

Supplementary Information I. Details for Greenland

Table S1. List of floristic macroalgal investigations in Greenland organized according to region (West, East, South), latitude, and period of the survey. Key studies used in evaluation of trends in composition (for Table 1, Fig. 1) are marked by *. Studies including information on *Platysiphon verticillatus* are marked by **. GEM: Greenland Ecosystem Monitoring.

Region Author(s)	Site	Latitude (°N)
General		
*Pedersen, 2011	General	
West Greenland		
**Wilce, 1962	Inglefield Bredning	78
*Wilce, 1964	Qaannaq	78
*Wegeberg, 2011	Baffin Bay	71-78
Rosenvinge, 1893	Greenland	60-72
Rosenvinge, 1898	Greenland	61-73
*Jónsson, 1904	Greenland	60-71
Krause-Jensen et al., 2012	Nuuk-Siorapaluk	64-78
*Andersen et al., 2005	North Star Bay	76
Hansen and Schlütter, 1992	Disko	69
Hansen et al., 2013	Disko Bay area	67-70
Marba et al., 2017	Nuuk, Disko Bay	64, 69
GEM, MarineBasis Disko (2018-)	Disko Bay	69
Krause-Jensen et al., 2019	Disko Bay area	67-70
GEM, MarineBasis Nuuk (2007-2011, 2012-)	Nuuk	64
Schoenrock et al., 2018	Nuuk	64
Wegeberg, 2007	Qaqortoq	61
East Greenland		
Kjellmann, 1883	Arctic Sea	?
*Lund, 1951	Jørgen Brønlund's Fjord	82
**Wegeberg, 2012a	Greenland Sea	68-81
*Rosenvinge, 1910	Danmarkshavn, Store Koldewey Island	77
*Lund 1938, **1959	Kejser Franz Josephs Fjord, Scorebysund	70-72
*Jónsson, 1904	Greenland	60-74
Rosenvinge, 1893	Greenland	60,65,70
*Rosenvinge, 1933	Kangerlussuaq, East Greenland	68
Rosenvinge, 1898	Greenland	60
Borum et al., 2002	Young Sound	74
GEM, MarineBasis Zackenberg (2003-)	Young Sound	74
Krause-Jensen et al., 2007	Young Sound	74
Krause-Jensen et al., 2012	Nuuk-Siorapaluk	64-77
**Birklund et al., 2006	Mestersvig	72
*Wegeberg, Geertz-Hansen 2016-17 unpubl.	Tasiilaq to Danmarkshavn	66-77
South Greenland		
*Pedersen, 1976	Cape Farewell	60
*Wegeberg, 2012a	Cape Farewell	60
Høgslund et al., 2014	Cape Farewell, Kitsissut	60

Table S2. Species registered in the Cape Farewell area, S. Greenland, in a survey in 1970 (Pedersen, 1976) and in a survey in 2011 (Wegeberg, 2012b).

	1970	2011
Rhodophyta		
<i>Acrochaetium microscopicum</i> (Nägeli ex Kützing) Nägeli	x	x
<i>Acrochaetium secundatum</i> (Lyngbye) Nägeli	x	x
<i>Bangia fuscopurea</i> (Dillwyn) Lyngbye	x	x
<i>Calocolax neglectus</i> F. Schmitz ex Batters	x	
<i>Clathromorphum compactum</i> (Kjellman) Foslie		x
<i>Coccotylus truncatus</i> (Pallas) M.J. Wynne & J.N. Heine	x	x
<i>Devaleraea ramentacea</i> (Linnaeus) Guiry	x	x
<i>Euthora cristata</i> (C. Agardh) J. Agardh	x	x
<i>Fimbrifolium dichotomum</i> (Lepechin) G.I.Hansen	x	x
<i>Grania efflorescens</i> (J. Agardh) Kylin	x	
<i>Rhodophysema lundii</i> (Edelstein) C.W.Schneider & M.J.Wynne	x	x
<i>Harveyella mirabilis</i> (Reinsch) F.Schmitz & Reinke	x	x
<i>Hildenbrandia rubra</i> (Sommerfelt) Meneghini	x	x
<i>Lithothamnion glaciale</i> Kjellman	x	
<i>Meiodiscus spetsbergensis</i> (Kjellman) G.W.Saunders & McLachlan	x	x
<i>Membranoptera denticulata</i> (Montagne) Kylin	x	x
<i>Palmaria palmata</i> (Linnaeus) F. Weber & D. Mohr	x	x
<i>Pantoneura fabriciana</i> (Lyngbye) M.J. Wynne	x	
<i>Phycodrys rubens</i> (Linnaeus) Batters	x	x
<i>Phymatolithon tenue</i> (Rosenvinge) Düwel & Wegeberg	x	
<i>Savoiea arctica</i> (J. Agardh) M.J. Wynne	x	x
<i>Polysiphonia stricta</i> (Mertens ex Dillwyn) Greville		x
<i>Ptilota serrata</i> Kützing	x	x
<i>Rhodochorton purpureum</i> (Lightfoot) Rosenvinge	x	
<i>Rhodomela lycopodioides</i> (Linnaeus) C. Agardh	x	x
<i>Rhodophysema elegans</i> (P.Crouan & H.Crouan ex J.Agardh) P.S.Dixon	x	x
<i>Rubrointrusa membranacea</i> (Magnus) S.L.Clayden & G.W.Saunders	x	x
<i>Scagelothamnion pusillum</i> (Ruprecht) Athanasiadis	x	x
<i>Turnerella pennyi</i> (Harvey) F. Schmitz	x	
<i>Wildemania miniata</i> (C. Agardh) Foslie	x	x
<u>Sum Rhodophyta</u>	<u>28</u>	<u>23</u>
Phaeophyceae		
<i>Agarum clathratum</i> Dumortier	x	x
<i>Alaria esculenta</i> (Linnaeus) Greville	x	x
<i>Ascophyllum nodosum</i> (Linnaeus) Le Jolis	x	x
<i>Battersia arctica</i> (Harvey) Draisma, Prud'homme & H. Kawai	x	x
<i>Chaetopteris plumosa</i> (Lyngbye) Kützing	x	x

