The challenge of economically viable aquaculture of the cold-water sea cucumber *Parastichopus tremulus* in Norway

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Abstract

The cold-water sea cucumber *Parastichopus tremulus* has been identified as a potential aquaculture candidate for sea ranching and integrated aquaculture, mainly due to its high market value. Success, however, depends on whether economically viable growth and survival rates can be achieved during the different life stages. Results from preliminary studies on this species' behaviour in captivity related to feeding and physiology are used to evaluate a probable production time to commercial size and the species' suitability in integrated aquaculture systems.

Keywords: Norwegian red sea cucumber, *Parastichopus tremulus,* biology, growth, aquaculture, IMTA

Introduction

Cold temperatures and slow growth are challenges to cultivating marine species at high latitudes. Seasonal variations in particular influence which species and which life stages can be grown extensively or semi-intensively in the sea or in land-based systems supplied with natural seawater. Low trophic species such as bivalves and macroalgae are typically grown in sea-based systems, utilising only the food produced by nature itself. Even though Norway has a long tradition of cultivating cold-water fish species, the aquaculture of invertebrate species is less developed and characterised by boom-and-bust cycles, depending partly on varying growth conditions, but also due to immature farming practises and obstacles in business development. It is a long-term goal of the Norwegian government to diversify the species that are cultured, and the red sea cucumber, *Parastichopus tremulus,* is among the species listed as a new marine species with the potential for aquaculture in Norway (Akvaplan-niva 2019). A recent review of North Atlantic sea cucumber aquaculture prospects by Landes et al. (2019) concluded that monoculture, polyculture and integrated multi-trophic aquaculture (IMTA), including with *P. tremulus*, could be strategies for diversifying Norwegian aquaculture production. However, biological and technical constraints related to life in captivity still hinder the next step forward in developing a sea cucumber industry based on this species (Christophersen and Sunde 2021). Further substantial research efforts are required to fill the knowledge gaps related to the reproduction, growth and development stages, nutritional requirements, water quality and environmental conditions, all of which are crucial for building a sustainable industry.

Parastichopus tremulus – a suitable deposit-feeding species in integrated aquaculture systems?

The ability of deposit-feeding sea cucumbers to feed on particulate organic waste produced by, for example, mussel farming (Zamora and Jeffs 2011) has led to interest in research on the potential of combining sea cucumber culture with the aquaculture of other species, either in polyculture or more tightly integrated IMTA systems (Zamora et al. 2018). The inclusion of deposit-feeding organisms in mathematical IMTA models opens possibilities for optimising production in integrated aquaculture systems (Cubillo et al. 2016). In Norway, the aquaculture industry is dominated by the aquaculture of salmonids (Atlantic salmon, rainbow trout and trout), which in 2020 reached an output of 1.48 million tonnes (Norwegian Directorate of Fisheries 2021). In comparison, the aquaculture of molluscs, crustaceans and echinoderms is marginal, with a total annual production of only 2071 tonnes (Norwegian Directorate of Fisheries 2021). There has been an increased interest in recent years in integrating the farming of seaweed and other low trophic species with existing salmonid farms to create IMTA systems.

Atlantic salmon and rainbow trout production in Norway takes advantage of the geographical features of Norway's long sheltered coast and uses open cage systems located in areas of good water quality. Feed waste from open cage-based fish farms is continuously being reduced due to technological innovations, but fish farms still release substantial amounts of dissolved nutrients and particulate matter annually. In addition, land-based aquaculture systems face the problem of accumulation of particulate waste (sludge). This waste represents a potential feed resource for suspension-feeding species as well as deposit-feeding lower trophic species. Research on other species as "add-ons" to salmonid aquaculture in Norway has, to a large extent, focused on macroalgae, blue mussels, polychaetes and ascidians, whereas comparatively little has been carried out on sea cucumbers. The inclusion of sea cucumbers in IMTA systems has the potential to decrease the sediment and nutrient loads to the environment, thus contributing to healthy waters and added production value.

