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REVIEWS

Distribution patterns and biological aspects of *Strongylocentrotus droebachiensis* (Echinoidea: Echinoida) in Russian waters of the Barents Sea: implications for commercial exploration

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Abstract Sea urchin roe is a high-quality product in terms of its nutritional value, valuable biochemical composition, and acquired taste. Urchin stocks, however, have been overfished worldwide and new candidates for commercial harvesting and aquaculture are required to satisfy the demand from the expanding market. The green sea urchin *Strongylocentrotus droebachiensis* from Russian waters of the Barents Sea may be considered a new source for potential consumers. We summarized available information regarding distribution patterns, feeding, reproduction, and growth as well as studies focused on farming of this species to assess the fishery and aquaculture potential of the area. This species is abundant in the coastal zone where it is commonly associated with laminarian kelp. The brown algae *Saccharina latissima* is the primary diet for *S. droebachiensis* but it also consumes animal foods. Red king crabs are the main predators for sea urchins but they do not significantly affect the *S. droebachiensis* population. A spawning peak of *S. droebachiensis* is registered in March–April. Green sea urchins reach a commercial size of 50 mm diameter at age 6 and the estimated stock of commercial urchins is 50,000–81,000 t. The most promising sites for harvesting are Varanger-fjord and Bolshoy Oleniy Island plus Porchnikha Bay. The best harvesting seasons are February–March and September–October. Sea-based rearing systems appear to be the most suitable approach for sea urchin aquaculture based on grow-out of adult animals fed on algal or mixed diets.

Keywords Barents Sea · *Strongylocentrotus droebachiensis* · Distribution · Feeding · Growth · Reproduction · Fishery · Aquaculture

Introduction

The green sea urchin *Strongylocentrotus droebachiensis* (Muller 1776) is considered the most frequent and abundant member of the family Strongylocentrotidae (Mortensen 1943). Being an Arctic-boreal species, *S. droebachiensis* is widely distributed in the Atlantic and Pacific oceans (Mortensen 1943; Jensen 1974; Bazhin and Stepanov 2012; Scheibling and Hatcher 2013; Scheibling et al. 2020). In the North Atlantic, this species occurs from the Canadian Archipelago and Greenland down the east coast of North America to Cape Cod, USA, and across to Iceland, the Shetland Islands and northern Scotland, Norway, Denmark and the tip of Sweden. It is also found in the Barents Sea, White Sea, Kara and Chukchi Seas. In the three latter seas, however, it has sporadic distribution. In the North Pacific, this species occurs along the east coast of Siberia to the middle of the Kuril Island chain and east coast of Sakhalin Island, and

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from the Aleutian Islands and Alaska down the west coast of North America to Oregon, USA (Scheibling and Hatcher 2013; Scheibling et al. 2020). In areas of its distribution, this species plays an important ecological role being, in particular, a determinant of the distribution and abundance of macroalgae and some invertebrate benthic animals (Propp 1977; Anisimova 1998). For this reason, green sea urchins have been considered pests at benthic sites where their intensive grazing impacts kelp forests and limits food sources available to other species including commercially important lobsters and crabs (Wharton and Mann 1981).

As important ecological engineers *S. droebachiensis* have attracted the attention of scientists worldwide including Russian specialists. In the Barents Sea, regular studies regarding the biology and ecology of this species have been undertaken since the 1920s (Diakonov 1926). Subsequent research has centered on the fishery and aquaculture potential of this species (Zenzerov 1999; Shatsky 2012a, b). A bulk of studies conducted by scientists from different countries has indicated the high commercial value of *S. droebachiensis* both for the medicine and food industries (McBride 2005).

The edible part of green sea urchins is represented by the male and female gonads (also called "roe") which consist of nutritive phagocytes and germinal cells. The quality and quantity of the sea urchin gonads are vital characteristics in the market because these parameters play a crucial role in the profitability of the processing operations. The size of the sea urchin roe, the flavors and texture depend on time of year (Siikavuopio 2009; James et al. 2015, 2017). Roe of green sea urchins are yellow/orange and are described as having a rich, slightly sweet, briny flavor with a lingering aftertaste. Top-quality sea urchin gonads are characterized not only by large size, but also firm texture (containing few or no gametes), consistently high sensory scores, and yellow to orange color (James et al. 2015). The gonads of green sea urchin are rich in valuable bioactive compounds, such as carotenoids, polyunsaturated fatty acids, phospholipids, and sulfated fucans (Pozharitskaya et al. 2015). In the northwest Atlantic, green sea urchins are smaller in size but their tastes are sweeter compared to the red sea urchin *Strongylocentrotus franciscanus* from the Pacific coast of the USA. Now such a high-quality product sells in Japanese markets for as much as 1.2€/individual sea urchin or 30€/kg (James et al. 2017) and in Canadian markets for 30€/kg (Stefánsson et al. 2017). The average coast of sea urchin roe varies from 370 to 1200 US$/kg (https://www.soposeafood.com; https://fultonfishmarket.com).

Globally, yields of green sea urchins from wild populations have declined as a result of overfishing (Scheibling and Hatcher 2013; Vadas et al. 2015; Scheibling et al. 2020). A domestic Russian market for sea urchin roe has not yet developed and only recently this species has been included in stock management in response to growing interest from Asian markets. The fishery for *S. droebachiensis* in Russian waters of the Barents Sea was opened in 2017 and since 2019 this species has also been harvested by amateur fishermen.

Taking into account that sea urchin stocks have been overfished worldwide and new populations should be involved in global exploration, the Barents Sea S. *droebachiensis* seems to be a promising candidate for large-scale commercial fishery and aquaculture (Dvoretsky and Dvoretsky 2020a). In this paper, we summarized important data regarding distribution patterns, feeding, reproduction, and growth of green sea urchins in Russian waters of the Barents Sea to evaluate the fishery and aquaculture potential of the area.

Distribution

In the Barents Sea, *S. droebachiensis* is distributed in the coastal zone, south-eastern part of the sea including Goose Bank, Moller Bank and North Kanin Bank (Fig. 1). It also occurs near Bear Island (Spitsbergen Bank), in the coastal Svalbard waters, near Novaya Zemlya and near Franz Josef Land (Grieg 1935; Anisimova 1998; Zakharov et al. 2018; Dvoretsky and Dvoretsky 2024). Recently, sea urchins have been found as occasional epibionts of large crustaceans in shallow waters of the Barents Sea (Dvoretsky and Dvoretsky 2021a).

