Population ecology of sand gobies (*Pomatoschistus minutus*) in a newly-restored Danish coastal environment, Gyldensteen Lagoon

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Introduction

Successful restoration of coastal habitats requires an understanding of variation in the processes that underpin population recovery. The sand goby is an abundant demersal fish along northern European coasts, and ideal for determining how coastal fish population colonise and use restored environments. The coastal Gyldensteen Lagoon on the Danish Island of Fyn was re-flooded in 2014, and current SDU research is seeking to understand the re-establishment of marine biodiversity and food-webs. Here, we measured sand goby population structure, habitat associations, dietary variation with ontogeny and in space and time, and the presence of microplastics in fish from Gyldensteen Lagoon. Data were collected in summer 2018 and autumn 2019. Population structure and habitat associations were also examined at two other nearby coastal lagoons (Nærå Strand and Odense Fjord) to place the seasonal Gyldensteen recruitment in a broader context.

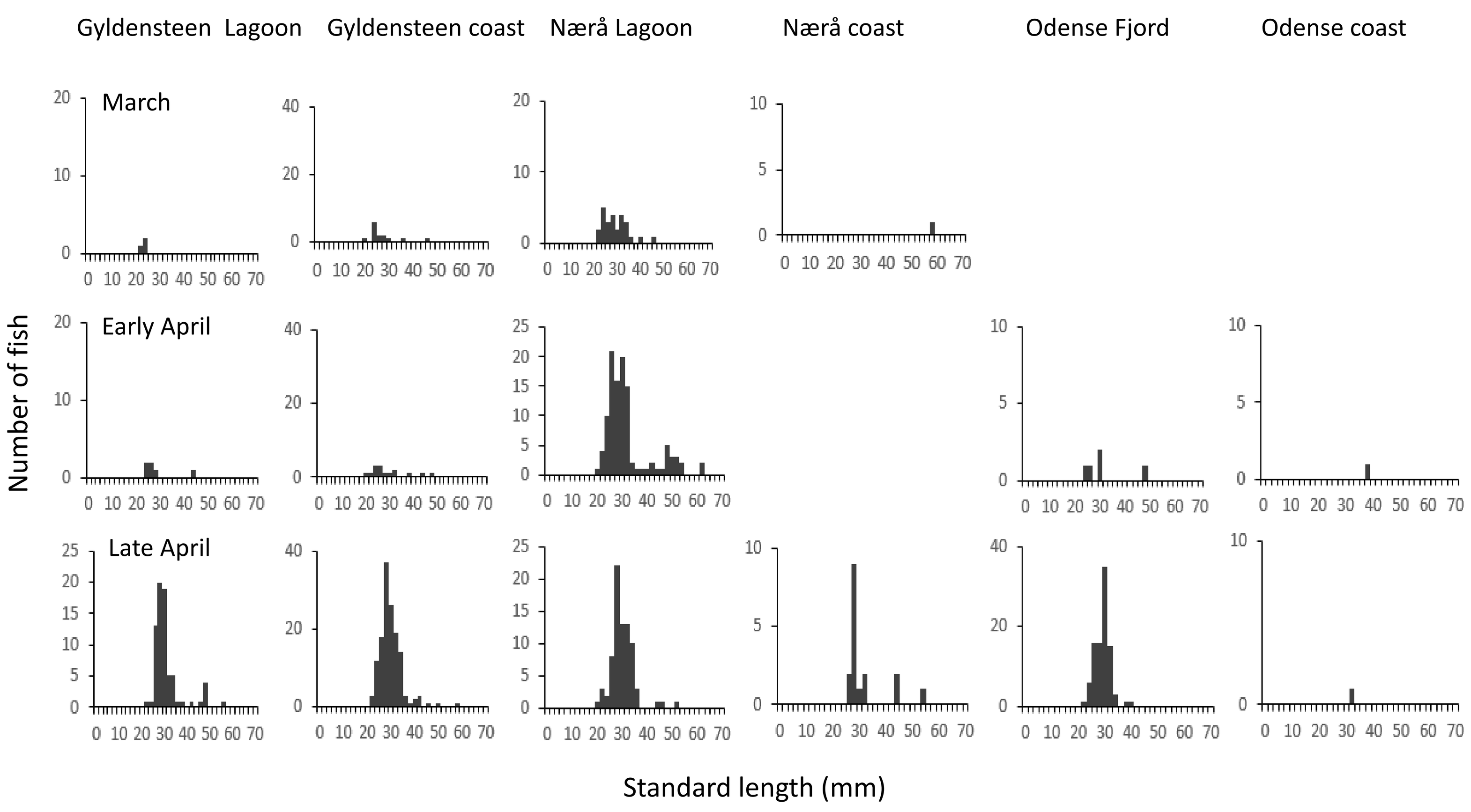
Sand goby, *Pomatoschistus minutus*

The flooding of Gyldensteen Lagoon in 2014 (left), and the present-day coastal lagoon (right)