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The red sea cucumber *Parastichopus tremulus* has been identified as a potential aquaculture candidate for sea ranching and integrated aquaculture, mainly due to its high market value (Landes et al. 2019; Schagerström et al. 2021). However, its suitability in such systems, and the possibility of establishing a viable aquaculture industry will, among other factors, depend on whether economically viable growth and survival rates can be achieved. Their potential for North American sea cucumber species to be part of an IMTA system has been demonstrated (Nelson et al 2012; Hannah et al. 2013). The first steps in assessing the suitability of *P. tremulus* will, therefore, be to document its capacity for consuming waste from other aquaculture organisms (fish, shellfish, seaweed/kelp) as well as evaluating its performance and growth in open-water systems versus under controlled environmental conditions. We have several ongoing projects in our lab investigating the potential for growth and nutrient recycling of *P. tremulus* in integrated aquaculture systems, including studies on the uptake of nutrients from different feed sources, the effect of water quality, and the development of larval and broodstock rearing practices.

In our lab, initial feeding trials have documented that *P. tremulus* will feed on a mixture of sand and dried sludge obtained from a local fish farm (J. Sunde and G. Christophersen, unpublished). Analyses are ongoing, comparing nutrient uptake from sludge and a standard feed mix of sand and dried *Sargassum* spp. In the same project, we also explore growth and survival of *P. tremulus* by placing sea cucumbers in cages underneath salmon fish farms. Similar studies have been performed on other cold-water sea cucumber species, with varying results. For instance, Sun et al. (2020) found that the suspension-feeding sea cucumber *Cucumaria frondose*, cultured in the effluent from a land-based salmon farm, assimilated nutrients from the fish waste but decreased in size during a long-term experimental period, and had smaller organ indices compared to wild controls. Hannah et al. (2013) found seasonal growth patterns of small and large *Parastichopus californicus* when it was co-cultured with sablefish. Fortune (2018) also found seasonal variation in growth rates of juvenile *P. californicus* placed underneath a Pacific oyster farm, and registered negative growth rates during the autumn and winter seasons. At present, growth rates of the different stages of *P. tremulus* as well as seasonal variations in nature are unknown and therefore we lack the baseline knowledge for comparing to what extent modified environmental conditions are beneficial in terms of biomass production.

Initial growth studies on small individuals

In our lab, experimental animals originated from the nearby fjords of Ålesund in Møre og Romsdal County (62°N and 6°E) in western Norway (Fig. 1). The sea cucumbers were obtained from bycatch in commercial coastal trawl and pot fisheries, and primarily intended as broodstock for inducing spawning in captivity. The majority (76%) of *P. tremulus* individuals that we received during the period 2017–2021 had a body length between 10 and 20 cm, corresponding to a total wet weight of 28–297 grams, while 6% measured ≤ 8 cm in length (Fig. 2). The potentially smallest mature specimens we have observed in our lab, based on the presence of gonad tissue, were approximately 8 cm in length (Christophersen et al. 2021). We cannot conclude this is the size at first maturity based on so few observations, although it does indicate that *P. tremulus* reached adulthood by this size. Nevertheless, juvenile sizes of different sea cucumber species in the field have been reported as ranging between 0.3 and 21 cm in length (Shiell 2004), with the smallest registered specimen of *P. tremulus* measuring 2 cm (Kjerstad et al. 2015). The maximum juvenile length of another temperate sea cucumber, *Australostichopus mollis*, is reported to be <7 cm (Slater et al. 2010), and Fortune (2018) included specimens from 1 to 10 cm contracted length in juvenile studies of *P. californicus* in Canada.