The most common aggregations are registered in the coastal zone of the Kola Peninsula where green sea urchins occupy the shallow subtidal zone on rocky bottoms (bedrock outcrops, cobbles, boulders, and grounds encrusting with coralline red algae *Litotamnion*) or kelps of the brown alga *Saccharina latissima* (also referred to as "laminarian kelps") from

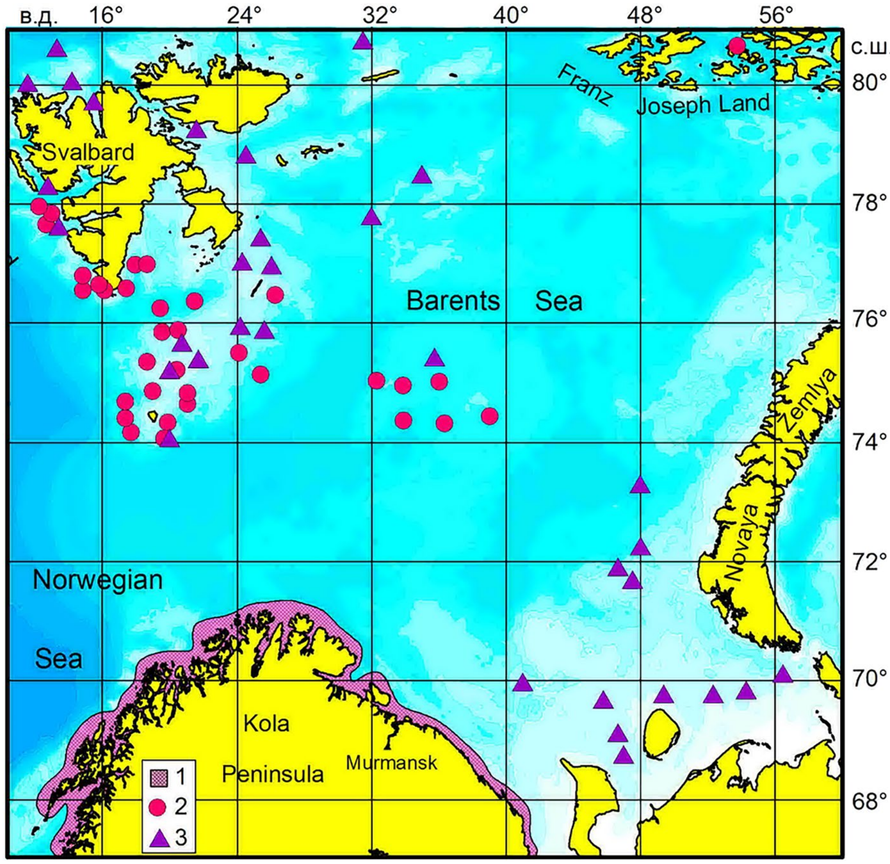


Fig. 1 Distribution of *Strongylocentrotus droebachiensis* in the Barents Sea and adjacent waters (adapted from Anisimova 1998; Zakharov et al. 2018). 1—coastal waters (Anisimova 1998), 2—open sea (Anisimova 1998), 3—open sea (Zakharov et al. 2018)

0.2–3.0 to 20–30 m (Propp 1971, 1977; Drobysheva et al. 1979). In waters off the south-western Svalbard coast and Spitsbergen Bank, *S. droebachiensis* was found at 50–230 m depth where it has overlapping distribution with a sympatric species (*S. pallidus*) (Anisimova 1998). In this area, the abundance and biomass of green sea urchins are low accounting for 2 ind. m^{-2} and 5 g m^{-2}, respectively. Previous studies in other deepwater areas showed that green sea urchins on sedimentary bottoms in deeper water are sparsely distributed and rely on drift algal subsidies from adjacent macroalgal beds (Scheibling and Hatcher 2013; Scheibling et al. 2020).

Green sea urchins have been shown to exhibit seasonal migrations within this depth range being the most abundant at 5 m in the summer-autumn period and 10–15 m in winter (Propp 1971). In semi-closed and closed bays and fjords, the most abundant aggregations were found on hard bottoms and the abundance decreased from the open sea areas to the coastal zone affected by freshwater runoff. The mean abundance of *S. droebachiensis* in coastal aggregations can vary from 2–15 to 12–30 ind. m^{-2} (Drobysheva et al. 1979; Anisimova 1998) with a mean density of 10–15 ind. m^{-2} (Table 1). The highest abundance was registered to be 40–70 ind. m^{-2} at deep-water sites and 100–200 ind. m^{-2} at shallow-water sites (Propp 1971; Jus and Zenzerov 1983; Antipova et al. 1984; Miljutin 2003). More recent studies conducted in the coastal zone of the Barents Sea have shown that the average abundance and biomass of *S. droebachiensis* were 5 ind. m^{-2} and 330 g m^{-2}, respectively (Shatsky 2012a, b).

Feeding and predators

Strongylocentrotus droebachiensis is an omnivorous grazer feeding on a wide range of prey including algae and invertebrates and as well as bacteria and dissolved organic material (Propp 1977; Scheibling and Hatcher 2013; Scheibling et al. 2020). The brown alga *Saccharina latissima* (=*Laminaria saccharina*)

Table 1 Mean abundance (ind. m^{-2}) and biomass (g m^{-2}) of *Strongylocentrotus droebachiensis* at different coastal sites of the Kola Peninsula, Barents Sea

Location	Coordinates	Abundance	Biomass	Source
Varanger-fjord	69° 42′ 36 N 31° 25′ E	26	33	Shatsky et al. (2022)
Kola Bay	69 °06′ N 33° 24′ E	1	12–63	Zuyev (2012)
Bolshaya Sharkovka Bay	69° 12′ 37″ N 34° 56′ 38″ E	10	600	Antipova et al. (1984)
Dolagaya Bay	69° 11′ 23″ N 34° 57′ 41″ E	6	680	Anisimova and Frolova (1994)
Teriberskaya Bay	69° 10′ 20″ N 35° 08′ 38″ E	9	700	Antipova et al. (1984)
Teriberskaya Bay	69° 10′ 20″ N 35° 08′ 38″ E	11	400	Miljutin (2003)
Orlovka Bay	69° 10′ 41″ N 35° 10′ 34″ E	8	440	Antipova et al. (1984)
Yarnyshnaya Bay	69° 06′ 11″ N 36° 03′ 08″ E	16	740	Golikov et al. (1993)
Dalnezelenetskaya Bay	69° 07′ 32″ N 36° 05′ 47″ E	4–40	80–1660	Propp (1971)
Dalnezelenetskaya Bay	69° 07′ 30″ N 36° 04′ 36″ E	17–19	540–1060	Buyanovsky and Rzhavsky (2007)
Porchnikha Bay	69° 04′ 36″ N 36° 17′ 01″ E	10	600	Antipova et al. (1984)
Bolshoy Oleniy Island	69° 03′ 52″ N, 36° 19′ 48″ E	6	340	Antipova et al. (1984)
Shirokaya Bay	68° 48′ 06″ N 37° 14′ 54″ E	15	1190	Antipova et al. (1984)

is the main food source for green sea urchins at coastal sites of the Kola Peninsula. The feeding rates of green sea urchins depend on food type and to a lesser extent on density, body size, reproductive stage, temperature, and season (Scheibling and Hatcher 2013; Scheibling et al. 2020). Research experiments conducted in the coastal region of the Barents Sea revealed varying feeding rates in *S. droebachiensis* individuals, ranging from 0.18 to 0.65 g of wet algal weight per 68-g individual in winter, 0.57–1.68 g in spring, and 0.17–0.86 g in summer and autumn (Ryabushko 1978). The annual feeding rate was calculated to be 2 kg m^{-2} (range 1.6–5.3 kg m^{-2}), which corresponds to 23% of the total macroalgal production per year (Ryabushko 1978; Kholodov 1981).