<i>Chorda filum</i> (Linnaeus) Stackhouse	X	
<i>Chordaria flagelliformis</i> (O.F.Müller) C.Agardh	X	X
<i>Coilodesme bulligera</i> Strömfelt	X	X
<i>Delamarea attenuata</i> (Kjellman) Rosenvinge	X	X
<i>Desmarestia aculeata</i> (Linnaeus) J.V. Lamouroux	X	X
<i>Desmarestia viridis</i> (O.F.Müller) J.V.Lamouroux	X	X
<i>Dictyosiphon chordaria</i> Areschoug	X	
<i>Dictyosiphon foeniculaceus</i> (Hudson) Greville	X	X
<i>Ectocarpus fasciculatus</i> Harvey		X
<i>Ectocarpus siliculosus</i> (Dillwyn) Lyngbye	X	X
<i>Elachista fucicola</i> (Vellay) Areschoug	X	X
<i>Eudesme virescens</i> (Carmichael ex Berkeley) J. Agardh	X	
<i>Fucus distichus</i> Linnaeus	X	X
<i>Fucus vesiculosus</i> Linnaeus	X	X
<i>Gononema aecidioides</i> (Rosenvinge) P.M. Pedersen		X
<i>Halosiphon tomentosus</i> (Lyngbye) Jaasund	X	
<i>Haplospora globosa</i> Kjellman	X	
<i>Hedophyllum nigripes</i> (J. Agardh) Starko, S.C. Lindstrom & Martone	X	X
<i>Hincksia ovata</i> (Kjellman) P.C. Silva	X	X
<i>Isthmoplea sphaerophora</i> (Carmichael) Gobi	X	X
<i>Laminaria solidungula</i> J.Agardh	X	X
<i>Laminariocolax aecidioides</i> (Rosenvinge) A.F. Peters	X	
<i>Laminariocolax tomentosoides</i> (Farlow) Kylin	X	
<i>Leptonematella fasciculata</i> (Reinke) P.C.Silva	X	X
<i>Mikrosyphar polysiphoniae</i> Kuckuck	X	X
<i>Myriactula clandestina</i> (P.L.Crouan & H.M.Crouan) Feldmann	X	
<i>Omphalophyllum ulvaceum</i> Rosenvinge	X	
<i>Papenfussiella callitricha</i> (Rosenvinge) Kylin	X	
<i>Petalonia fascia</i> (O.F.Müller) Kuntze	X	
<i>Phaeostroma longisetum</i> (S. Lund) P.M. Pedersen		X
<i>Phaeostroma parasiticum</i> Børgesen	X	X
<i>Phaeostroma pustulosum</i> Kuckuck	X	
<i>Pogotrichum filiforme</i> Reinke	X	X
<i>Punctaria plantaginea</i> (Roth) Greville		X
<i>Pylaiella littoralis</i> (Linnaeus) Kjellman	X	X
<i>Pylaiella varia</i> Kjellman	X	X
<i>Ralfsia fungiformis</i> (Gunnerus) Setchell & N.L. Gardner	X	
<i>Ralfsia verrucosa</i> (Areschoug) Areschoug	X	
<i>Saccharina latissima</i> (Linnaeus) C.E.Lane, C.Mayes, Druehl & G.W.Saunders	X	X
<i>Saccorhiza dermatodea</i> (Bachelot de la Pylaie) J. Agardh	X	X
<i>Scytosiphon complanatus</i> (Rosenvinge) Doty	X	X
<i>Scytosiphon lomentaria</i> (Lyngbye) Link	X	X

<i>Sorapion kjellmanii</i> (Wille) Rosenvinge	x	
<i>Stictyosiphon tortilis</i> (Gobi) Reinke	x	x
<i>Symphycarpus strangulans</i> Rosenvinge	x	
Sum Phaeophyceae	<u>46</u>	<u>34</u>
Chlorophyta		
<i>Acrosiphonia arcta</i> (Dillwyn) Gain	x	x
<i>Acrosiphonia sonderi</i> (Kützing) Kornmann	x	x
<i>Blidingia minima</i> (Nägeli ex Kützing) Kylin	x	
<i>Bolbocoleon piliferum</i> Pringsheim	x	
<i>Capsosiphon fulvescens</i> (C. Agardh) Setchell & N.L. Gardner	x	
<i>Chaetomorpha ligustica</i> (Kützing) Kützing	x	x
<i>Chaetomorpha melagonium</i> (F. Weber & D. Mohr) Kützing	x	x
<i>Chlorochytrium cohnii</i> E.P. Wright	x	
<i>Chlorochytrium dermatocolax</i> Reinke	x	x
<i>Epicladia flustrae</i> Reinke	x	
<i>Eugomontia sacculata</i> Kornmann	x	
<i>Gomontia polyrhiza</i> (Lagerheim) Bornet & Flahault	x	
<i>Kornmannia leptoderma</i> (Kjellman) Bliding	x	
<i>Monostroma grevillei</i> (Thuret) Wittrock	x	x
<i>Ostreobium quekettii</i> Bornet & Flahault	x	
<i>Percursaria percursa</i> (C. Agardh) Rosenvinge	x	
<i>Prasiola meridionalis</i> Setchell & N.L. Gardner	x	
<i>Pseudendoclonium submarinum</i> Wille	x	
<i>Pseudendoclonium fucicola</i> (Rosenvinge) R. Nielsen	x	
<i>Pseudothrix groenlandica</i> (J. Agardh) Hanic & S.C. Lindstrom	x	x
<i>Rhizoclonium riparium</i> (Roth) Harvey	x	
<i>Rosenvingiella constricta</i> (Setchell & N.L. Gardner) P.C. Silva		x
<i>Rosenvingiella polyrhiza</i> (Rosenvinge) P.C. Silva	x	
<i>Sarcinastrum urospora</i> Lagerheim		x
<i>Spongomorpha aeruginosa</i> (Linnaeus) Hoek	x	
<i>Syncoryne reinkei</i> R. Nielsen & P.M. Pedersen		x
<i>Ulothrix flacca</i> (Dillwyn) Thuret	x	
<i>Ulothrix speciosa</i> (Carmichael) Kützing	x	
<i>Ulva prolifera</i> O.F. Müller	x	x
<i>Ulvaria obscura</i> (Kützing) Gayral ex Bliding	x	
<i>Ulvaria splendens</i> (Ruprecht) K.L. Vinogradova		x
<i>Ivella scutata</i> (Reinke) R. Nielsen, C.J. O'Kelly & B. Wysor	x	
<i>Urospora penicilliformis</i> (Roth) Areschoug	x	x
<i>Urospora wormskioldii</i> (Mertens) Rosenvinge	x	
Sum Chlorophyta	<u>30</u>	<u>13</u>
Overall sum	104	70

Supplementary Information II. Details for Iceland

Table S3. Overview of some baseline studies on marine vegetation in Iceland. Most span a time interval, but data was not collected multiple times in the same area and are therefore not applicable to analyse trends. Site, study period (time intervals separated by /), vegetation type

COUNTRY # Site	Study period	Vege tation type	Metric	Ref.
ICELAND				
Breiðafjörður	2016	i	<i>Acophyllum</i> biomass and size	Gunnarsson et al., 2019
Circum Iceland	2012/2014	i	Habitat type distribution	Ottósson et al., 2016
Circum Iceland	1973/2005	i	Species composition, biomass, cover, depth range, distribution.	Ingolfsson et al., 2006
Circum Iceland	1972/1999	i, s	Species list	Gunnarsson et al., 2002
Álftafjörður Lónsfjörður, Papafjörður, Hornafjörður Mjóifjörður	1968/1977	i, s	Species composition	Munda, 1999
Hornstrandir, Steingrímsfjörður, Skagaströnd, Fljót, Ólafsfjörður, Tjörnes, Melrakkaslétta, Langanes	1965/1968/1975/ 1980	i, s	Species composition	Munda, 1994
Circum Iceland	1975/1976	i, s	Species composition	Munda, 1992
Circum Iceland	1964/1972/1977	i, s	Species composition, biomass	Munda, 1987

(intertidal macroalgae (i), subtidal macroalgae (s)), metric, and reference are indicated in the table.