With the exception of growth rates during larval rearing (Schagerström et al. 2021), no published results on the growth of *P. tremulus* exists. Due to a lack of reared juveniles, we selected the smallest individuals from sea cucumbers that had been kept under lab conditions for one to two years prior to the experiment in order to perform a baseline growth study of the "next stage" (Fig. 3). Because of their age, these individuals were most probably beyond the stage of being termed juveniles. Their initial size varied from 42 to 92 mm in length and from 5 to 25 g total wet weight. They were held in flow-through tanks supplied with unfiltered seawater from 40 m depth and without extra bottom substrate. The animals were occasionally fed but were allowed to empty their intestines a couple of weeks prior to the experiment. Twenty-four individuals were distributed in three experimental (fed) groups and one control group, respectively, each consisting of six individuals with a total biomass of 79.1 ± 6.1 g (mean ± sd, n = 4). The average start weight of individuals was 13.2 ± 6.4 g (mean ± sd, n = 24). The control group was supplied only with unfiltered seawater, with no supplementary feed other than the organic matter present in the incoming water. The fed groups were provided additional feed at a 50:50 (vol:vol) mix of *Sargassum* sp. (dried powder) and sand (particle size 0.6–1.0 mm) in excess during the whole growth period (approx. 30% dried weight *Sargassum* per animal wet weight every 14 days). Growth was calculated monthly, based on individual length and weight measurements, as a specific daily growth rate (SGR)(%/day) using the equation

$$SGR = \frac{\ln S2 - \ln S1}{t} \times 100$$

where S = mean size (length or weight) at final (S2) and previous (S1) sampling time, and t = length of growth interval (days).

