	type	0.44	0.19	2.34	0.019
non-gobiid richness	intercept	0.91	0.12	7.87	< 0.001
	type	0.33	0.10	3.30	< 0.001

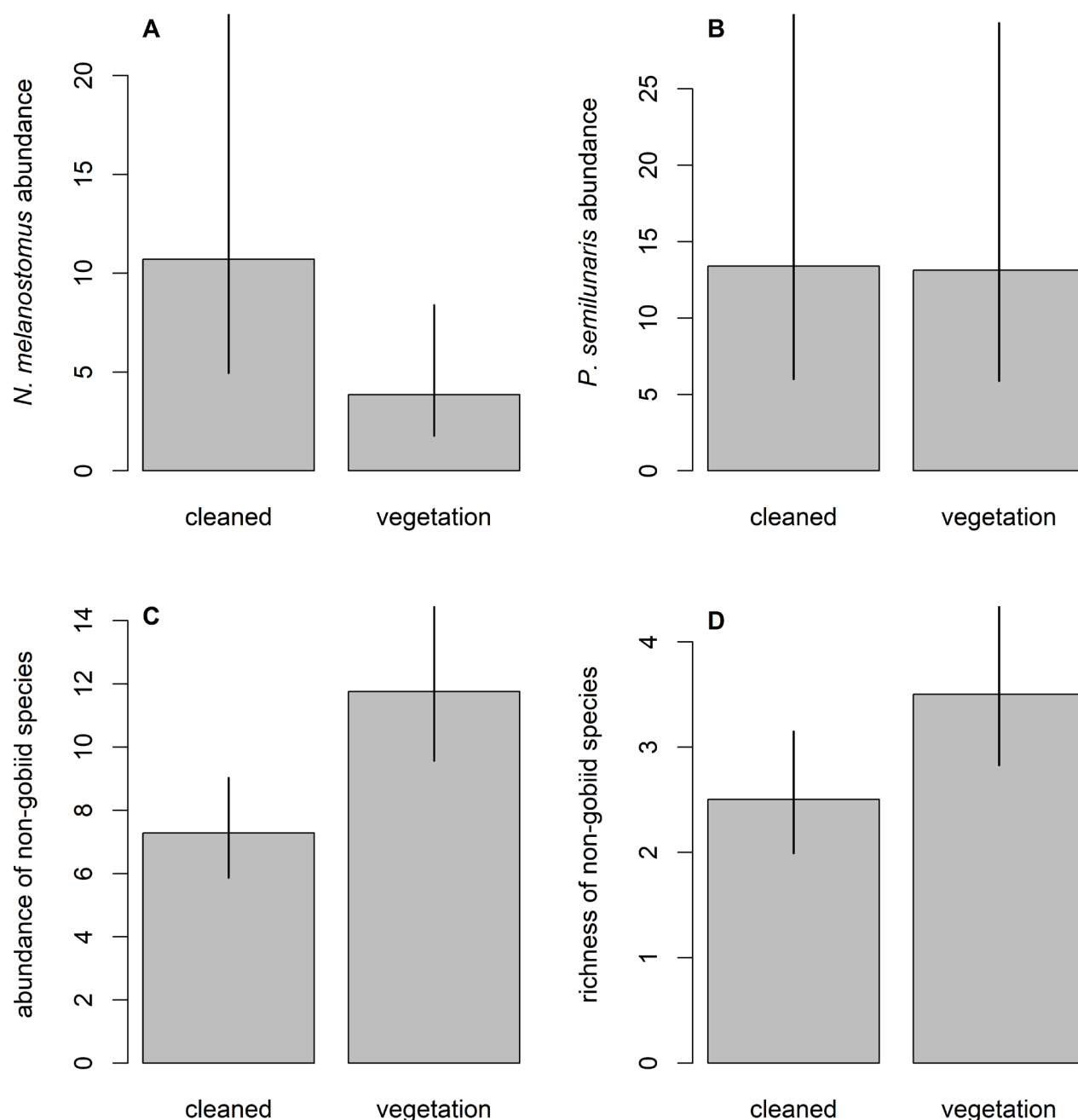


Fig. 2. Abundance of A) round goby *Neogobius melanostomus*, B) tubenose goby *Proterorhinus semilunaris*, C) non-gobiid species, and D) non-gobiid species richness at cleaned and vegetated sites, as predicted by GLMM (negative binomial distribution detected for A-C, Poisson for D). Vertical lines represent 95% confidence intervals.

no evidence of round gobies on the sandy bottom in the middle of the river. Sampling always took place during the day between 9:00 and 17:00 and all sampling runs were performed by the same person to eliminate personal error. Fish collected from each section were placed into individual buckets and, at the end of the marked section, handed to assistants on the bank for further analysis. All fish captured were measured for standard length (SL) to the nearest 1 mm. Round gobies were sexed based on their urogenital papilla. Small individuals with indistinguishable papilla (SL < 40 mm) were

identified as juvenile. After measurement, all fish were released back into the middle of the section from which they were caught.