Supplementary Information III. Details for Svalbard

Details on climate change in Svalbard

Detailed information on abiotic factors (hydrography, salinity, air, seawater temperature, and irradiance), soft and hard bottom benthic communities as well as zoo- and phytoplankton composition is readily available from two western fjord systems, especially Kongsfjorden ($78^{\circ} 55' \text{ N}$, $11^{\circ} 56' \text{ E}$) but also Isfjorden ($78^{\circ} 19' \text{ N}$, 15° E). They represent the largest fjord systems of the archipelago and are well studied. Both fjords are strongly impacted by environmental change (Nilsen et al., 2008; Hop and Wiencke, 2019). Northeastern Spitsbergen, van Mijenfjorden ($77^{\circ} 47' \text{ N}$, $15^{\circ} 33' \text{ O}$), and Hornsund ($76^{\circ} 58' \text{ N}$, $15^{\circ} 43' \text{ O}$), both located further south on the island of Spitsbergen, are still considered to possess Arctic characteristics with respect to their temperature conditions, but there is recent evidence of change as well (Muckenhuber et al., 2016). In general these areas are less well investigated, and, with the exception of Hornsund (i.e. Weslawski et al., 1988, 2010; Grzelak and Kotwicki, 2012) data on hydrography and benthic community composition are rather scarce and scattered. Some information for Grønfjorden, a side arm of Isfjorden is also available but unfortunately only published in Russian language and thereby has not been considered here (e.g. Ryzhik and Voskoboinikov, 2003; Matishov et al., 2004; Tretyakov et al., 2007; Meshcheryakov, 2017).

A recent analysis of hydrographic data facilitated by permanent moorings in Kongsfjorden established along the fjord transect revealed an increase in seawater temperature since 2002. For the year 2006, data reveal a significant impact of Atlantic water connected to an upward-shift in seawater temperature (Hop et al., 2019). In the subsequent years sub-zero monthly averaged seawater temperatures have only been recorded in the system twice, in the winter seasons of 2009 and 2010. Therefore, it is suggested that a shift from an Arctic to a sub-Arctic system has happened in Kongsfjorden in 2006 (Hop et al., 2019).

The increasing mass transport of relatively warm Atlantic water drives the system from an Arctic to a more boreal state (Tverberg et al., 2019; Hop et al., 2019) and largely prevented sea-ice formation in the central part of Kongsfjorden for the last decade (Pavlova et al., 2019). The interplay of water convection and sea-ice formation has major implications for the onset of phytoplankton blooms in Kongsfjorden leading to very late blooms under shallow convection and no sea-ice in years with warm winters (Hegseth et al., 2019).

Supplementary Information IV. Macrophyte flora of the Russian Arctic coast: Brief review of species richness, communities, and relevant oceanographical conditions and current climatic changes

*Olga Maximova, Ulyana Simakova, Vassily Spiridonov**

Shirshov Institute of Oceanology, Nakhimovskiy Prospekt, 36, Moscow, 117997
Russia

*Corresponding author, E-mail: vspiridonov@ocean.ru, valbertych@gmail.com

Macroalgal flora of the Russian Arctic coast is highly unevenly studied. Disregarding the research intensity issue, there is a clear gradient of diminishing species richness from the west to the east (Barents and White to the Laptev Sea) with some increase towards the Chukchi Sea. There are also gradients of decreasing species richness from the south to the north in the Barents Sea, and increasing from the continental coast of Siberia (in the Kara and Laptev Seas) towards the High Arctic Archipelagoes (Table SI-V-1).

The southern Barents Sea

European Arctic continental coast in Russia can be further subdivided into the western and the eastern parts. The western part includes the shore eastward of the Russian – Norwegian border in the Varanger-fjord, Kola Peninsula (southwestern Barents Sea), and the White Sea. The eastern part includes the Chioshskaya Bay, the continental coast and islands of the Pechora Sea. The southwestern Barents and the White Sea are considered as the part of the Low Arctic or Subarctic Phytogeographical region, with a macroalgal flora similar to the Norwegian Sea coast of the Scandinavian Peninsula. The south-eastern Barents Sea is referred to as the High Arctic Phytogeographical region (Zinova, 1974). The coastal zone of the Kola Peninsula in the Barents Sea (historically called Murman or Murmansk Coast) is influenced by the Murmansk Current and the Murmansk Coastal Current, transporting the Atlantic water. The Barents Sea in general is affected by increasing input of the warm and haline Atlantic water and the most dramatic, for the Eurasian Arctic, decrease of seasonal sea ice which became particularly strong since 2004 (Onarheim et al., 2018; Trofimov et al., 2018). However, the Kola Peninsula coastal zone in the Barents Sea has been practically ice free in the historical time. Limited long-term data on particular inlets indicate some warming of the water in the last decade with a seemingly stable pattern of the seasonal water column evolution (Il'in et al., 2016; Deart et al., 2017). No long-term studies on the nutrients cycling in the coastal waters have been published.

In the Varanger-fjord and along the Murmansk Coast, the shores provide suitable habitats for macroalgae due to extensive areas with rocky and other hard substrates. There is a nearly continuous belt of intertidal and subtidal communities extending along the coastline. The respective flora is most species rich and taxonomically diverse compared to any other marine algal floras of the Russian Arctic. Although the estimates of species richness are largely outdated (Table S4). Intertidal communities are dominated by fucoids, mainly *Ascophyllum nodosum* and *Fucus vesiculosus* (up to 95–99% of the total biomass). At the exposed rocky shores kelp species (*Laminaria digitata*, *Saccharina latissima*) are ascending to the lower intertidal. The biomass of

intertidal macrophytes ranges from 1.5 to 10 kg/m², and the width of the fucoïd belt varies from 5-8 to 25-30 m (Kuznetsov and Shoshina, 2003; Blinova, 2007).

Kelp communities along the Murmansk Coast are dominated by *Laminaria digitata*, *Saccharina latissima* and *Alaria esculenta*, while the composition of subdominants and less common species, and spatial structure of these communities varies from site to site. The width of kelp belt may reach to 1–1.5 km (in some protected bays and in the straits between small islands and the mainland, the wet biomass varies from 5 to 12 kg m⁻². In the 1960 – 1980s, a description of macrophyte communities and assessment of harvestable biomass of kelp species was made for particular bays and fjords of the southwestern Barents Sea along the Kola Peninsula Coast. They could be of potential value in case methodologically comparable new assessments should be made for the same areas (Blinova, 1964, 2007; Propp, 1971; Sorokin and Peltikhina, 1991; Kuznetsov and Shoshina, 2003; Malavenda and Malavenda, 2012; Malavenda and Metelsky, 2013).