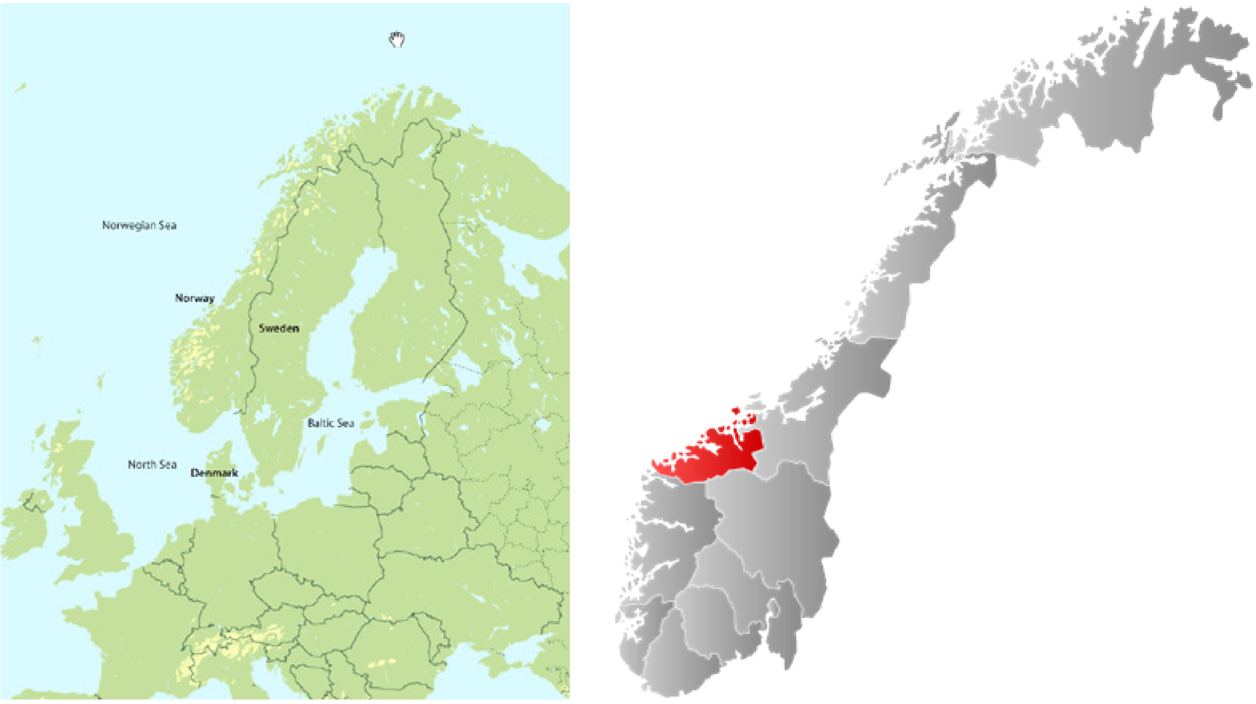

Figure 1. Norway showing the location of Møre og Romsdal County, in red. (Images: https://www.visitnorway.com/maps [left] and Wikimedia Commons, CC-BY-SA-3.0 [right])

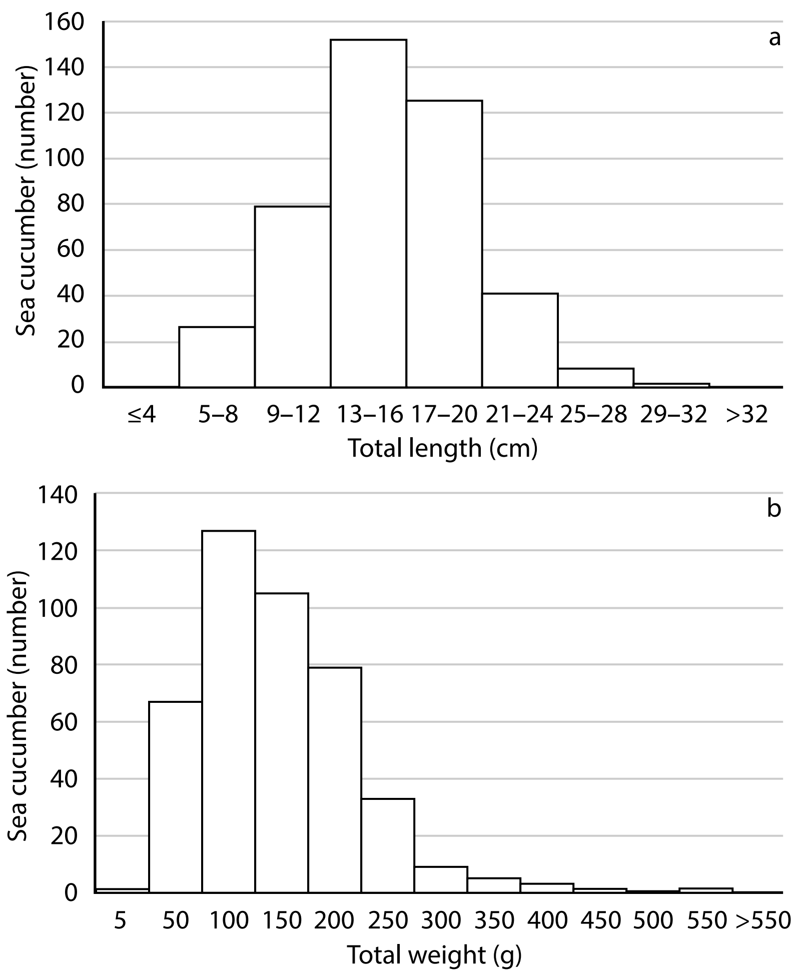

Figure 2. Frequency distribution of sea cucumbers according to their length (2a) and weight (2b) during the period 2017–2021 (n = 432).

Figure 3. Experimental group of *Parastichopus tremulus* kept under lab conditions.

The temperature and salinity of the incoming water in our lab varies with the season. Salinity varies between 31 and 34 ppt. During the experimental period, the temperature fluctuated from 8.2 to 12.7°C, with a mean temperature 9.4 ± 0.8 (SD) (Fig. 4). Temperature was measured every 15 minutes using waterproof temperature loggers (Hobo TidbiT v2). At the depths at which the sea cucumbers are caught (100–200 m) the temperature is 7–9°C throughout the year, whereas 6–14°C is normal at depths of <50 m.