Population structure

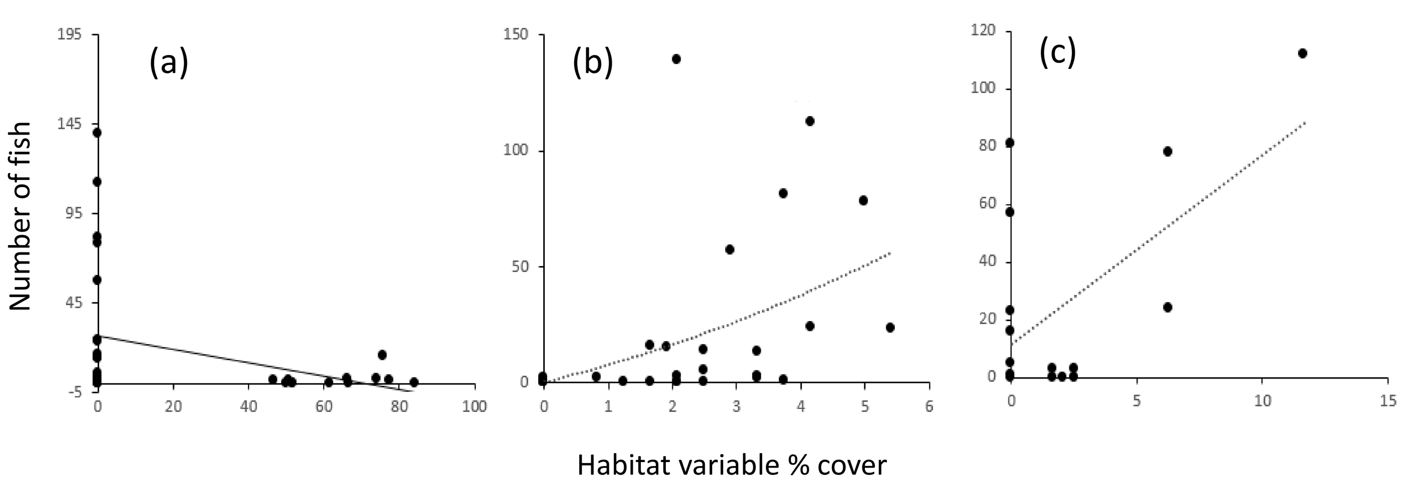
In 2019, sand goby arrival at the three study locations varied from late February or early-March (Gyldensteen, Nærå) to late March (Odense), and largely comprised a single cohort – likely spawned in 2018 (figure below). A weaker cohort of larger fish was seen at some sites (e.g. Nærå Lagoon, Early April), but diminished over time. Abundances were highest in the lagoon at Nærå and Odense, but were similar between the lagoon and coastal sites at Gyldensteen.

Ovary development (Gonadosomatic Index, GSI) among locations in 2019 tracked water temperature, although spawning had not commenced by late April. Across lagoon sites, mean GSI increased from 3.2% in March to 14.8% by late April. At the Gyldensteen coast sites, mean GSI increased from 4.3% in March to 12.9% in late April. Mean GSI within Gyldensteen Lagoon was around half that of the other two sites in early April, but the three locations had overall similar levels by late April (Gyldensteen 10.6%, Odense 12.3%, Nærå 12.9%). At Gyldensteen, mean GSI in early and late April was slightly higher in fish from the coastal sites than in the lagoon.