Data analysis

Generalised linear mixed models (GLMM) were used to test for differences in the abundance of round goby, tubenose goby and non-gobiid species (pooled) and in richness of non-gobiid species (pooled) between vegetated and cleaned sites. In each case, negative binomial distribution was detected for abundance and Poisson for richness.

Site identity and date were set as random factors in each model. All analyses were conducted using R v. 3.5.2 (R Core Team 2018).

Results

The effect of cleaning was apparent in the abundance of all three fish groups tested, with the abundance of round goby being significantly higher at cleaned sites than vegetated sites (GLMM, $n = 130$, $P < 0.001$), while the opposite held true for the abundance and richness of non-gobiid species (GLMM, both $n = 130$, $P = 0.019$ and $P < 0.001$, respectively). Surprisingly, there was no difference in the mean abundance of tubenose goby between cleaned and vegetated stretches (GLMM, $n = 130$, $P = 0.839$; Fig. 2, Table 2).

Discussion

This study clearly confirmed the affinity of round goby to rip-rap habitat and, by implication, its important role in the species' spread across Europe. It has been recognised for some time that rocky habitats are readily colonised by round goby, and that shores stabilised with rip-rap have contributed significantly to their establishment and spread along large channelised rivers (Ray & Corkum 2001, Erős et al. 2005, Wiesner 2005, Poláček et al. 2008, Roche et al. 2013). While sub-optimal for most native European fish species, rip-rap represents optimal habitat for speleophilic species such as round goby, which use the interstitial spaces as shelter and spawning sites. Such sites are then guarded aggressively by the large territorial males, forcing smaller or less competitive individuals away. It should be noted that round gobies are capable of utilising a range of other habitats, from lakes and reservoirs (e.g. Didenko 2013, Bhagat et al. 2015) to shallow gravelly or silty stretches (e.g. Taraborelli et al. 2009), however, in such cases, while juveniles are widely found in habitats with coarse to fine substrates and sparse vegetation, older juveniles and adults always show a preference for coarse substrates such as stony litter, rock formations and rip-rap (Leslie & Timmins 2004, Didenko 2013). This is further supported by our own study, where round gobies were caught in both cleared and vegetated stretches, but were caught significantly more often in the cleared rip-rap habitat (Fig. 2, Table 2), and were always found at significantly higher abundances (see Roche et al. 2020). While we cannot exclude the possibility that the trends observed were caused by differences in

electrofishing catch efficiency in the two habitat types, use of other sampling methods on the study stretch, such as angling (data not presented), gave very similar results, suggesting that the observed differences were in fact due to habitat preference and not sampling selectivity.

Our study also confirmed that non-gobiid species (both native and non-native) tended to avoid the rip-rap in preference of the silted/vegetated stretches (Fig. 2), with both abundance and diversity significantly higher in the latter (Tables 1 and 2; see also Šlapanský et al. 2017, Roche et al. 2020). While it might be argued that small non-gobiid species could have been outcompeted by the larger and more aggressive round goby in the rip-rap, forcing them to use the vegetated areas instead, this is highly unlikely, not least as most of the species using the vegetated stretches were eurytopic, limnophilic and, especially, phytophilic/phyto-lithophilic species (Table 1) that tend to naturally avoid rip-rap and/or prefer complex vegetated habitats that provide food, shelter and nursery/spawning habitat (Šlapanský et al. 2017, Roche et al. 2020). On the other hand, they could be preventing spread into the rocky stretches from the vegetated areas. It is now well known that channelisation and replacement of natural shores with rip-rap bank stabilisation provides sub-optimal habitat for most European native fish species, leading to community guild shifts such as rheophilic species being replaced by eurytopic species (e.g. see Ramler & Kackeis 2019). Indeed, this was precisely the situation found along the River Dyje before the round goby had even arrived on the river in 2008 (Roche et al. 2020).

In this study, tubenose goby showed an equal preference for rip-rap and vegetation (Fig. 2, Table 2). Intuitively, one might have expected the smaller tubenose goby to be outcompeted by the larger, more aggressive round goby, forcing it to use the vegetation more. Indeed, this is what we expected based on the shift in dominance observed when round goby first entered the system (Šlapanský et al. 2017, Roche et al. 2020). Cartwright et al (2019), in a recent laboratory-based study, were able to demonstrate that while tubenose goby were habitat generalists, they did spend more time in vegetation (see also Janáč et al. 2012, Ondračková et al. 2019), and that they would spend more time defending plant shelters than rock shelters, particularly against other tubenose gobies, with the result that the "resident" fish usually won.