The control group grew less than the fed groups during the period May to October. The average length of the studied animals varied between months (Fig. 5a), and SGR over the total period was 0.02/day in the control group and 0.08%/day in the fed groups. The biomass growth showed diverging growth in wet weight between the unfed and fed sea cucumbers from May to July (Fig. 5b). Thereafter, growth slowed down and negative growth rates were observed from July to October in the fed groups, whereas the control group seemed to level out in size (Fig. 5, Table 1). Across the growth period, the control group showed negative growth based on weight (-0.09%/day) and the fed groups positive growth (0.03%/day). The highest interval growth rate in length was 0.21%/day, and for weight 0.28%/day (Table 1).

Reflections on the potential of cultivating *Parastichopus tremulus*

Successful aquaculture relies on the ability to close and maintain the complete life cycle of the target species in captivity, and predictably provide spat (juveniles) to farming operations. More research and investment are needed to be able to understand the biology of the different *P. tremulus* life stages and achieve viable production. The different life stages (larvae, juveniles, adults) require conditions that suit their physiology and feeding habits. We assume that the metabolism (oxygen consumption) of cold-water sea cucumber species is lower than that of warmer water species when in their natural habitat, and that *P. tremulus* will, therefore, grow more slowly than tropical species. In aquaculture,

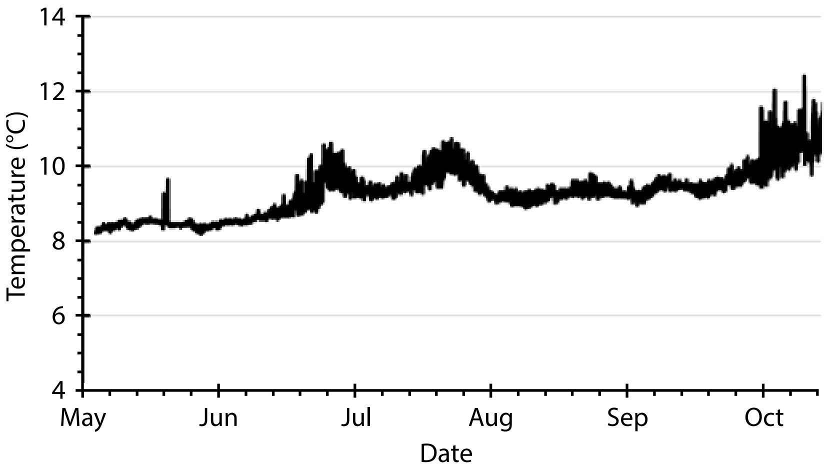

Figure 4. Temperature during the experimental period from May to October 2021.