Foraging activity by *S. droebachiensis* from the Barents Sea has been observed to be particularly intensive during March to May, both in natural environments and under controlled conditions (Anisimova 1998). During the spawning period, which typically occurs in late spring, green sea urchins refrain from feeding, resulting in a high prevalence of *S. droebachiensis* individuals with empty stomachs (40–45%), typically occurring in April and May (Kuznetsov 1946). Along the coastal waters of the Barents Sea, the food preferences of *S. droebachiensis* are influenced by depth and season. During the summer, sea urchins show a preference for sporophytes, young gametophytes, old fronds, and decomposing thalli of the brown seaweeds *Saccharina latissima* and *Alaria esculenta*, favoring these items over well-developed summer thalli of the same species. Additionally, green algae from the intertidal zone are also preferred by *S. droebachiensis* during the summer. As autumn arrives and the availability of brown macroalgae decreases, sea urchins migrate to deeper areas, resulting in a decline in the significance of *Saccharina* in their diet, while the contribution of other algae such as *Desmarestia* (containing sulfuric acid), fucoid algae (e.g., common intertidal genera *Fucus* and *Ascophyllum*), and the green algae *Urospora* increases substantially (Kuznetsov 1946; Anisimova 1998).

Recently, Evseeva (2016) has studied the food composition of adult green sea urchins (test diameter 48.6–81.4 mm, weight 37.9–164.7 g) in Ura Bay and found 10 species of brown algae, 12 species of red algae, 9 species of green algae, and one species of diatom algae in the digestive tracts of *S. droebachiensis*. There was a seasonal shift in food preference of green sea urchins: laminarian kelps dominated the diet in March–June while *Desmarestia* in October–November (Evseeva 2016). Low feeding activity is also registered in the polar night period (December-January). Prior to the beginning of spawning, food consumption seems to stop (Anisimova 1998). In contrast to adult specimens, young sea urchins which occur in deeper areas mainly consume red algae and detritus but can consume *S. latissima* as well and exhibit continuous feeding activity over a year. Laboratory observations revealed that recently settled juveniles ingest bacterial and microalgal prey as well as benthic detritus. A shift in feeding behavior is observed 6–8 months after the settlement when young individuals start to consume macroalgal species (Anisimova 1998).

Natural diets of green sea urchins also contain animal food. Long-term studies showed that in the upper intertidal zone of the Barents Sea, epiphytes (Hydroidea, Bryozoa, Spongia), as well as gastropods and bivalves (especially *Mytilus edulis*), were the most common animal food items in stomachs of *S. droebachiensis* (Anisimova 1998). In Ura Bay, 50.9% of green sea urchins were found to be fed on animal food, but the proportional weight of these food items was as low as < 4% (Evseeva 2016). In deepwater habitats (50–100 m), the ration of *S. droebachiensis* is mainly composed of detritus and sedentary animals. In addition, some authors indicated the presence of conspecific tissues in the digestive tract of green sea urchins from the coastal Barents Sea (Kuznetsov 1946; Evseeva 2016).

Both juvenile and adult green sea urchins are prey to a wide range of marine fish and invertebrates (Scheibling 1996; Fagerli et al. 2014). In recent decades, in the Barents Sea, the red king crab *Paralithodes camtschaticus* has become the most important predator for *S. droebachiensis* (Dvoretsky and Dvoretsky 2015). After the establishment of the population, the abundance of *P. camtschaticus* reached substantial values in the coastal Barents Sea (Dvoretsky and Dvoretsky 2018) where its distribution overlaps the distribution of *S. droebachiensis* (Dvoretsky and Dvoretsky 2020b, 2022a). According to the 2004–2006 data by Pavlova (2009), one adult crab consumes 1–9 sea urchins per day or 0.2–8.0% of its weight while one juvenile crab consumes 1–3 sea urchins or 3–28%.

Reproduction

The process of gametogenesis and spawning in green sea urchins is an interactive, multistage sequence with two major phases being storage of nutrients in intragonadal storage cells and production of gametes. Thus, the partitioning of food assimilates between gonadal and somatic growth is complicated by the substantial nutritional storage function of the gonads, which provide a nutritive microhabitat for germ cells of *S. droebachiensis* (Scheibling and Hatcher 2013; Scheibling et al. 2020). The timing of the reproductive cycle is regulated by the complex interaction of endogenous and exogenous drivers among them food availability and water quality, temperature, photoperiod, lunar cycle, and water-borne chemicals have been shown to influence the frequency of events and rates of reproductive processes in green sea urchins (Scheibling and Hatcher 2013; Scheibling et al. 2020).

Adult sea urchins are either male or female, with a normal sex ratio of 1:1, both sexes normally spawn once per year and release their gametes (eggs or sperm) into the water column (this is called broadcast spawning) where mixing and fertilization of the eggs occurs (James et al. 2017; O'Hara and Thórarinsdóttir 2021). Following the phagocytosis of the relict gametes after spawning, gonad growth accelerates through the summer first through the accumulation of nutritive phagocytes, reaching maximum rates in autumn when the proliferation of primary oocytes and initiation of vitellogenesis (spermatogenesis in males) begins. The maturation and storage of ova and sperm (at the expense of nutritive cell mass) proceeds through the winter, as gonad mass continues to increase at a decelerating rate into early spring when spawning begins. Near-synchronous spawning in intermittent pulses or mass spawning events proceeds over 1–2 months in spring, and the cycle starts anew (Scheibling and Hatcher 2013; Scheibling et al. 2020).

