

On the distribution of the Arctic endemic alga *Laminaria solidungula* (Laminariales) in the White Sea

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Abstract. The morphological and anatomical features of the specimens of the brown alga *Laminaria solidungula* collected in the White Sea are provided. Environmental conditions for the growth and reproduction of this species in the White Sea are analyzed. The probable timing of penetration of this species into the White Sea and possible scenarios of changes in its distribution in response to global warming are discussed.

Keywords: *Laminaria solidungula*, Phaeophyceae, Arctic endemic, brown algae, Solovetsky Islands, White Sea, Russia.

О распространении арктического эндемика *Laminaria solidungula* (Laminariales) в Белом море

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Резюме. Приводятся подробные данные о находках бурой водоросли *Laminaria solidungula* в Белом море, включающие результаты морфологического и анатомического изучения талломов и условия произрастания. Анализируются условия роста и размножения вида в Белом море. Обсуждаются вероятное время проникновения вида в Белое море и возможные сценарии изменения его распределения в условиях глобального потепления.

Ключевые слова: *Laminaria solidungula*, Phaeophyceae, арктический эндемик, бурые водоросли, Соловецкие острова, Белое море, Россия.

In an epoch of global environmental change, insight on changing geography of endemic Arctic species attracts much interest. Endemic species *Laminaria solidungula* J. Agardh is widespread along the entire Arctic Ocean. It is found in Alaska (Dunton, Jodwalis, 1988), Canadian Arctic (Taylor, 1957; South, 1983; Sharp *et al.*, 2008), Greenland (Schoenrock *et al.*, 2018), Spitsbergen (Vinogradova, 1995; Fredriksen *et al.*, 2019), and the seas of the Russian sector of the Arctic (Sinova, 1929; Vinogradova, 1986, 1999; Mikhaylova, 2006; Vinogradova, Shtrik, 2005).

Although most of the perennial kelp populations of *Laminaria solidungula* are truly the arctic, its refuge populations are known from sub-Arctic regions (Fig. 1), particular, in the Newfoundland fjords (53°08'08"N, 55°50'40"W) (South, 1983: 393–395) and off the northeastern coast of the Labrador Peninsula (59°59'04"N, 69°56'52"W) (Sharp *et al.*, 2008: 495). The records of this species in the southernmost areas of the

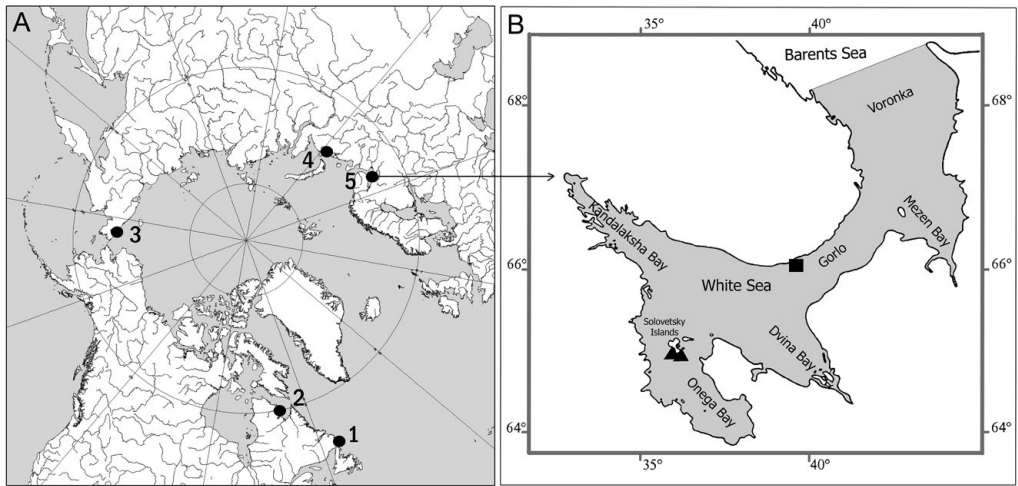


Fig. 1. Maps of the records of *Laminaria solidungula* at the southernmost distribution range boundaries.

A – map of the Arctic Ocean: 1, 2 – the Labrador Peninsula (South, 1983: 393–395; Sharp *et al.*, 2008: 495); 3 – the Kolyuchinskaya Bay, the Chukchi Sea (Vinogradova, 1999: 20); 4 – the Dolgy Island, the southeastern Barents Sea (Mikhaylova, 2006: 104); 5 – the White Sea; B – map of the White Sea: square – the Gorlo Strait, the White Sea (Vinogradova, Shtrik, 2005: 1597); triangles – the Solovetsky Islands, the White Sea (original data).

Arctic may allow understanding the successful survival of *L. solidungula* at the southern margin of its range.