Habitat associations

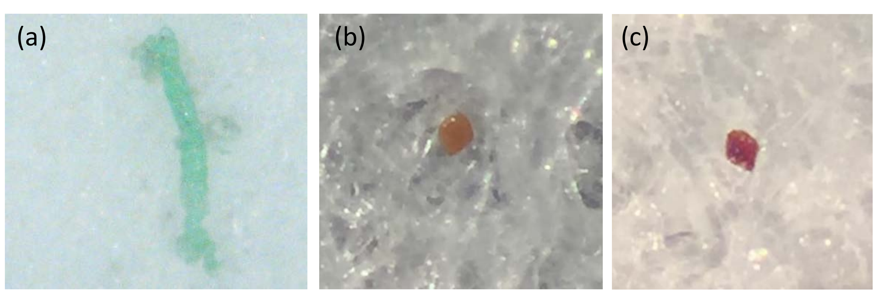
Multiple regression analyses were used to examine links between physical habitat and sand goby abundances across both the coast and lagoon sites. A weak negative relationship was found with percent cover of fine sand (adjusted $R^2 = 0.088$, a below) and a stronger and positive relationship with percent cover of mussel shells (adjusted $R^2 = 0.180$, b below) across both lagoon and coastal sites. In contrast, when sand goby habitat associations were examined across just the five lagoon sites, a significant positive relationship was found between fish abundances and the percent cover of large stones (200–399 mm diam. adjusted $R^2 = 0.304$, c below).



Microplastic contamination

The presence of microplastic pieces was examined for sand gobies sampled at Gyldensteen (two lagoon sites, 1 adjacent coastal site) in July and August 2018. Overall, microplastic pieces were found in the digestive tracts of 15.1% of individuals and in the other body tissues of 7.1% of fish. In total, 20.3% of sand gobies from Gyldensteen contained some type of microplastic in them. The most abundant type of plastic was red particles, both in digestive tracts and bodies (table below). Within the two lagoon sites, 22.1% of fish had microplastic in their digestive tract, compared to 12.9% of fish from the open coast site.

Shape	Colour	Digestive tract (%)	Body (%)
Fibre	Green	1 (0.5)	1 (0.5)
Pellet	Purple	1 (0.5)	1 (0.5)
	Transparent w. blue dots	4 (1.9)	2 (0.9)
Particle	Red	15 (7.1)	3 (1.4)
	Green	3 (1.4)	1 (0.5)
	Orange	5 (2.4)	1 (0.5)
	Yellow	4 (1.9)	
	Black	1 (0.5)	
Film	Transparent	1 (0.5)	1 (0.5)
Fragment	Black w. glitter	2 (0.9)	1 (0.5)
	Blue/black-mix	1 (0.5)	1 (0.5)
	Red/black-mix	1 (0.5)	
	Red/blue/black-mix	1 (0.5)	
	Blue/white-mix		1 (0.5)
	Blue/green-mix		2 (0.9)
	Black/transparent-mix		1 (0.5)
Thread	Transparent		1 (0.5)
Total		**40**	**17**