East of the Kola Peninsula, the sea is seasonally ice covered and hard substrates are limitedly present along the shore. There kelp communities are patchy (on the eastern shore of the Kanin Peninsula or on Vaigach Island) or entirely lacking in some large bays, such as Chioshskaya Guba; however, this information is limited (Sorokin and Peltikhina, 1991).

Eelgrass meadows are very fragmentarily distributed along the coast of the Varanger-fjord and the Barents coast of the Kola Peninsula. Historically, they were reported for Vaida-Guba inlet (Varanger-fjord) (Zenkevich, 1963), although they were not found there during the surveys of 2011, 2015 and 2016. Instead, a *Zostera marina* population has been found in the neighboring closed inlet Guba Malaya Volokovaya (Simakova et al., 2016). The other extensive subtidal eelgrass spot is located several hundred kilometers to the east in Guba Ivanovskaya. It became known in the early 1960 (Blinova, 1964, 2007; P.P. Strelkov, pers. comm.).

White Sea

The White Sea was covered by ice for nearly half a year for most of the 20th century but usually for lesser time in the 2000s-2010s; (Dumanskaya, 2012; Pantyulin, 2012a). Its important oceanographic features are freshening of the coastal waters compared to the Barents Sea and significant warming of coastal waters in summer, in particular in its inner part. Otherwise, the main subdivisions of the White Sea (i.e. the Gorlo Strait dividing the outer and inner parts of the Sea, its central part, and the main bays) significantly differ in their oceanographical conditions, i.e. stratification in the Kandalaksha Bay vs the unstratified water column in the Gorlo and the Onega Bay, the Severnaya Dvina River runoff in the Dvina Bay, extreme tidal regime of the Mezen Bay etc. (Berger and Naumov, 2001; Filatov et al., 2004; Pantyulin, 2012b). Due to the peculiar status of the White Sea as a semi-landlocked basin and the isolation from the direct input of the Atlantic water, its regime is largely determined by regional scale processes such as the winter production of cold and salt water in the Gorlo Strait, which is physically resistant to climate change (Kosobokova et al., 2004; Pantyulin, 2012b; Spiridonov et al., 2017). The effects of changing climate in the last decades is mostly attributed to variation in timing of winter sea ice cover (Pantyulin et al., 2012a). Until the early 2010s no significant trends (but variation correlated with the North Atlantic oscillation index) were observed in the maximum extent of sea ice

and seasonal pattern of temperature in the upper water column (on the basis of data from thirteen permanent stations; Drozdov and Usov, 2014). At the same time, the data from the station in the Dvina Bay indicate a significant trend of average surface water temperature increase and earlier spring warming to the mid-2010s (Stasenkov, 2017). This may be particularly related to the warming effect of the Severnaya Dvina river runoff. Similarly, to the coastal Barents Sea, no long-term studies of the nutrient cycling is available for the White Sea.

The White Sea macroalgal flora is richer than the floras of other seas of the Eurasian Arctic and includes about the same number of species as the Barents Sea flora (Table S4). It is generally similar to it, belonging to the Subarctic –Low Arctic Region with a significant fraction of boreal species (Zinova, 1974; Vozzhinskaya and Luchina, 1995). The shore morphology and the presence of rocky and other hard substrates of most shores (except the eastern sedimentary coast of the Dvina and the Mezen Bays) generally facilitate the formation of diverse and numerous (about 40) macroalgal associations, including those with kelp and seagrass species. The intertidal zone is characterized by massive development of fucoids, filamentous algae and eelgrass. Subtidal kelp communities are dominated by *Laminaria digitata* and *Saccharina latissima* (with wet biomass of up to 18 kg/m²), and are usually extended to 10–12 m depth, being followed by diverse red algae communities in the deeper zone, to 20–30 m depth (Vozzhinskaya, 1986; Mikhaylova, 2000; Naumov, 2001; Blinova, 2007; Maximova, 2017a; Mikhaylova et al., 2017, 2019). Of particular importance are communities co-dominated by *Anfelia plicata*, which may build up a significant biomass and used to be harvested commercially. This significantly worsened the condition of stock, although the most recent accurate data were collected in limited localities in 2004 (Mikhaylova, 2014).

Most studies of macrophyte communities in the past were associated with their commercial exploitation (Gemp, 1962; Blinova, 2007; Shoshina, 2012). In the White Sea, kelp species have been commercially exploited since the early 20th century (Pronina, 2011); several macrophyte species are also collected by the local population for various use in the household (Maximova, 2017a).

The eelgrass (*Zostera marina*) is fairly common in the White Sea and performs a number of ecosystem functions. It underwent a drastic decline all over the region in 1961 with numerous ecosystem consequences (Vekhov, 1992; Maximova, 2017a). For the description of the process of recovery and the present situation see the main text of this paper.

Siberian continental coast

A major portion of the continental coast in the south-eastern Barents Sea, Kara, Laptev and the western East-Siberian Sea comprises thermoabrasive, accumulative sedimentary shores, estuaries and lagoons, and is influenced by the river run off the great Eurasian rivers, Ob, Yenissei, Lena, Yana, Indigirka, and Kolyma (Sergienko, 2011; Krylenko, 2017). The lack of hard substrates, abrasion of near shore sediments by sea ice, high turbidity and decreased salinity all negatively influence the presence of macrophyte communities. The main characteristic feature of Arctic macrophytobenthos is the absence of littoral vegetation due to severe winter conditions. It is, therefore, not surprising that they are virtually not known along the continental coast from the Pechora Sea eastward to the Kolyma River mouth area

(East Siberian Sea) (Maximova, 2016, 2017b). Only two coastal regions are known to be inhabited by macroalgal communities. The first of them is the south-western region of the Kara Sea with Baydaratskaya Guba, There is rather rich macroalgal flora in the region: 89 species, and in Baydaratskaya Guba 49 species forming about 30 communities with biomass from 0.1 to 2.7 kg/m², and a unique *Zostera marina* population that is unique for Siberian Seas (Vozzhinskaya et al., 1996; Vozzhinskaya et al., 1997; Vinogradova, 1999). The second one is located on the outer boundary of the Lena Delta (south of the Laptev Sea) where only one patch of *Laminaria solidungula* + red algae community was recorded (Gukov, 2001). Furthermore, the rocky shores of Taymyr Peninsula may host yet undiscovered kelp communities which were first discovered by Kjellman (1883). Besides, seasonal ephemeroïd vegetation (some filamentous species) may develop on muddy coasts.