The White Sea is not truly arctic, but a rather sub-arctic basin. Over four decades, in the 1970s–2010s, the monitoring of the harvesting sites has been performed once every three years by the Northern Branch of the Polar Institute of Fisheries and Oceanography (SevPINRO, Arkhangelsk, Russia) for estimating the stocks of commercial algae (Pronina, 2002, 2011; Pronina, Repina, 2005). In the White Sea, commercial kelp species are *Saccharina latissima* (L.) C. E. Lane *et al.*, *Laminaria digitata* (Huds.) J. V. Lamour., and *Alaria esculenta* (L.) Grev. No other kelp species have been registered here.

The first published record of *Laminaria solidungula* in the White Sea refers to the Gorlo Strait area (Vinogradova, Shtrik, 2005: 1597) (Fig. 1). This finding of few small specimens is based on the results of processing the materials obtained during the expedition of the Russian Institute of Fisheries and Oceanography (VNIRO, Moscow, Russia) in 2003. Unfortunately, in the English summary of this publication, this species was mistakenly indicated as “*Laminaria bongardiana*” (the species from the northern Pacific Ocean, unknown for the White Sea and thus not mentioned in the text of this paper) instead *L. solidungula* (Vinogradova, Shtrik, 2005: 1599). This mistake may lead to confusion in understanding the distribution of *L. solidungula* in the White Sea for the non-Russian-speaking reader. In addition, these authors mentioned the

really first finding of this species in the White Sea, but, unfortunately, without indicating the sampling date, coordinates, descriptions, and without providing the images of the specimens (Vinogradova, Shtrik, 2005).

In this short communication, accurate information about the first two records of *Laminaria solidungula* in the White Sea is provided and the environmental conditions for the growth and reproduction of this species in the White Sea are discussed.

Material and Methods

The specimens of *Laminaria solidungula* were found in the summer of 1993 and 1996 by the author at the Solovetsky Islands, located in the central part of the White Sea, during the survey sampling for replenishing the herbarium (Fig. 1). The sporophytes were collected by SCUBA diving in the kelp community under the canopy of dominant large species *Saccharina latissima* and *Laminaria digitata*. Despite the identification of the specimens of *L. solidungula* by K. L. Vinogradova (Vinogradova, Shtrik, 2005) appears to be quite reliable, our search of them in Herbarium of the Komarov Botanical Institute RAS LE (LE) was resultless.

Specimens examined: **Russia, White Sea**, Solovetsky Islands, Pechak Cape, 64°57'10"N, 35°45'03"E, depth 6–7 m, 1 VII 1993, *Yu. A. Morozov* (Ю. А. Морозов), det. *Mikhaylova*, LE A0000162; *ibid.*, Pechakovskaya Salma Strait, 64°58'53"N, 35°42'46"E, depth 6–7 m, 30 VIII 1996, *Mikhaylova*, specimens nos. 1 and 2 stored in the herbarium of SevPINRO, Arkhangelsk.

The specimens were measured and the thallus microstructures were examined at cross-sections of the stipe and blade under an upright light microscope Zeiss Axio Scop.A1 equipped with the camera AxioCam ICc 1.

Results and Discussion

Description of the first finding. Holdfast disk-like, thallus length 56 cm, stipe length 5 cm, new blade length 35 cm, old blade length 21 cm, blade width 14 cm, soral area on the old blade (Plate I: 1), sporangia at the stage of spore development (Plate II: 1), mucilage canals in the stipe (Plate II: 2).

Description of the second finding. Holdfast disk-like, thallus length 23 and 32 cm, stipe length 3 cm, blade length 20 and 29 cm, blade width 8 and 11 cm (Plate I: 2, 3), linear mucilage canals in the interior of the stipe cortex of the specimen no. 2 (Plate II: 3).

Unambiguous taxonomic characters, both morphological (disk-shaped holdfast) and microstructural (mucilage canals in the stipe) of the collected specimens (Plates I, II) clearly indicate the presence of this species in the flora of the White Sea in the recent past. In addition, a soral area is observed on the old blade of the specimen LE A0000162 collected in the middle of summer 1993 (Plate I: 1); sporangia are at the stage of spore development (Plate II: 1). According to Roleda (2016), fertile *Laminaria solidungula* sporophytes, carrying sorus at different stages of maturity, have been observed in different areas of the Arctic throughout the entire year. However, sporogenesis predominantly occurs under darkness and during a short-day period of the year (Roleda, 2016). The

coastal areas of the Solovetsky Islands are covered by ice from November to May; this provides the low-light conditions necessary for sporogenesis and gametogenesis. Most likely, the fertile sporophytes, which were collected in the White Sea in summer, started sporogenesis during winter or early spring, similarly to the fertile specimens described from Svalbard during the summer period (Roleda, 2016).