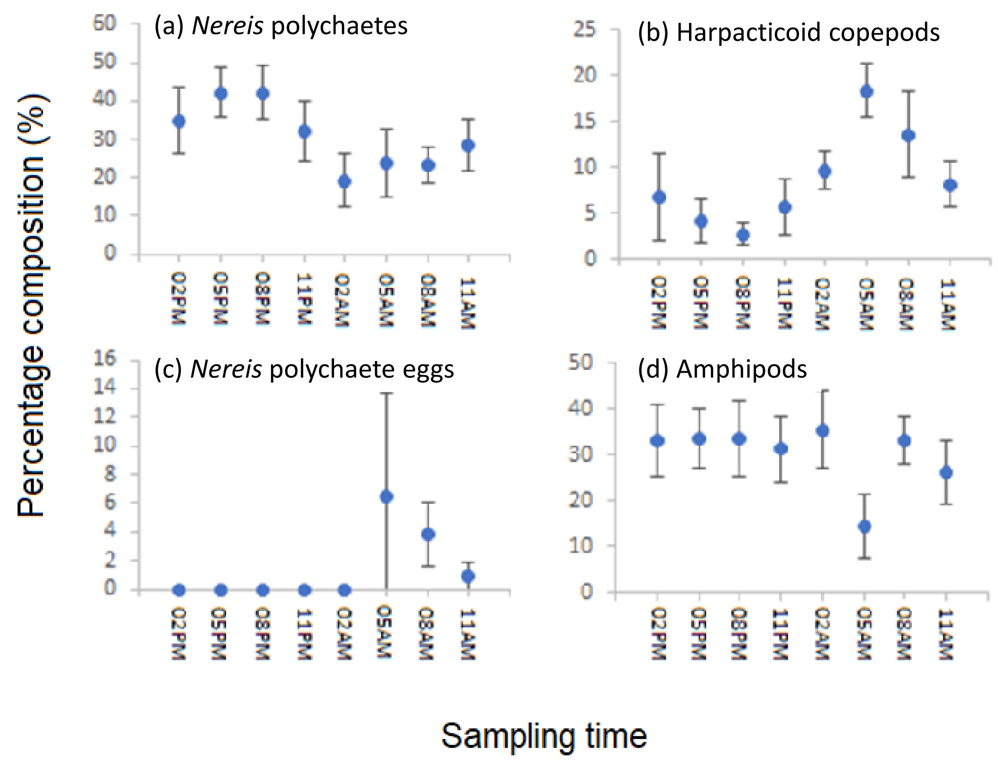


Examples of microplastic pieces from sand goby digestive tracts. (a) green fibre, (b) orange particle, (c) red particle.

Dietary variation

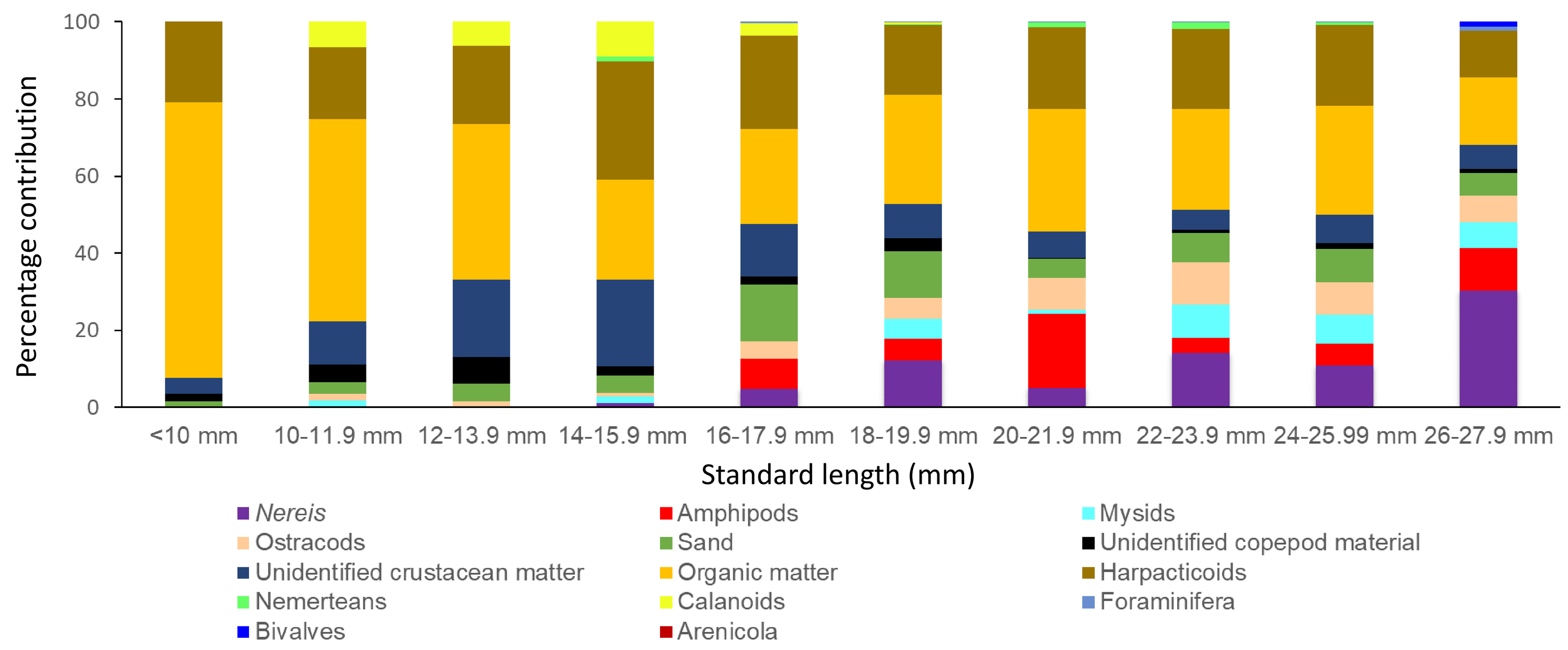
The overall gut content composition at Gyldensteen was dominated by *Nereis* polychaetes, amphipods, harpacticoid copepods and unidentifiable organic matter (collectively, 68.2%). Significant spatio-temporal variation was detected between three sites (coast, two lagoon sites) and two months (July, August 2018). SIMPER analyses found that the difference between months was mostly due to a shift from *Nereis* and harpacticoids in July to amphipods, ostracods, mysids and unidentified crustacean material in August. The SIMPER analysis of site variation found that crustacean material was more important in the diet of open coast fish while *Nereis* and ostracods were more important to the diet of fish within the lagoon.