High Arctic Archipelagos

Novaya Zemlya

Novaya Zemlya Archipelago is located between the Barents and the Kara Sea. It includes two large islands, North (Severnyi) Island, and South (Yuzhnyi) Island, separated by the fjord-like deep and narrow Matochkin Shar Strait, and numerous small islands and skerres (especially in the southwestern bays of Southern Island (Litvin and Lymarev, 2003). A number of bays of the Northern Islands receive glacial discharge from marine terminated glaciers which have undergone significant retreat in the beginning of the 21st century (Carr et al., 2014; Makarenko et al., 2018).

The Barents Sea coast and most of the Archipelago is relatively poorly studied with regard to macroalgal flora; most of the species are compiled on the basis of old collections (Sinova, 1929; Flerov, 1932; Flerov and Korsakova, 1932). The only place for which there is some material for studying macroalgal flora dynamic is Ledianaya Gavan' Bay in the very north on the Kara side but close to the formal border between the Barents and the Kara Sea. It was investigated three times: at the end of 19th century (Kjellman, 1883; 24 species of macroalgae), at the very end of 20th century (Strick et al., 2000; 24 species) and 17 years later (Shoshina and Anisimova, 2013; 28 species). The united list includes 41 species.

The western shores are mostly rocky, of the fjordic type, with a complex coastline but low tidal magnitude (up to 1 m), providing a variety of habitats for macroalgal communities. Unfortunately, for most part of the Barents coast of Novaya Zemlya, only historical descriptions of these communities, based on collection by dredging (Flerov, 1932), and rare material from littoral and sublittoral zones of Krestovaya Guba (Shirshov, 1933) are available. In the skerry inlets of the southwestern coast of Yuzhnyi Island several sites were investigated with the purpose of harvestable biomass assessment in 1965 (Gemp and Byzova, 1976) and 1988 (Sorokin and Peltikhina, 1991). They revealed rich communities with complex vertical structure, dominated by *Saccharina latissima*, *Laminaria digitata* and *Alaria esculenta* similar in composition to the ones on the coast of the Kola Peninsula. They differ however in the absence of the intertidal belt of fucoids which occurred instead subtidally, owing to the gouging effect of fast ice. The kelp zone extends from 1-3 to 9-16 m, depending on the exposure of the coast and the impact of fast ice (Sorokin and Peltikhina, 1991).

The eastern shores of Novaya Zemlya are also poorly studied with regard to macrophyte communities although the known species richness of macroalgae is

higher than on the West Coast (Table S4) (Maximova, 2016). However, subtidal macroalgal, in particular kelp communities were recorded in the recent years in some fjords, i.e. Blagopoluchia Bay and Ledianaya Gavan' Bay at Northern Island. These fjords are without a marine-terminated glacier. The intertidal zone is devoid of macroalgae, and the subtidal zone is dominated by soft bottom with fragmented kelp communities where hard substrate is present (dominated by *Laminaria digitata*, *Saccharina latissima*), *Fucus distichus*, and red algae (*Odonthalia dentata*, *Phycodryas rubens*, *Euthora cristata*, *Polyostea arctica* and others) (Shoshina and Anisimova, 2013; Maximova, 2015; Udalov et al., 2016). Although it is expected that several climate-related factors (e.g. shortening of sea ice period, increasing glacial discharge, and transformation of marine-terminated glaciers to land-terminated glaciers) likely impact macroalgal communities, a complete absence of long-term studies on in the coastal zone of Novaya Zemlya precludes any conclusions.

Franz Josef Land

Franz Josef Land (FJL) with its 192 large and small islands (over 80% of land covered by glaciers) is the northernmost archipelago in the Eurasian sector of the Arctic. The archipelago is influenced by cold Arctic and the Kara shelf waters in the surface layers and the Barents and the Atlantic waters in subsurface layers. Numerous straits of various width, depth and orientation, diverse bays, fjords and inlets, the presence of ice shores and iceberg calving, fast ice of varying extent and seasonality, and availability of different kinds of substrates form a variety of local conditions (Litvin and Lymarev, 2003). FJL has experienced climatic changes following the general trend for the Barents Sea: increasing average and winter air temperature (although the temperature in July shows a slight negative trend; Shilovtseva and Romanenko, 2016), and decreasing sea ice cover in the coastal zone of the archipelago (Grémilet et al., 2015). Another aspect of the regional climatic changes is the increase of glacial discharge: ice mass loss doubled in the years 2011 – 2015 compared to 1953 – 2010 (Zheng et al., 2018). In the inshore environment, this leads to the decrease of the area of marine-terminated glacier, formation of new straits and islands, and numerous new inlets (Ziaja and Ostafin, 2019).

The marine algal flora of the Archipelago is studied probably better than that of Novaya Zemlya and includes a similar number of species to the Kara side of the latter (Table S4). Species richness of the macroalgae flora in FJL is, thus, relatively high for the High Arctic zone and the composition is similar to the marine flora of Greenland (Vinogradova, 1987; Vinogradova and Shoshina, 1994). FJL hosts most high latitude known kelp communities. They were first recorded there by Nansen (1897) in the northern part of the archipelago yet in the significantly cooler than nowadays climatic period of 1890s. Average winter temperature in 1899 -1914 was 1.8–4.6 °C lower than the modern period (Araźny et al., 2019). The intertidal zone is only seasonally occupied by some green macroalgae, i.e. *Acrosiphonia* spp. In the upper subtidal depth (2 – 3 m) peculiar communities dominated by *Devaleraea ramentacea* and *Battersia arctica* are recorded in particular areas (Golikov and Averintzev, 1977; Averintzev and Vinogradova, 1990). Subtidal habitats below 3 m with the presence of hard substrates are characterized by mosaic distribution of kelp- and red algae-dominated communities. Kelp communities occur across the archipelago; although they had not been recorded in the areas where permanent fast ice was present in 1970 (Golikov and Averintzev, 1977). In 1991, the kelp communities in Tikhaya Bay at Hooker Island were dominated by *Saccharina latissima*, *Laminaria digitata*,

Laminaria solidungula, and *Alaria esculenta* patchily occurring between 3-4 and 10-15 m depth, with subdominants *Devaleraea ramentacea*, *Desmarestia aculeata*, and *Chaetomorpha melagonium* (Averintzev, 1992; Averintzeva, 1994). In 2013 in one of the sites studied in 1991, no kelp community was found, possibly as a result of increased siltation due to intensification of glacier melting (Gagaev et al., 2019). The impact of climatic changes on the FJL macroalgal communities needs thus to be further assessed using detailed surveys of historically studied sites, analysis of changes in species composition, projective cover and biomass of the dominant species.