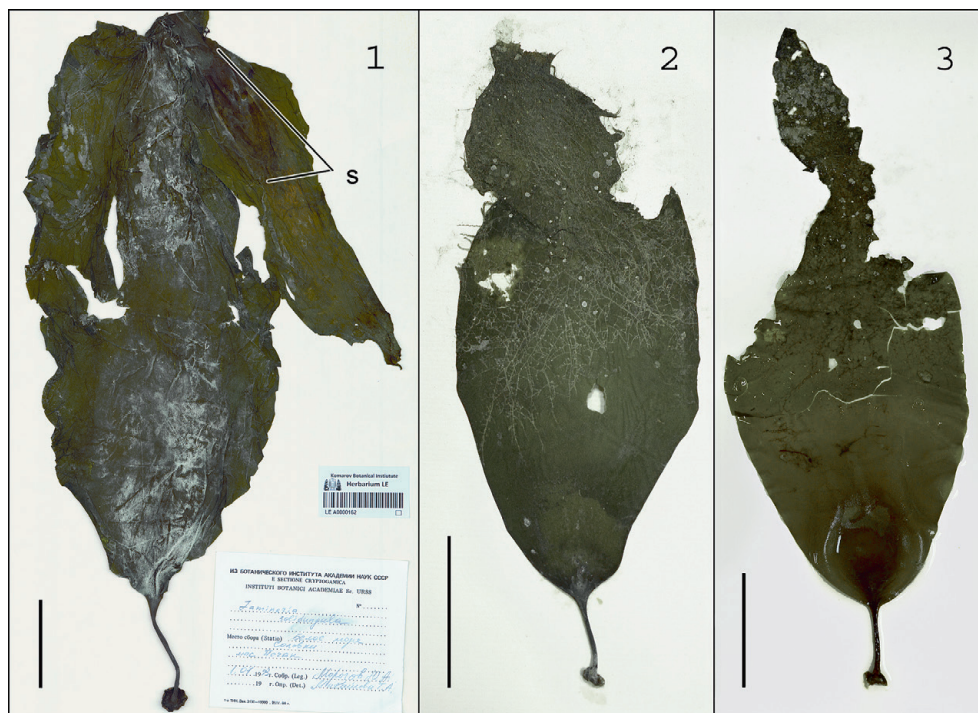


Plate I. Specimens of *Laminaria solidungula* from the White Sea.

1 – specimen LE A0000162; 2, 3 – specimens nos. 1 and 2 from the Herbarium of SevPINRO.
s – soral area on the old blade of the specimen. Scale bars: 5 cm.

The upper limit of temperature tolerance of *Laminaria solidungula* gametophytes is 19–20°C; however, this parameter for sporophytes is lower than that for gametophytes (tom Dieck, 1993). Sporophyte growth optimum ranges from 5 to 10°C, and the upper limit of temperature tolerance limit is 16°C (tom Dieck 1992; Müller *et al.*, 2009). Simultaneous increasing temperature to 15°C and decreasing salinities to 25 ‰ are environmental stress factors for the physiological and biochemical responses of *L. solidungula* (Diehl *et al.*, 2020).

In summer, in the Pechakovskaya Salma Strait of the Solovetsky Islands, the average sea surface temperature and salinity are 11°C and 26.5 ‰, respectively, in the winter, –1.3°C and 24.2 ‰ (Chugaynova, 2007).

Therefore, the environmental conditions along the Solovetsky Islands region are not stressful for *Laminaria solidungula* since the combination of water temperature