Spawning in *S. droebachiensis* from Dalnezelenetskaya Bay was studied by Propp (1977). This author concluded that sea urchins spawn in July. However, seasonal studies of gonad development in *S. droebachiensis*, as well as histological screening conducted by Jus and Zenzerov (1983), showed that in this area, the highest values of the gonadosomatic index (GSI = gonad weight/body weight, %) are registered in February (Fig. 2). A sharp decline of the index takes place in March–April indicating a spawning peak in this period. A second but less large increase of the GSI is usually registered in June–July similar to the results obtained by Propp (1977). According to Sennikov and Matyushkin (1994), in July–August, pre-spawning sea urchins (23.5–25.6% GSI) were registered along the Kola Peninsula in small proportions (6–10% of the total number). Both the number of spawning urchins and GSI were higher in the eastern part of the area

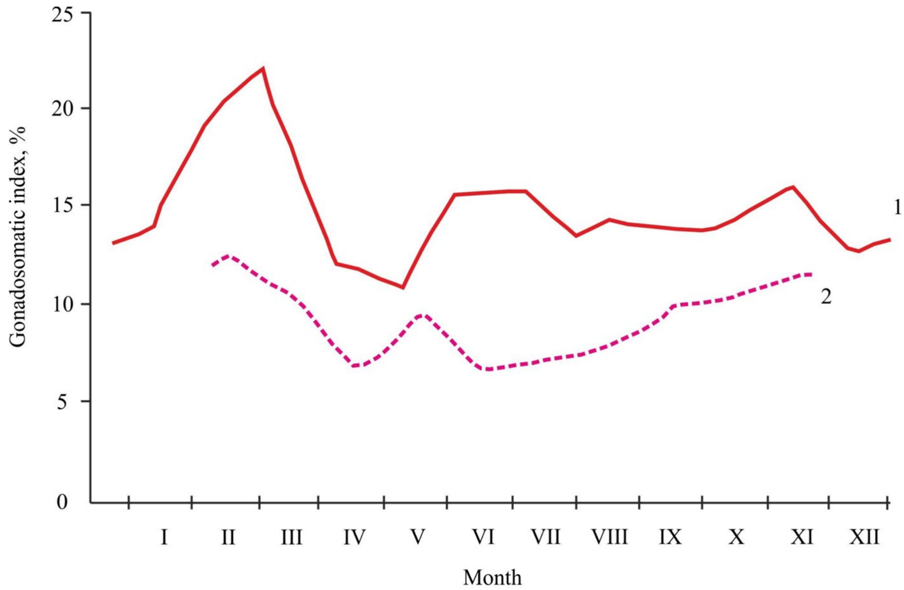


Fig. 2 Seasonal dynamics of the gonadosomatic index in *Strongylocentrotus droebachiensis* from coastal waters of the Barents Sea. 1—Dalnezelenetskaya Bay, females; 2—eastern part of Ura Bay, combined data (adapted from Jus and Zenzerov 1983; Shatsky 2012b)

compared to the western part. Indeed, the GSI of *S. droebachiensis* from Ura Bay were lower than in Dalnezelenetskaya Bay which is located 367 km east of Ura Bay (Fig. 2). At the sites of western Murman, the highest GSI and high-quality products (roe) are registered in February–March and September–November (Shatsky 2012b).

There are two main periods in the annual gonad cycle: (a) dormant stage when the gonad is generally small and in poor condition, and the gonads slowly increase in size as they produce storage cells, nutritive phagocytes (summer-autumn period, 7–9 months), and (b) spawning stage when gametogenesis occurs and the number of storage cells in the gonads reduces and these are replaced with reproductive cells (winter-autumn season, 3–5 months) (Oganesyan 1995). The GSI as an indicator of the reproductive status of sea urchins depends on depth, food availability and quality, and population health (Anisimova 1998). In the Barents Sea, the highest GSI is usually registered in individuals at shallow-water sites where laminarian kelps are abundant whereas lower GSIs are registered at deep-water sites dominated by red and coralline algae and at shallow-water sites on grazed laminarian kelps (Anisimova 1998).

Many authors found strong correlations between spawning in *S. droebachiensis* and phytoplankton blooms associated with warming surface waters in spring (Scheibling and Hatcher 2013; Scheibling et al. 2020) suggesting that the concentration of phytoplankton is the most important driver of the reproductive timing in green sea urchins.