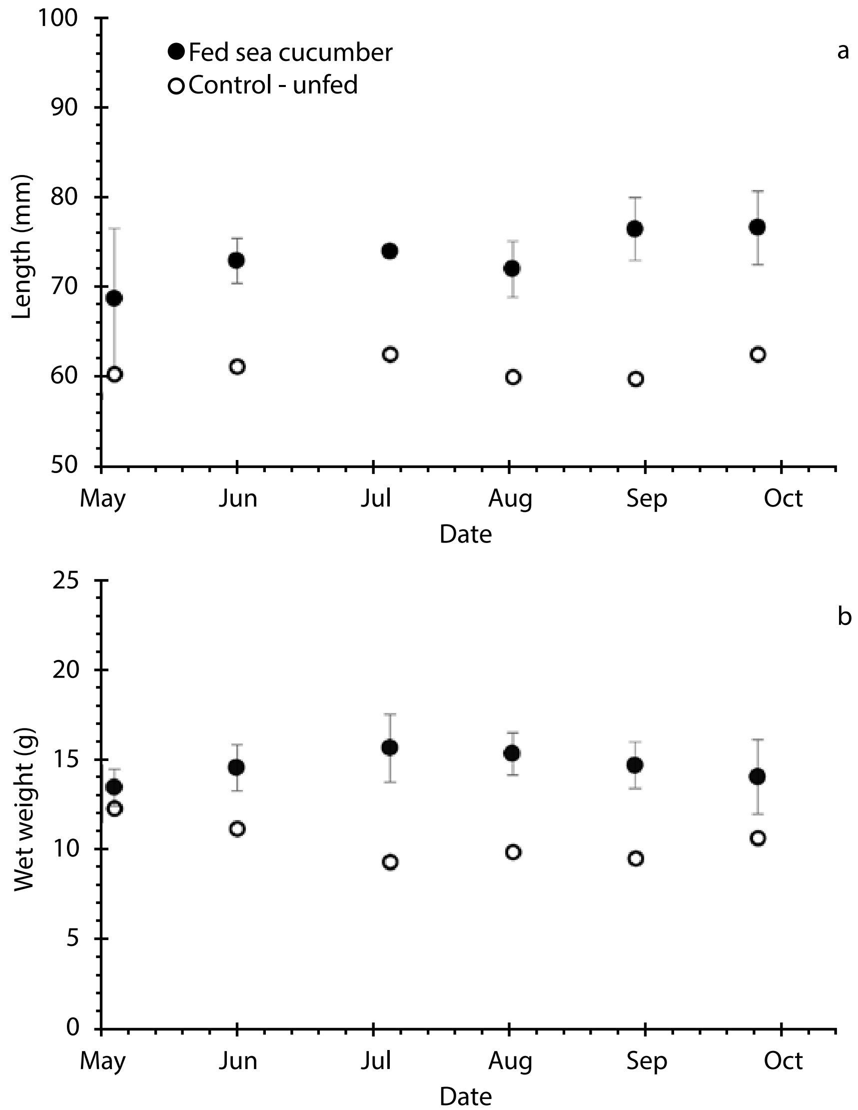

Figure 5. Length a) and weight b) of *Parastichopus tremulus* from May to October. Control animals were only supplied with unfiltered seawater. Black circles show the average ± SD growth of sea cucumber groups (n = 3) provided with additional feed.

Table 1. Monthly specific growth rate (SGR%/day) of *Parastichopus tremulus* total length and total weight. Control animals were supplied unfiltered seawater only. The "Fed" columns shows the average growth of sea cucumber groups (n = 3) provided additional feed.

SGR	Length (%/day)		Weight (%/day)	
Period	Control	Fed	Control	Fed
May–Jun	0.05	0.21	-0.34	0.28
Jun–Jul	0.06	0.04	-0.52	0.20
Jul–Aug	-0.15	-0.10	0.20	-0.07
Aug–Sep	-0.01	0.21*	-0.13	-0.15*
Sep–Oct	0.16	0.01	0.40	-0.16

*One sea cucumber died during the time interval.

temperature and feed conditions can be optimised to facilitate growth. The combined effects of temperature and food concentration have been studied for *P. tremulus* larvae, showing the possibility of growing pelagic larvae at temperatures above what we assume would normally be experienced in nature (Schagerström et al. 2021). Specific growth rates of larvae in our lab were between 18% and 20%/day during the first week, and 1–4%/day until day 20. Larvae were reared at an approximate mean temperature of 15°C (Christophersen and Sunde 2021). Whether adequate growth rates can be achieved during later stages remains to be seen.

Our study is very preliminary and includes many biases, given the low number of individuals per test group (n = 6), and the uncertainty related to the age and variation in size, which is related to the age of the individuals used.