Severnaya Zemlya Archipelago

Severnaya Zemlya Archipelago (SZA) separates the Kara and the Laptev Sea. It comprises four major islands: October Revolution, Bolshevik (separated by the deep Shokalsky Strait), Komsomolets, and Pioneer; and around 70 smaller islands, being separated from the Taymyr Peninsula by the shallow Vilkitsky Strait of some 50 km width. About half of the archipelago area is covered by glaciers, both land and marine terminating ones, providing intensive calving of icebergs (Litvin and Lymarev, 2003). The largest in the Eurasian Arctic ice shelf is located in the Matusевич Fjord of the October Revolution Island (Sharov et al., 2015). Striking impact of the river runoff that is peculiar of the Kara Sea directly is almost negligible in its north-easternmost portion, so the coastal zone of the archipelago is dominated by the Arctic water mass and its coastal modification transformed by the discharge of local rivers and glaciers and summer warming. The SZA archipelago is tightly blocked by sea ice for most of the year, although flaw polynyas are extensively developing (Spiridonov et al., 2011, 2017; Marchenko, 2012). Although current climatic transformation is affecting the archipelago via the general trends of decreasing summer sea ice and the timing of fast ice breakup, there are less documented effects of changes at the regional scale than for other Eurasian Arctic archipelagoes. The dynamics of ice caps and glacier is complex (Bolshiyarov et al., 2016) and there is no indication of rapid melting as in several other Arctic islands. The Matusевич Ice Shelf showed a tendency of decrease from 1995 to 2009 and underwent catastrophic breakout in 2012 following the extreme rise of air temperature and increasing precipitation (Sharov et al., 2015). Small islands in the south and the west of the archipelago composed of disperse permafrost sediments demonstrate high rates of coastal erosion. This is apparently related to the increase of the ice-free period accounting for longer exposure of the shores to wave action (Gavrilo et al., 2020).

The kelp communities dominated by *Saccharina latissima* were first discovered in the subtidal zone on soft bottom with pebble over permafrost sediments at small islands on the Kara side of SZA (Sedov Archipelago) in 1982 (Averintzev, 1989). This site, located within the area of the intensified coastal erosion has unfortunately not been revisited. The expedition of 2019 confirmed moderate species richness of macroalgae (mostly widespread Arctic-Boreal species with Atlantic affinity, Table S4) and a broad occurrence of kelp and kelp communities found at various localities between 3.5 and 15 m depth. Three kelp species were recorded: *Saccharina latissima* (most widespread and the only one occurring in the north, at Komsomolets and October Revolution Islands, *Alaria esculenta* and the less common Arctic endemic *Laminaria solidungula*. Ice gouging is the leading factor shaping the projective cover and general appearance of kelp communities. In some protected sites, i.e. on the boulder coastal slope in Akhmatov Bay, a typical kelp forests with *Desmarestia aculeata* and red

algae as subdominants, and calcareous algae on the ground was observed. Although even near the east coast of Krasnoflotskie Islands (on the Kara side) where the seabed is constantly scoured by icebergs, solitary specimens of *A. esculenta* were recorded (Gavrilo et al., 2020). Sparse *S. latissima* was also present among grounded icebergs on the muddy clay bottom in the Matusevich Fjord (T.A. Mikhailova, U.V. Simakova, V.A. Spiridonov, unpubl.). This indicates possible expansion of marine vegetation to the areas previously occupied by the ice shelf.

New Siberian Islands

The New Siberian Islands, separating the Laptev and the East Siberian Seas are surrounded by the shallow shelf sea and consist of three groups of islands: Lyakhovskie Islands, Anjou Islands, and De Long Islands. Most of them are relatively low, covered by thick permafrost layer, devoid of glaciers but have numerous rivers and mostly thermoabrasive coasts (Litvin and Lymarev, 2003). A vast area fast ice connects the southern part of the archipelago to the mainland. In the north, the fast ice belt is narrower and surrounded by flaw polynyas which have a significant impact on the ecosystem (Spiridonov et al., 2011, 2017; Marchenko, 2012). In the 2010s, the Laptev Sea became practically ice free by September (Onarheim et al., 2018). In the area of New Siberian Islands there is a tendency for later fast ice formation and earlier breakup (Selyuzhenok et al., 2013). Thermoabrasive coasts of the islands undergo accelerating degradation in the early 21st century (Pizhankova and Dobrynina, 2010). Although the inshore marine sediments are dominated by mud and sands, the presence of significant fraction of coarse substrate provides conditions for patchy development of species poor (Table S4) kelp communities dominated by *Laminaria solidungula* and *Coccotylus truncatus* at 3–9 m depth in the southern and the southwestern parts of the archipelago (recorded in 1973). Surprisingly, the macroalgal communities on the western and the northwestern sides where appropriate stony substrate is also present, lack kelp species (Golikov et al., 1990; Maximova, 2017b). Kelp communities in the archipelago are likely affected by the changes of fast ice regime and increasing thermoabrasion of the shores but no data are available to assess its contemporary status.

East Siberian and Chukchi Seas

The shelf areas to the east of the mouth of the Kolyma River are less influenced by the freshwater runoff from the great Siberian rivers. The coastal zone is very shallow, especially in the East Siberian Sea, thermoabrasive and lagoon accumulative shores are dominating but in the relatively frequent segments of the abrasive and denudational shorelines, rocky capes are present as well (Krylenko, 2017). The transformed Pacific water is widely distributed in the Chukchi Sea although with significant variation from year to year (Luchin and Panteleev, 2014; Pisareva et al., 2015). The coastal zone is influenced by the cold Siberian Coastal Current (Weingartner et al., 1999) although particular bays have their own oceanographical regime (Babkov, 1994). Both seas are experiencing a strong decline of summer sea ice in the last decades that results in extension of the ice-free season to September and October (Onarheim et al., 2018; Plotnikov and Rudenko, 2018).

Although the macroalgal flora of the region is more diverse than in the Laptev Sea and the Siberian Arctic archipelagoes, the thermoabrasive and accumulative shores in general do not facilitate the development of continuous belts of kelp communities. The Chaun Bay in the East Siberian Sea has peculiar conditions characterized by the,

unusual for the region, summer warming of the surface layer, to about 10 m depth (Babkov, 1994). It is known as a local “hotspot” of biotic diversity, with a significant fraction of Pacific Boreal – Arctic species, including macroalgae. Species rich kelp communities dominated by *Laminaria solidungula* and *Saccharina* spp., with the subtidal presence of *Fucus distichus* have been recorded (Vinogradova, 1992; Golikov et al., 1994). Similar conditions are characteristic for the lagoon Rodgers Bay of Wrangel Island (Golikov et al., 1987) and the semi-enclosed Kolyuchinskaya Bay in the Chukchi Sea where kelp communities resemble those in the Chaun Bay (Golikov et al., 1998; Vinogradova, 1999). More fragmented kelp communities dominated by *Laminaria solidungula* are known for cape areas, i.e. near Schmidt Cape in the De Long Strait (Golikov et al., 1987). The real extent of kelp communities along the coast of Wrangel Island and Chukotka Peninsula is unknown but they likely occupy most of areas adjacent to rocky capes. However, all known kelp sites were surveyed already decades ago, mostly in the 1980s and no actual data exist on the impact of ongoing climatic changes, i.e. longer ice-free season and thermoabrasion of the shores are available.