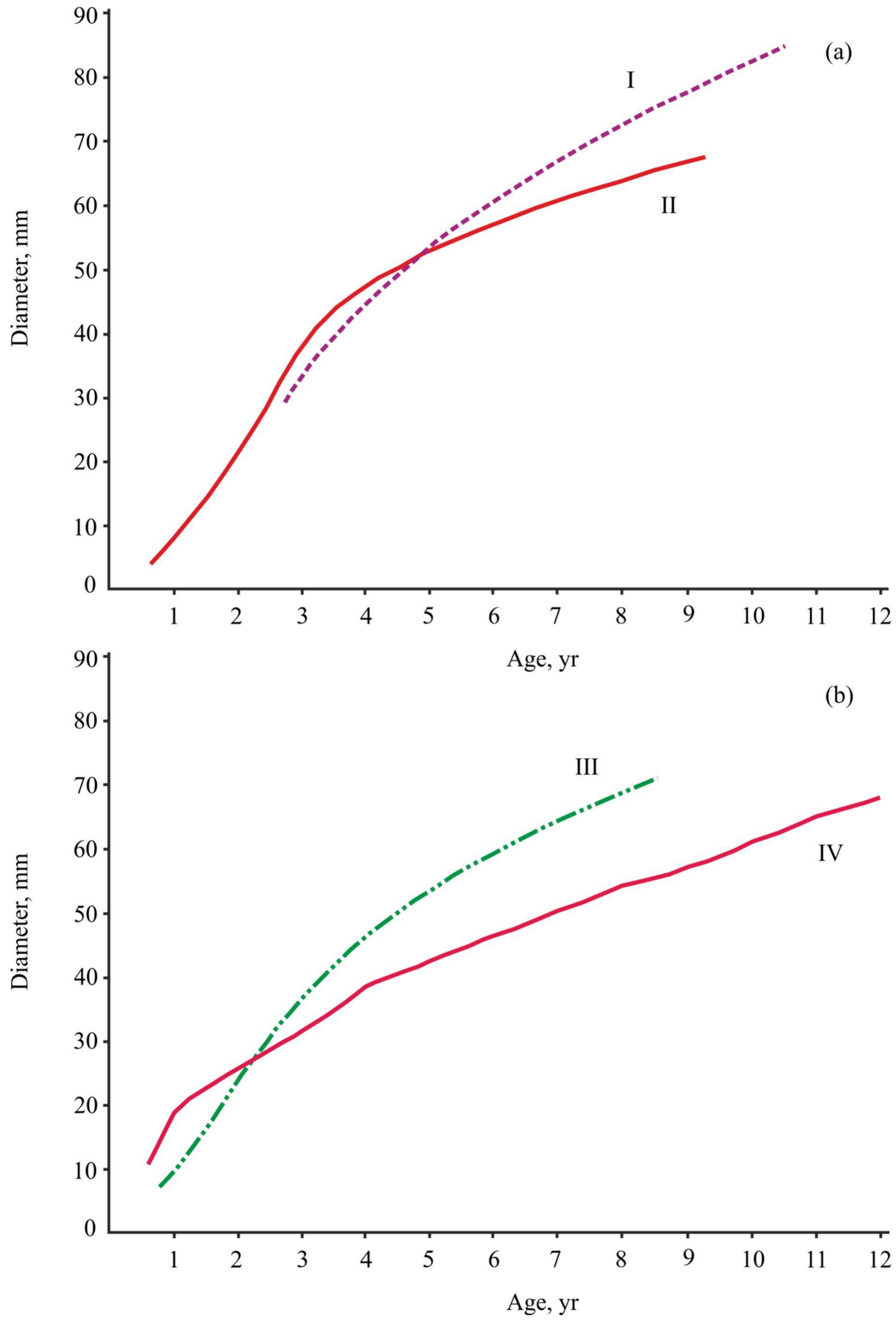
Growth

Gross absorption efficiencies of preferred algal food items by green sea urchins vary from 9–91% of the ingested food depending on body size (age) and season (Meidel and Scheibling 1999; Kelly et al. 2012; Scheibling and Hatcher 2013). In the wild, realistic assimilation efficiency is calculated to be 60 ± 10% for a 50-mm diameter *S. droebachiensis* fed on kelp. In Dalnezelenetskaya Bay, nutrient-specific absorption efficiencies of N, P and C were found to be 80, 60 and 30%, respectively (Propp 1977). The author concluded that the protein concentration may limit the growth of some organs in *S. droebachiensis*. In the Barents Sea, 3-year-old *S. droebachiensis* allocated less than 20% of their total production to gonad growth, while larger 6-year-old individuals allocated 45%, and 8-year-old animals allocated less than 33%. Thus, at peak reproductive size (and age), almost 7 times more energy was allocated to gonad growth than to somatic growth (Propp 1977).

Strongylocentrotus droebachiensis is a slow-growing and long-lived species that exhibits great phenotypic plasticity of growth in response to environmental conditions (Scheibling and Hatcher 2013; Scheibling et al. 2020). In the Barents Sea, growth curves for *S. droebachiensis* typically show a rapid increase of size with age towards an asymptotic level (Fig. 3). However, a lag phase in growth followed by acceleration to intermediate size was registered for 1–2-year-old sea urchins reared under laboratory conditions where water temperature was 1 °C higher than in natural conditions (Anisimova 1998). For these first few years post-settlement individuals the growth curve was approximated by equation:

$$D = 9.39 \cdot T^{1.102},$$

Fig. 3 Growth curves of *Strongylocentrotus droebachiensis* in Yarnayshnaya Bay (**a**) and Dalnezelenetskaya Bay (**b**). Adapted from: I—Propp 1977; II—Golikov et al. 1993; III—Propp 1977; IV—Buyanovsky and Rzhavsky 2007



where D is the diameter (mm), T is a time period from spawning to the time of age determination (years) (Anisimova 1998).

Growth in sea urchins is usually described by a von Bertalanffy growth equation:

$$L = L_{\infty}\left(1 - e^{-k(t-t0)}\right),$$

where L is the predicted test diameter at age t years, L_{∞}—the asymptotic diameter, K—the growth constant, t0—the hypothetical age at size zero.

In the Barents Sea, the growth constant may reach 0.27 which was the same as in the coastal waters of Kodiak, Alaska and higher than in northern Norway and the Northern part of the Sea of Okhotsk (Table 2). In general, the animals at age 1–9 have the same diameters as their conspecifics from the Norwegian Sea and the Sea of Okhotsk (Buyanovsky and Rzhavsky 2007).

The lifespan of *S. droebachiensis* in the Barents Sea was estimated to vary between 8–10 and 10–12 years (Propp 1977; Anisimova 1998). According to recent studies conducted in Dalnezelenetskaya Bay, diameters of *S. droebachiensis* at age 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, and 12 were 15–21, 22–26, 27–34, 32–39, 37–45, 40–50, 42–53, 45–61, 50–62, 51–70, 54–40, 55–70 mm (Buyanovsky and Rzhavsky 2007). Green sea urchins from deeper waters exhibit lower growth rates, lifespans, and sizes (Anisimova 1998).

The onset of sexual maturity can be delayed for years in dense populations of *S. droebachiensis* with little food (Propp 1977). At the western sites of the Kola Peninsula, green sea urchins become mature at age 5+ (45–46 mm diameter) (Shatsky 2008, 2010) while *S. droebachiensis* individuals from the eastern part of the Kola Peninsula reach reproductive conditions at age 3.5–4.5 (29–30 mm diameter) (Propp 1977). For comparison, Munk (1992) reported that sexual maturity of *S. droebachiensis* from Kodiak, Alaska was reached at age 2–3 and size at 50% maturity was 25.2 mm. In the Sea of Okhotsk, sexual maturity of *S. droebachiensis* was registered at age 3.5–4 (27–32 mm test diameter) (Belyj 2006).

The size-weight relationship in green sea urchins from the coastal Barents Sea is described by the following equation (Propp 1977):

$$W = D^{2.46},$$

where W is the wet weight (g), D is the test diameter (mm).

Fishery perspectives

According to the growth rates of *S. droebachiensis*, the optimal size (test diameter) for commercial harvesting is 50 mm. It is reached after 6 years of growth under natural conditions (Shatsky 2010, 2012b).

The total number of green sea urchins/total stock in the coastal Barents Sea fluctuates from 778 to 1202 million individuals/ 50.2–80.9 thousand metric tons. Usually, sea urchin aggregations cover 20–50% (in exceptional cases 70%) of the total square of the seafloor (Shatsky 2012b). A cluster analysis based on an extensive survey of the coastal zone of the Kola Peninsula showed two distinct areas of the distribution

Table 2 Von Bertalanffy growth parameters for *Strongylocentrotus droebachiensis* in different geographical locations

Location	Water body	Growth constant	Asymptotic diameter	References
Yarnyashnaya Bay	Barents Sea	0.14	110	Propp (1977)
Dalnezelenetskaya Bay	Barents Sea	0.22	83	Propp (1977)
Yarnyashnaya Bay	Barents Sea	0.27	74	Anisimova (1998)
Dafjord	Norewgian Sea	0.11	92.4	Sivertsen and Hopkins (1995)
Hansnes	Norewgian Sea	0.18	68.5	Sivertsen and Hopkins (1995)
Musvaer	Norewgian Sea	0.17	60.7	Sivertsen and Hopkins (1995)
Hjelmoy	Norewgian Sea	0.17	55.5	Sivertsen and Hopkins (1995)
Kodiak Island	Pacific Ocean	0.28	89.4	Munk (1992)
Gertner Bay	Sea of Okhotsk	0.15	69.6	Belyj (2006)
Nedorazumneia Island	Sea of Okhotsk	0.11	87.1	Belyj (2006)

of *S. droebachiensis* (Fig. 4): (a) Western Murman, i.e., the area situated to the west of Kola Bay (69° 06′ N, 33° 24′ E) plus the area from Dolgaya Bay (69° 11′ 18″ N, 34° 57′ 35″ E) to Bolshoy Oleniy Island (69° 4′ 2″ N, 36° 21′ 59″), and (b) the area Zapadnaya Zelenetskaya Bay (69° 17′ 3″ N, 33° 43′ 19″ E) to Maliy Oleniy Island (69° 14′ 31″ N, 34° 43′ 20″ E) plus the area from Kekurkaya Bay (68° 57′ 28″ N, 36° 43′ 21″ E) to Cape Svyatoy Nos (68° 9′ 26″ N, 39° 44′ 32″ E). The first cluster was composed of larger sea urchins (diameter 61–70 mm), while the second cluster included areas with a predominance of smaller specimens (diameter 11–50 mm) (Shatsky 2012b).