In this study, the supplied seawater was not temperature controlled, but followed the natural seasonal fluctuation. The incoming water was supplied from a shallower depth (40 m) than from where the sea cucumbers originally were caught (100–200 m). We offered what is currently our standard feed (*Sargassum* spp. and sand mix), a mix often provided as the main feed component in *Apostichopus japonicus* aquaculture (Shi et al. 2015). Our preliminary results suggest that *P. tremulus* achieves low growth rates in culture under these conditions. Weight-specific growth rates were lower (<0.5 SGR %/day) in late spring-summer than the >1 SGR %/day found for *P. californicus* (Hannah et al. 2012), but similar to this study, we also measured negative growth rates. Our study is still ongoing and will follow the growth development for 12 months under present conditions, before replacing the feed type and/or feed distribution method. Currently, it is difficult to evaluate if the negative growth response is due to suboptimal environmental conditions or nutrition, or to a seasonal feeding and growth pattern where feeding ceases during autumn and winter, as postulated by other authors (Jespersen and Lützen 1971). Manipulation with temperature and feed quality is likely to improve growth compared to the results we have obtained so far.

We do not know the size-at-age of *Parastichopus tremulus*, but the results indicate that the species is slow growing, similar to other sea cucumber species living at higher latitudes such as *Cucumaria frondosa* (Hamel and Mercier 1996; So et al. 2010) and *P. californicus* (Cameron and Fankboner 1989; Paltzat et al. 2008; Fortune 2018). The low growth rates measured in our preliminary studies are in line with previous oxygen consumption measurements of *P. tremulus* performed in our lab. We found that the average oxygen consumption rate (OCR) was 0.29 mg O_2/hour/individual (11.5 ± 1.5 cm, 60 ± 15 g) at 14°C, corresponding to 1.98 µg O_2/hour/g body weight (A. Landes unpublished). This is in accordance with Fox (1936), who measured individuals weighing 130 g and found the OCR at a temperature of 6°C to be between 0.70 and 2.30 µg O_2/hour/g body weight, with an average of 1.80 µg O_2/hour/g body weight. In comparison, faster growing species living at higher temperatures, such as the tropical *Holothuria scabra* show OCR orders of magnitude higher (12–60 µg O_2/hour/g at 27°C) and a decrease in OCR with increasing body weight (Kodama et al. 2015; Kühnhold et al. 2019). Juveniles of the temperate species *Actinopyga japonicus* that weighed <5 g and grown at 15°C and 18°C also showed OCRs within a similar range (Dong and Dong 2006).

To what extent the growth of *P. tremulus* can be modulated in culture by manipulating environmental conditions and optimising feed composition remains to be seen. There are indications, however, that even under optimal conditions, this species might be much slower growing than temperate and tropical species that are already cultured in large volumes. There is also the question of whether the animals go through seasonal feeding behaviours, cessation in feeding or intestine atrophy during the winter months (Jespersen and Lützen 1971; Fankboner and Cameron 1985; Hannah et al 2013; Fortune 2018), a matter that further complicates the development of aquaculture management practices. Based on our average size measurements and two of the higher positive SGRs (0.20 and 0.05) we attempted to predict an approximate time to rear the larvae to commercial size, which is 15 cm in length, according to whole traders. Based on length–growth measurements, the estimated time needed to reach a length of 15 cm from a start length of 7 cm will be between one and four years under our laboratory conditions. Based on the corresponding weight growth measurements and the equivalent weights (115 g from a start weight of 15 g), estimates of time to commercial size will be between 3 and 11 years. Assuming that the experimental animals of approximately 7 cm are a minimum of two to three years old, and that an additional growth period of a minimum of one to two years is needed, these estimates suggest that commercial size (length) could be reached within four to five years.

Our results indicate that *P. tremulus* is a slow-growing species. Under the conditions used in this first experiment, economically viable aquaculture production seems unlikely at this stage. However, a production cycle of four to six years is not unusual for marine species in cold-water areas. More knowledge is needed to explore the possibilities of reducing the production time during the different stages within the biological limits of *P. tremulus*. It is to be expected that growth can be increased through development of suitable feeds and improved culture technology, and that profitable production of *P. tremulus* may be possible in the future. However, substantial research efforts are still needed to establish the nutritional requirements and optimal rearing conditions for this species.

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