Bering Strait and the northwestern Bering Sea

The northwestern Bering Sea as part of the Russian Arctic is considered here in the restricted sense including the Bering Strait and the Anadyr Gulf. This region is characterized by a variety of shore types and coastal processes (Spiridonov et al., 2011; Krylenko, 2017), complex oceanographic regime dominated by the influence of the Navarin and the Anadyr Currents (Verkhunov, 1995). The Bering Strait is the single gateway for productive Pacific waters entering the Chukchi Sea, and this input is showing a tendency to increase (Woodgate et al., 2015). The area is seasonally ice covered but numerous polynyas are developed along the shores of Chukotka Peninsula, being one of the key factors for the marine biodiversity (Spiridonov et al., 2011, 2017). The sea ice season in the last decades tends to be significantly shorter (Onarheim et al., 2018) with particularly strong negative trend and variation for sea coverage in December, April and May (Plotnikov and Vakulskaya, 2012; Plotnikov et al., 2019). The macroalgal flora belongs to the North Pacific Phytogeographic Zone and significantly differs in taxonomic composition from that of the Eurasian Arctic Region (Zinova, 1974; Klochkova, 1998). However, there have been practically no studies of kelp communities except of few surveys of their most shallow parts on the lower boundary of the intertidal zone in the last century (Kussakin and Ivanova, 1978; Vinogradova et al., 1978; Klochkova, 1998). Thus, even the historical baseline for the assessment of changes in the current climatic period is lacking.

In the Anadyr Liman (the external part of the Anadyr River estuary) the northernmost for the Asian Arctic coast intertidal eelgrass (*Zostera marina*) meadows are known since the 1970s and were repeatedly recorded in 2011–2015 (Simakova et al., 2016).

Conclusion

A variety of conditions along the Eurasian Arctic coastline suggests significant differences in response of kelp and seagrass communities to climate change. These communities themselves are by far understudied and there is an urgent need to revisit their historically surveyed sites in the Russian Arctic to document the current situation, comparing it to the baseline information on habitats, species composition, vertical structure, and biomass of macroalgal assemblages.

Table S4. Estimates of species richness of marine macroalgae in the Russian sector of the Arctic ocean.

Sea	Entire sea or part	Chlorophyta	Rhodophyta	Phaeophyceae	Total	Source
	Entire sea	34	74	70	178	Malavenda et al., 2018
	Varangerfjord and Murmansk Coast	39	75	80	194	Zinova, 1962
	Varangerfjord and Murmansk Coast	45	84	82	211	Vozzhinskaya, 1986
Barents	Varangerfjord and Murmansk Coast	27	66	60	153	Malavenda et al., 2018
	Southeastern part	9	37	18	64	
	Franz Josef Land Archipelago	17	17	26	60	
White	Entire sea	41	67	86	194	Kalugina, 1962
		39	69	75	186	Vozzhinskaya, 1986
Kara	Total	32	52	55	139	Vinogradova, 1999
	Southwestern part	14	30	29	73	Maximova, 2016 (compilation of several authors)
	East coast of Novaya Zemlya	9	27	32	68	Vinogradova, 1999
	Southeastern part	8	12	13	33	Vinogradova, 1999
	Northeastern part (including West Coast of Severnaya Zemlya Archipelago)	1	7	8	16	Vinogradova, 1999
	Severnaya Zemlya Archipelago (West Coast)	6	11	9	26	T.A.Mikhailova, U.V. Simakova, V.A. Spiridonov, unpubl.
Laptev Sea	Entire sea	9	17	13	39	Vinogradova, 1999; Maximova, 2017b; T.A. Mikhailova,

						U.V. Simakova, V.A. Spiridonov, unpubl.
	Severnaya Zemlya Archipelago (East Coast)	2	9	7	18	T.A.Mikhailova , U.V. Simakova, V.A. Spiridonov, unpubl.
	Continental coast	0	3	1	4	Gukov, 2001; Maximova, 2017b
	New Siberian Islands and neighborin g islands**	9	11	10	30	Vinogradova, 1999
East- Siberian	Mainly Chaun Bay	10	24	30	64	Vinogradova, 1999
Chukchi	Russian sector	16	27	26	69	Vinogradova, 1999
	Wrangel I.	5	12	12	29	
	Chukotka Coast	15	27	25	67	

*Part of the Franz Josef Land Archipelago is referred to the Kara Sea

** Part of the New Siberian Islands Archipelago is referred to the East-Siberian Sea

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Supplementary Information V. Modeling results

Table S4. Performance of SDM algorithms inferred with cross-validation (CV) and the final predictive surfaces, both for intertidal and subtidal species.

Algorithm	Realm	AUC (CV)	Sensitivity (CV)	AUC (Final)	Sensitivity (Final)
BRT	Intertidal	0.86±0.01	0.89	0.93	0.87
	Subtidal	0.83±0.03	0.89	0.85	0.84
AdaBoost	Intertidal	0.87±0.02	0.87	0.92	0.88
	Subtidal	0.80	0.85	0.84	0.87
Ensemble	Intertidal	-	-	0.93	0.90
	Subtidal	-	-	0.86	0.89

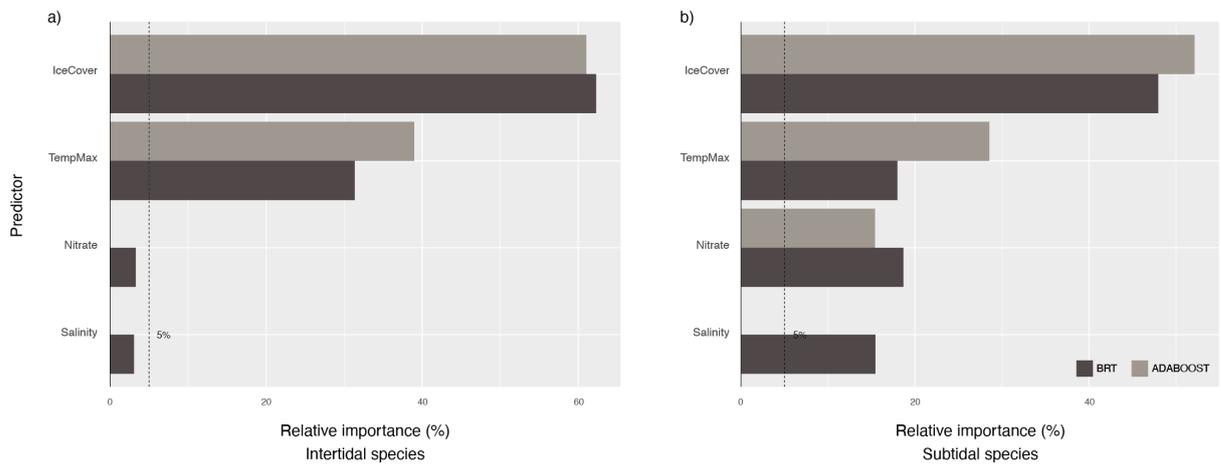


Figure S3. Relative contribution of each environmental predictor to the performance of the models developed for (left panel) intertidal and (right panel) subtidal macroalgae.