Diet shifts were also evident over a single diel cycle (figure below). Feeding on *Nereis* polychaetes appeared largely confined to daylight periods, while a prominent shift in feeding was detected at dawn: predation on *Nereis* eggs, a peak in the contribution of harpacticoid copepods, and a brief decline in the presence of amphipods in gut contents. Multivariate analyses (ANOSIM) found that the strongest dietary differences were between the afternoon and dawn samples or between early daylight and late morning.

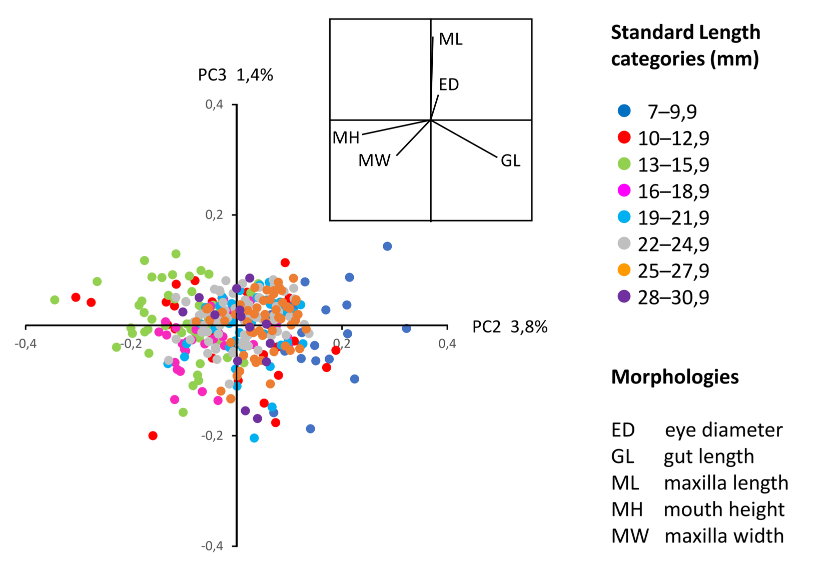


Diet components for which a diel shift in prey contribution was evident.

Diet shifts were also detected with increasing body size in fish 7.5 to 27.9 mm SL. Diet shifts at between 15 and 17.9 mm SL (bar graphs below). Fish smaller than 10 mm had a diet mostly consisting of harpacticoid copepods and unidentified organic matter, whereas fish between 10 and 16 mm also had an increasing presence of calanoid copepods, unidentified crustacean matter and sand. At around onset of the demersal lifecycle, fish > 16 mm SL shifted their diet towards *Nereis*, ostracods, amphipods and mysids, and also had an increased in the level of sand, along with a reduction or absence of calanoids.



We also examined changes in food-processing morphologies among 2.9 mm size-classes to establish how these might help drive ontogenetic dietary shifts, using principal components analysis (figure below). Larval fish had a disproportionately long gut, pelagic juveniles (10 to 15.9 mm SL) had a disproportionately large mouth width and height, and fish ≥ 25 mm SL had disproportionately long maxillae and larger eyes. Size-classes above 16 mm showed less morphological variation, suggesting that morphological development slows at around 16 mm when individuals begins to transition to the benthic environment.



Conclusion

Our data confirm that functional fish populations can establish within restored coastal environments, and that recognizing habitat variation and structure is important in determining adaptations and diet composition.

An onshore migration of sand gobies was evident along the coast of northern Fyn, similar to that observed previously along the Netherlands coast. The population at all Fyn locations was dominated by a single cohort throughout the entire sampling period, suggesting that the species largely has an annual lifecycle in Denmark. Although habitat associations were weak, patterns with fine sand and mussel shells in particular were thought to reflect the sand goby's preference for silty substrates and their use of mussel shells for shelter and nesting sites.

As habitats change during migration and with ontogeny, shifts in diet composition were also expected. Significant changes in diet composition were observed between different lifecycle stages, but also between nearby locations (150 to 400 m apart) and consecutive summer months. Clearly, fine-scale patterns need to be accounted for when seeking to understand how fish utilise environments such as Gyldensteen. Moreover, the sigificant presence of microplastics in Gyldensteen fish indicates that restoration efforts need to consider external factors such as this when assessing biotic responses.

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