In coastal aggregations, the percentage of commercial-sized *S. droebachiensis* individuals, characterized by a test diameter exceeding 50 mm, can range between 55 and 58% (Shatsky 2012b). A sustainable fishery for this echinoderm within the coastal waters of the Kola Peninsula necessitates not only high densities of *S. droebachiensis* (in excess of 10 ind m^{-2}) at depths ranging from 0 to 20 m but also the proximity of these areas to a shipping port. Furthermore, it is imperative that potential fishing locations are readily accessible via automobile. A recent investigation in the coastal regions of the Barents Sea (Labutin et al. 2023) identified a total of five sites that satisfy these prerequisites (Fig. 4). These include: (a) Varanger-fjord (Site 1, with the nearest port being Liinahamari), (b) Ura Bay (Site 2, with Ura-Bay as the nearest port), (c) Teriberskaya Bay (Site 3, with Teriberka serving as the nearest port), (d) Dalnezelenetskaya Bay and Yarnyshnaya Bay (Site 4, having Dalnie Zelentsy as the nearest port), and (e) Bolshoy Oleniy Island alongside Porchnikha Bay (Site 5, also with Dalnie Zelentsy as the nearest port). In terms of total abundance, total biomass, and commercial biomass, the preeminent values were documented at Site 4 (41 ind. m^{-2}, 1.7 kg m^{-2}, and 1.1 kg m^{-2}) and Site 5 (52 ind. m^{-2}, 2.5 kg m^{-2}, and 1.8 kg m^{-2}), whereas the maximum total stock, commercial stock, and commercial stock within sea urchin aggregations were observed at Site 1 (1480, 750, and 337 t, respectively), as illustrated in Fig. 5. Consequently, among these identified locations, Varanger-fjord along with Bolshoy Oleniy Island and Porchnikha Bay have been deemed as having the greatest potential for sea urchin harvesting, followed by Yarnyshnaya and Dalnezelenetskaya Bays (Labutin et al. 2023). Although the other sites also present viable options for harvesting, they are expected to yield lower returns. The superiority of these sites over other potential areas for sea urchin fishing is attributed to their well-developed logistical infrastructure, which encompasses not only an adequate roadway system but also the availability of energy resources (Shatsky 2012b). Given that a substantial proportion of harvested green sea urchins are destined for live export, the proximity of comprehensive infrastructural facilities near coastal fishing

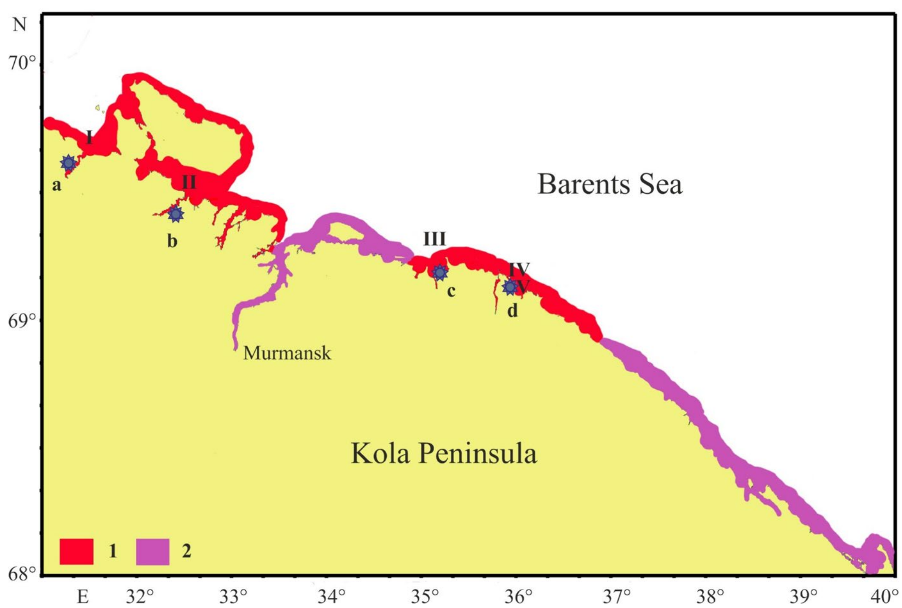


Fig. 4 Distribution of different-sized *Strongylocentrotus droebachiensis* in the coastal Barents Sea and the most suitable sites for harvesting and cultivation of green sea urchins. 1—diameter 61–70 mm, 2—diameter 11–50 mm. I—Varanger-fjord, II—Motovsky Bay, III—Teriberskaya Bay, IV—Yarnyshnaya Bay and Dalnezelenetskaya Bay, V—Bolshoy Oleniy Island and Porchnikha Bay. Shipping ports: a—Liinahamari, b—Ura-Bay, c—Teriberka, d—Dalnie Zelentsy (modified from Shatsky 2012b; Dvoretsky and Dvoretsky 2020a; Labutin et al. 2023)