In interspecific pairings, however, round goby almost always displaced resident fish, confirming its greater aggression. Interestingly, round gobies spent similar amounts of time in both habitat types, however, those in the vegetation were very often female, while those in the rocks were mainly male (Cartwright et al. 2019). As the mean size of fish used in these experiments ranged between 4.9 and 6.1 cm, this suggests that male round gobies begin acquiring and defending potential nest sites as soon as they reach sexual maturity (i.e. SL50 ca. 4.9 cm; see Konečná et al. 2014). The same authors were also able to show that tubenose gobies tended to be more nocturnal (see Błońska et al. 2017), using rock shelters more at night, while round goby spent more time in rock shelters during the day. While we did not set out to measure competitive interaction between these species, the findings of Cartwright et al. (2019) match well with our own observations, with both species being found in both habitats (Fig. 2) but with tubenose goby numbers significantly reduced in rip-rap colonised by larger and more aggressive round gobies. As tubenose gobies again became dominant when vegetation replaced rip-rap (see Roche et al. 2020), this strongly suggests that round goby outcompete tubenose gobies where rip-rap is the dominant habitat. As such, our experiment provides actual field evidence to support the laboratory findings of Cartwright et al. (2019). Finally, successful invaders are generally characterised by a range of life history traits, including habitat plasticity (Marchetti et al. 2004). Both our own findings (Šlapanský et al. 2017, Roche et al. 2020, this study) and those of Cartwright et al. (2019), indicate that presence of rip-rap is the main factor limiting eurytopic, limnophilic and phytophilic fish presence/abundance along the shoreline, irrespective of goby presence, and the main factor affecting the invasive success of gobies, with the more specialist and more aggressive round goby flourishing and outcompeting other species in rip-rap, but generalists such as tubenose goby flourishing when the rip-rap is covered with fine substrate and vegetation.

Our recent work on the River Dyje has shown how “natural” potamalisation processes brought about by climate change (see Roche et al. 2020) greatly improved the abundance and diversity of native and naturalised eurytopic, limnophilic and, especially, phytophilic/phyto-lithophilic species along the river bank by improving habitat variability and providing food, shelter and nursery/spawning habitat for small adults and juveniles. At the same

time, loss of its preferred habitat (rip-rap) resulted in a dramatic decline in round goby abundance. This suggests two things: first, that some effects of climate change may actually prove beneficial on a local scale (Roche et al. 2020), and second, that directed habitat modifications during river restoration programs could not only increase the abundance and diversity of native species but also provide a useful indirect method for mitigating the potential impacts of invasive round goby, or even prevent the establishment of the species in those rivers it has yet to invade.

A number of recent studies have shown how carefully directed river restoration measures can benefit native species and/or suppress round goby. Dorenbosch et al. (2017), for example, demonstrated how the placement of large woody debris in the heavily regulated Dutch River Rhine facilitated rapid colonisation of both fish and macroinvertebrate species and significantly increased fish density compared with rip-rap zones. The authors concluded that addition of woody debris served a range of ecological functions, ranging from fish nurseries to food web catalysts, and that woody debris was a “cost-effective management tool to stimulate aquatic fauna”. Round goby, which are also established along the Rhine, were unable to benefit from the new habitat as they are primarily bottom dwellers that require rocky substrate. Whereas the study of Dorenbosch et al. (2017) improved conditions for non-gobiid species at the expense of round goby, that of Ramler & Keckeis (2019) specifically investigated the effects of different restoration methods (side arm reconnection, groyne modification, groyne removal/gravel replacement) on the occurrence and abundance of non-native gobiids along the Danube. The authors noted that while small round gobies were able to utilise vegetation in the side channels (similar to our slow flowing vegetated banks) and adjusted groyne fields, replacement of groynes or rip-rap by gravel banks resulted in a significant reduction in the abundance of all gobiid species, and especially round goby.

This growing body of evidence suggests that shoreline modification has high potential for controlling invasive species, and particularly round goby. However, as outlined above, care needs to be taken in the type of intervention planned as they can be highly species or size/age specific. Furthermore, recent studies have shown that gobies are quite capable of overcoming barriers such as dams and

weirs during upstream colonisation (e.g. Roche et al. 2015) and may also be transported over long distances to new sites via anthropogenic means (Janáč et al. 2017). Indeed, despite the dramatic fall in abundance of round goby along our study stretch following potamalisation of the rip-rap, adult gobies were caught 12 km upstream in a surviving patch of rip-rap just one year after the population crashed (Roche et al. 2020), showing it is quite capable of crossing large distances over unfavourable habitat (Šlapanský et al. 2017, 2020). This suggests that any bankside restoration measures aimed at controlling round goby would have to be large-scale, which could make them very expensive. An alternative might be multiple shorter stretches, with vegetated silt/gravel banks alternating with rip-rap, which would reduce the overall abundance of both round and tubenose goby, while also improving conditions for non-gobiid species. This would be a cost-effective means of providing multiple ecosystem benefits for a wide range of species, particularly if different

restoration techniques are used in conjunction (e.g. woody debris, addition of gravel riffles, shallow areas, etc.). One could even envision the round goby becoming a flagship species for encouraging bankside restoration measures along channelised rivers.

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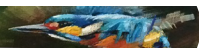
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