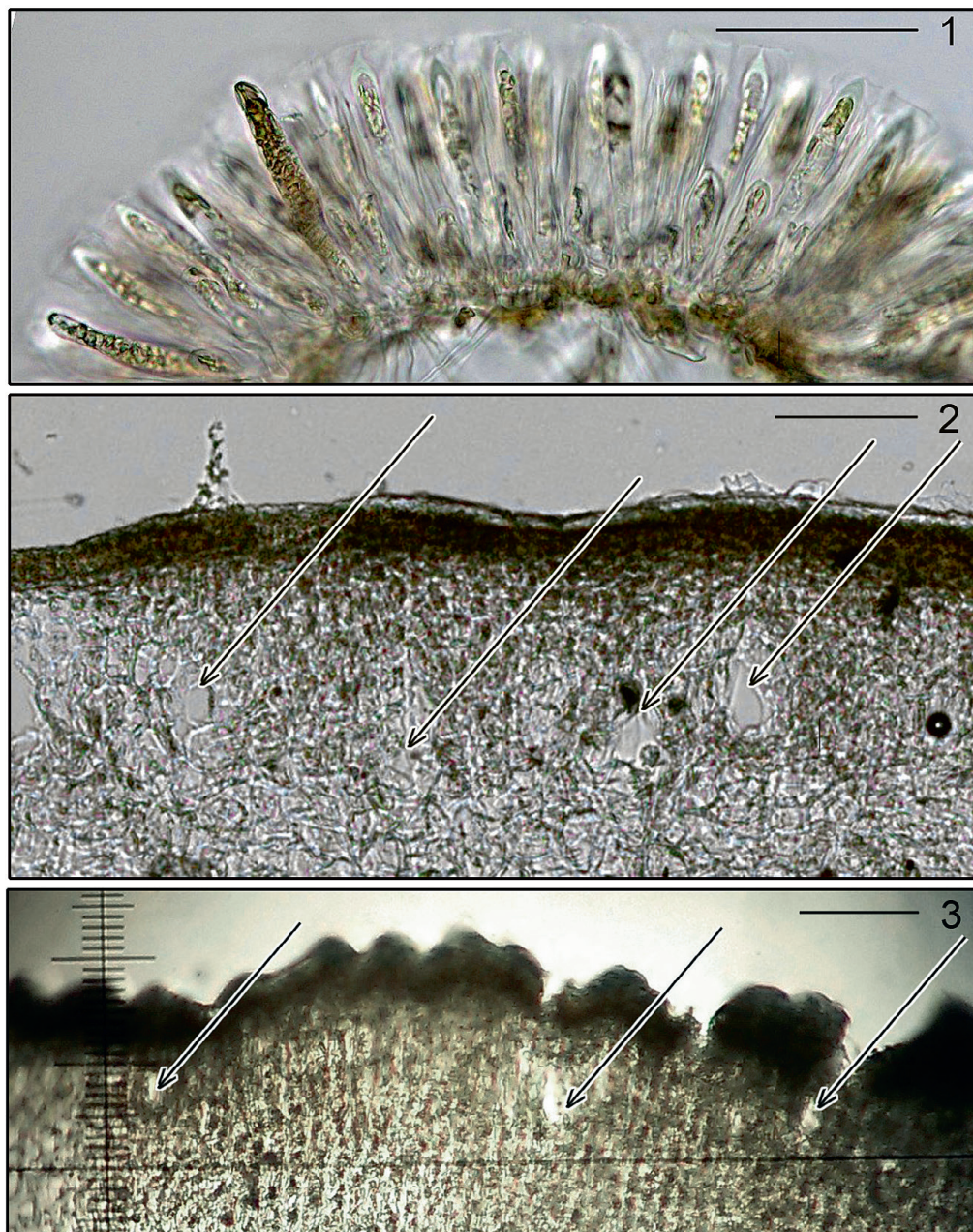


Plate II. Microstructural characteristics of *Laminaria solidungula* from the White Sea.
1 — sporangia on the cross-section of the blade of the specimen LE A0000162; 2, 3 — mucilage canals (indicated by arrows) on the cross-section of the stipes of the specimen LE A0000162 (2) and the specimen no. 2 from the Herbarium of SevPINRO (3).
Scale bars: 1 — 50 μm ; 2, 3 — 200 μm .

and salinity never reaches a critical level. Moreover, the specimens grow here at a depth of 6–7 m, where the water temperature in summer is definitely lower and the water salinity in winter is undoubtedly higher than critical values.

However, detection of this species by visual examination of underwater vegetation in the White Sea is difficult since *Laminaria solidungula* inhabits dense communities of other kelp species, and young *L. solidungula* and *Saccharina latissima* are similar in appearance. Nevertheless, collected during sampling specimens of *L. solidungula* are easy to identify due to the disk-shaped holdfast instead of rhizoids. It is unlikely that new records of this species may be explained by its accidental absence in previous samples because the species of *Laminaria* were the subject of the perennial special survey in the White Sea (Pronina, 2002, 2011; Pronina, Repina, 2005). Most likely, these records are a result of the recent penetration of *L. solidungula* into the White Sea (Vinogradova, Shtrik, 2005).

There are two ideas about how climate change may affect the distribution of *Laminaria solidungula* in the Arctic in the future. On the one hand, it is suggested that the southern boundaries of the Arctic species ranges will shift further northwards according to the 2080–2099 forecast of climate warming along with a simultaneous decrease in the water salinity. In particular, *L. solidungula* will become extinct off the Arctic island of the Novaya Zemlya, the southwestern coast of Greenland, the Hudson Bay, the southern coast of the Baffin Island, along the Labrador Peninsula, and Newfoundland (Müller *et al.*, 2009). On the other hand, some authors believe that considering the worst prognosis of 4°C temperature increase by 2100, photosynthetic activity and the growth of spores, gametophytes, and sporophytes of *L. solidungula* are unlikely to be affected negatively (Roleda, 2016).

In conclusion, it may be stated that nowadays temperature, salinity, and low-light conditions in the White Sea are suitable for the survival and reproduction of *Laminaria solidungula*; the distribution of this species here similar to the Labrador Peninsula is restricted to the super-cooled water masses, which may reach relatively shallow depths (Hooper, 1984).

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