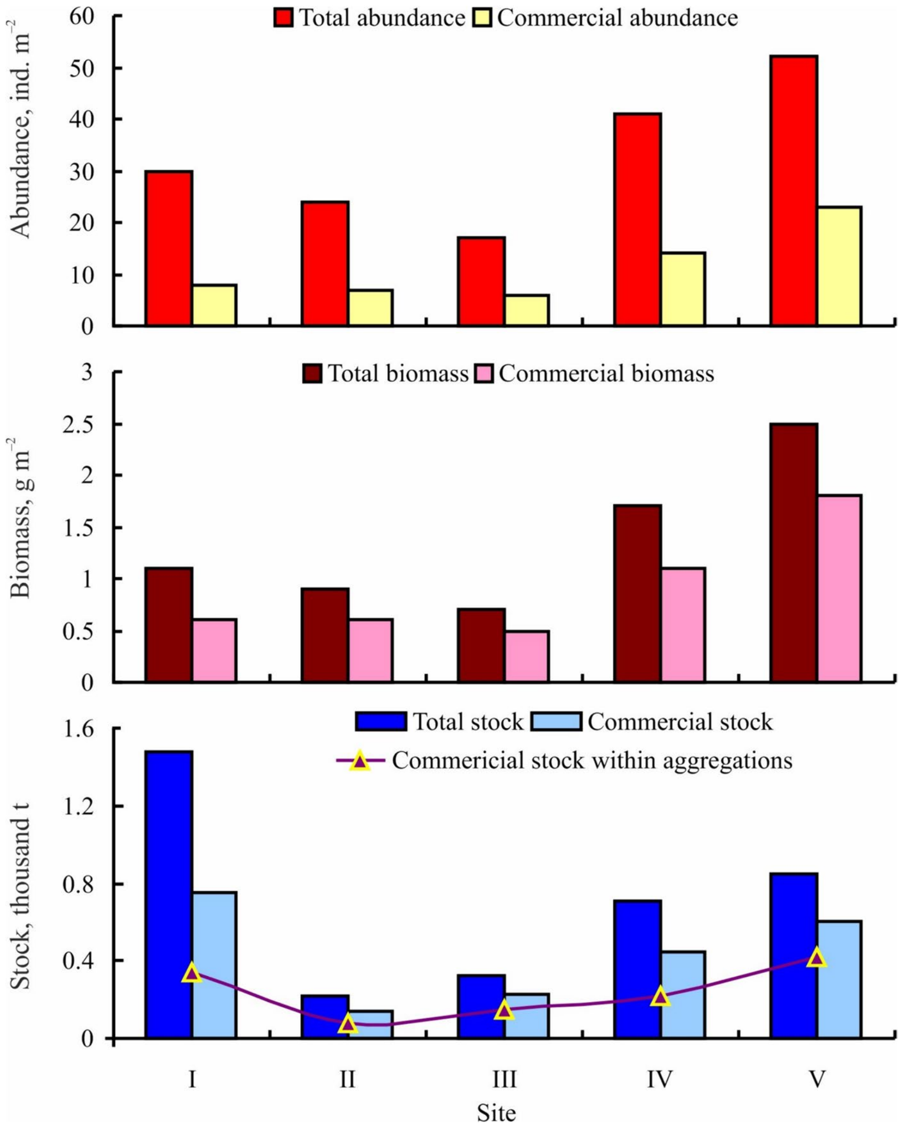


Fig. 5 Abundance, biomass and stock of *Strongylocentrotus droebachiensis* in the coastal Barents Sea. I—Varanger-fjord, II—Motovsky Bay, III—Teriberskaya Bay, IV—Yarnyshnaya Bay and Dalnezelenetskaya Bay, V—Bolshoy Oleniy Island and Porchnikha Bay (modified from Labutin et al. 2023)

zones becomes indispensable. Such infrastructure plays a pivotal role in ensuring the maintenance of optimal conditions for the urchins while in storage and in reducing the time required to transport them to Murmansk airport. The optimal periods for harvesting activities are February–March and September–October (Shatsky 2012b).

The assessments of green sea urchin stocks for commercial fishery has been conducted since 1978 when the total stock was estimated at 1250 t with a quota of 25 t (Drobysheva et al. 1979). In 1993, these parameters were estimated to be 7100 and 1420 t, respectively (Sennikov and Matyushkin 1994). From 2000 to 2010, the total stock of *S. droebachiensis* varied from 5000 to 7000 t and the total allowable catch varied from 350 to 1500 t. Actual landings were low with peaks in 2001 (30 t), 2002 (11 t), and 2006 (15 t). Most green sea urchins were harvested in the northern part of Kola Bay (Bakanev et al. 2022). During the period of 2011–2020 when diving surveys covered a much larger area, the total commercial stock was assessed at 60,000 t with an annual quota of 6000 t. The commercial harvesting was opened in 2016 with a total catch of 1.7 t. In the subsequent years, landings increased considerably accounting for 230.8, 254.2, 433.6, and 369.8 t in 2017, 2018, 2019, and 2020 with maximal daily catch rates (1.8–2.8 t) in the Western Coastal Area (Bakanev et al. 2022).

Aquaculture methods

In Russia, the goal of intensifying aquatic animal fisheries and aquaculture is a priority under the present world challenges (Dvoretsky and Dvoretsky 2020a, 2022b) and further efforts in developing new techniques and involving new species are highly recommended to maximize production and lower the impact of the high stocking rates on performance of aquatic organisms (Dvoretsky and Dvoretsky 2020a, 2021b, 2022b). There are three approaches for green sea urchin aquaculture in the coastal Barents Sea (Fig. 6): (a) reseeding natural habitats with farmed juveniles, (b) gonad enhancement of adult sea urchins harvested from wild populations, and (c) land-based closed-system aquaculture allowing control of each phase of the sea urchins biological cycle.

In vitro fertilization of green sea urchin eggs is the first step of *S. droebachiensis* cultivation. According to Zenzerov (1999), spawning of adult sea urchins can be induced by intracoelomic injection (2.5–4 ml) of 0.5% potassium chloride (KCl). The embryos of sea urchins are reared in glass incubators under controlled conditions with filtered seawater pumped from the open sea to provide natural salinity and temperature regimes. The water should be renewed twice a day. The embryos are kept constantly stirred by rotating at 30–60 rpm. The final stage before settlement and metamorphosis (echinopluteus) occurs at 30–40 d and the total survival rate of embryos may reach 88%. In *S. droebachiensis*, the duration of larval stages depends on temperature. Indeed, development from fertilized egg to the first pluteus stage requires 30 d at 0 °C, 12 d at 8 °C and only 6 d at 12 °C (Stephens 1972; Harris and Eddy 2015). The period from spawning to settlement for *S. droebachiensis* reared at 10 °C in laboratory culture lasts for 21 d (Harris et al. 2003). The low cost of the method used by Zenzerov (1999) is the reason for its potential in the restoration of degraded populations of *S. droebachiensis* and the development of its aquaculture in the Murmansk Region.