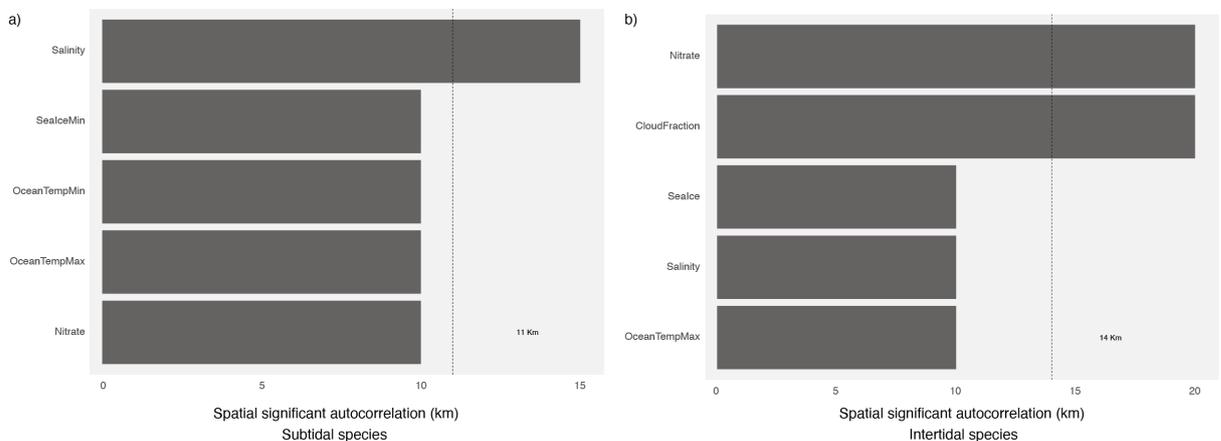


Figure S4. Spatial significant autocorrelation of each environmental predictor used in the models developed for (a) subtidal and (b) intertidal macroalgae.

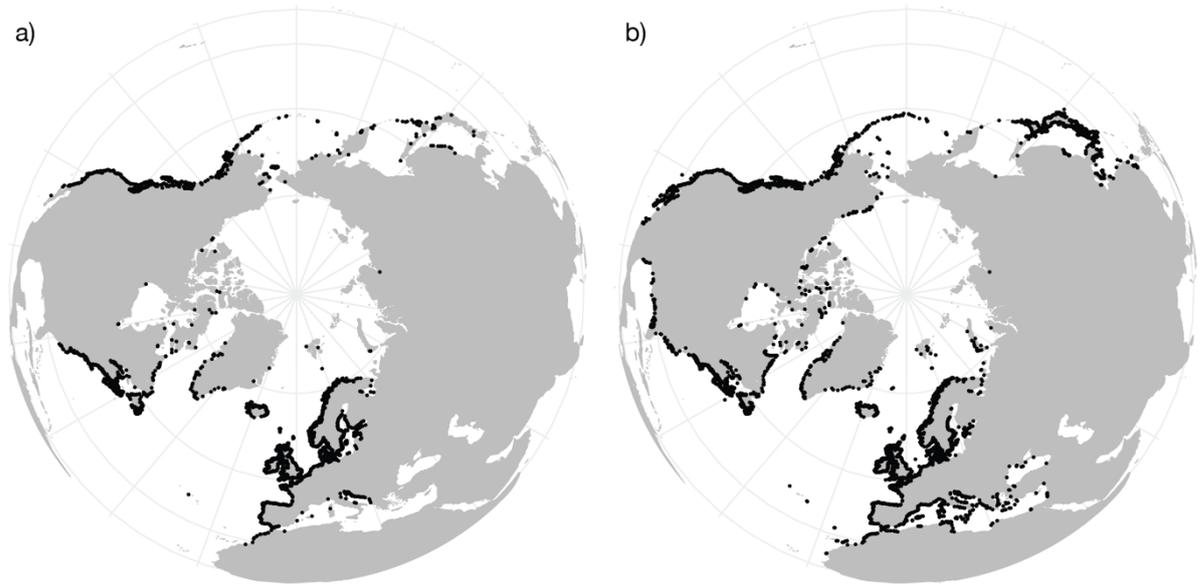


Figure S5. Records of occurrence in the models developed for (a) intertidal and (b) subtidal macroalgae.

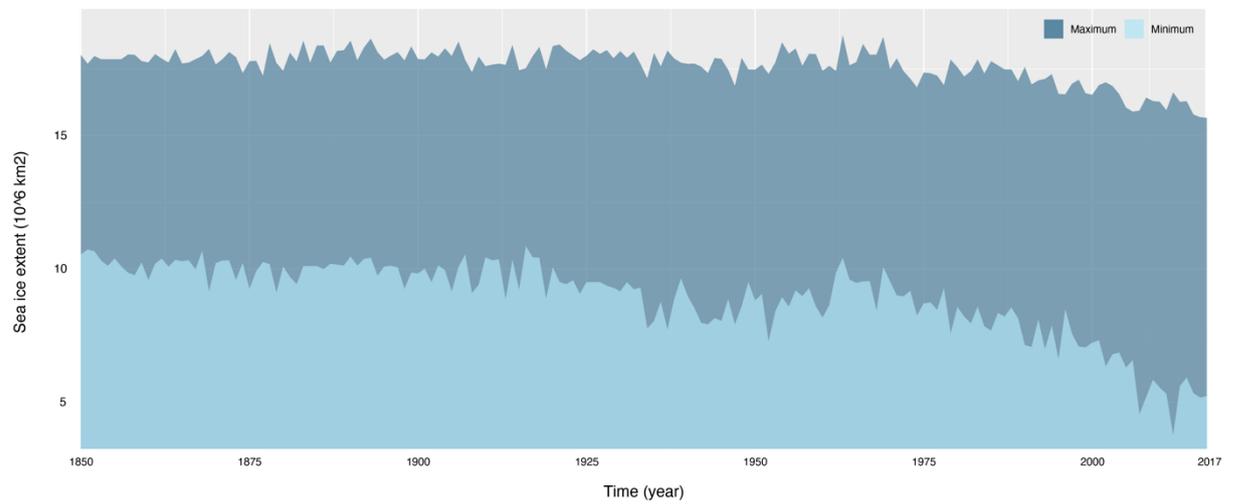


Figure S6. Maximum and minimum Arctic sea ice extent per year.