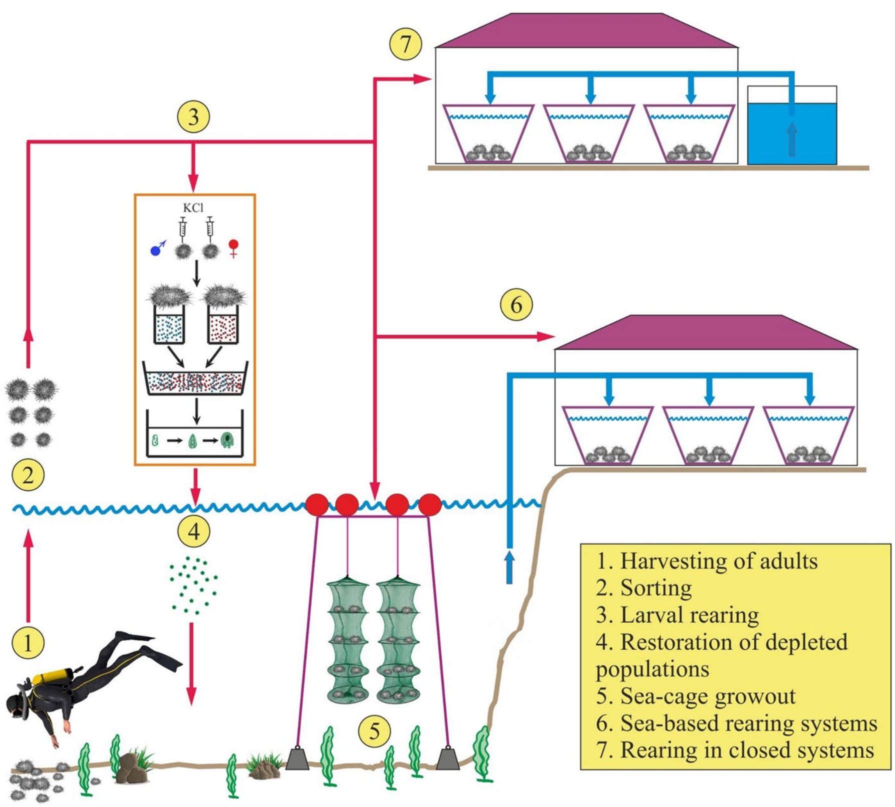


Fig. 6 Schematic of *Strongylocentrotus droebachiensis* aquaculture in the Barents Sea (modified from Dvoretsky and Dvoretsky 2020a)

Gonad enhancement of sea urchins reared in running-water systems does not require special equipment to maintain environmental conditions and may be applied in aquaculture. Experimental trials conducted by MMBI specialists showed that adult female sea urchins (diameter 55–65 mm, mean weight 100 g) collected in Dalnezelenetskaya Bay and then reared in cultivation tanks supplied with filtered seawater pumped from the open sea showed the constant feed intake rates over a 10-month study period (from October to July) (Matishov et al. 2011). The dynamics of water temperature in the cultivation tanks was the same as in the open sea (8 °C in October, 1 °C in February, and 5–6 °C in July). Oxygen levels were 6–7 mg L^{-1}. The animals fed on the flesh of sculpin (Cottidae spp.) and sandeel (*Ammodytes* sp.) showed 1.5–2 times higher gonad yields than wild conspecifics from the same area (control) and the animals fed on the brown alga *S. latissima*. The flesh of other fish species including cod (*Gadus morhua*), capelin (*Mallotus villosus*), wolffish (*Anarhichas* spp.), and herring (*Clupea harengus*) resulted in unacceptable gonad quality in terms of optimal gonad enhancement and the quality of roe. The same conclusion for fresh frozen herring as a diet for *S. droebachiensis* was made by Hooper et al. (1997) in Atlantic Canada.

Gonad enhancement experiments in a sea-based rearing system have been carried out in Ura-Bay (Shatsky 2012b) who reared adult green sea urchins (36–74 mm mean test diameter) in perforated plastic boxes placed at 0 and 5 m depth in the open sea for 120 days. Sea urchins were fed *S. latissima* (Group 1) and *Fucus vesiculosus* (Group 2). Daily feeding rations were 3%, 5%, and 10% of the body weight. Group 1 showed 2-times higher growth rates of the gonad weight and gonad index than wild sea urchins, while Group 2 had a lower growth rate than the control group. The best result was registered for the 3% feeding ration group (Shatsky 2012b). Another study tested a formulated diet developed by Dvinin (2005). This feed contains 70–80% of heat-treated low-cost fish by-products (skin, bones, and fins), 2% of vitamins, minerals, and/or carotenoids, and kelp-meal (*S. latissima* + *Fucus*). Adult green sea urchins (55–65 mm test diameter) fed on the formulated feed twice a week at a weekly ratio of 1–5% of the body weight showed an 172% growth rate (0.280 g per day) over a 3-month trial whereas the growth rate in control animals was 79% (0.085 g per day) (Mukhina and Pestrikova 2012). During 3-month trials, two groups of sea urchins (Group 1—small specimens with a mean diameter of 49 mm and Group 2—large specimens with a mean diameter of 61 mm) were reared in 600-L plastic tanks under controlled conditions in a recirculation system (Pavlova 2018). The sea urchins were fed a mixed diet containing meat of squid and *S. latissima* (ratio 10:1) twice a week. Growth rates of the gonad weight and GSI were 485 and 420% in Group 1, 400 and 310% in Group 2. Control animals attained significantly lower growth rates.

Although land-based systems with closed water circulation produced better results in comparison to sea-cage systems and water-flow systems with natural seawater, they are much more expensive because the additional costs involved. For this reason, sea-cage systems seem to be more suitable for sea urchin aquaculture in Russian waters of the Barents Sea. Commercial grow-out may be organized at the same sites as for commercial harvesting (Fig. 4). The optimal depth for sea cages or boxes is 5 m, stocking density 30 ind. per standard box (60 × 40 × 20 cm). The rearing periods of *S. droebachiensis* are 120 d for a natural diet (laminarian kelp) and 90 d for a mixed diet (kelp + animal food) or a formulated diet.

Conclusion

In the Barents Sea, green sea urchins are distributed in the coastal zone, south-eastern sea including Goose Bank, Moller Bank, and North Kanin Bank; near Bear Island, in the coastal Svalbard waters, and near Franz Josef Land. These animals are commonly associated with laminarian kelp with abundances up to 100–200 ind. m^{-2}. Below the rocky subtidal zone, *S. droebachiensis* occurs at low densities (2–5 ind. m^{-2}). Green sea urchins exhibit seasonal migrations being the most abundant at 5 m in the summer-autumn period and 10–15 m in winter. The brown algae *Saccharina latissima* is the primary diet for *S. droebachiensis* in the spring–summer period while *Desmarestia* dominated the diet in October–November. Sea urchins also consume animal foods such as hydrozoans, bryozoans, sponges, gastropods and bivalves because animal protein is necessary for maximal somatic and gonad growth. The red invasive king crab *Paralithodes camtschaticus* is the major predator for *S. droebachiensis* with consumption rates ranging from 0.2 to 8.0% of the total weight by one adult crab to 3–28% by one juvenile crab. The sex ratio of sea urchins is 1:1. They spawn once per year in March–April. The gonadosomatic index in sea urchins from eastern sites is higher than at western sites. Lifespan lasts 8–12 years. Green sea urchins become mature at age 3.5–5 (29–46 mm test diameter). The coast of the Kola Peninsula has promising potential for the development of sea urchin fishery and farming. Varanger-fjord on the western Murmansk coast as well as Bolshoy Oleniy Island and Porchnikha Bay on the eastern Murmansk coast are the best locations in terms of high sea urchin density and developed infrastructure. The optimal fishing seasons are February–March and September–October. In other seasons, high-quality products can be derived from grow-out cultures of *S. droebachiensis* in sea-cage or land-based systems with the use of natural or formulated diets.

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Declarations

Conflict of interest The authors declare no conflicts of interest.

Consent for publication All authors give their consent for publication.

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