TITLE

Baseline for the Northeast Atlantic (58 – 70° N) intertidal *Mytilus* species complex (*Mytilus spp*.)

RUNNING TITLE

“Mussel baseline”

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Abstract

**Aim:** During the last decades mussels have shown a poleward shift in the distribution along the Atlantic coast conceivably driven by elevated sea-surface temperatures. We aimed to determine the baseline for the Northeast Atlantic (58 – 70° N) *Mytilus* species complex, and to compare the present distribution to surveys conducted 60 years ago.

**Location:** Northeast Atlantic

**Methodology:** Baseline was obtained by investigating a total of 509 stations in the intertidal zone, in four regions comprising the environmental gradient from head of fjord to coast, and distributed over the latitudinal gradient from 58 – 70° N.

**Results:** The baseline shows a range in continuous abundance of mussels from 12 to 36 %, patchy abundance from 26 to 57 % and no or very limited mussel abundance from 26 to 46 % between the four regions. The presence of mussels in the southeast and west region was compared to previous surveys conducted 60 years ago. The data points to similar past and present presence of mussels in both regions, yet past major mussel fields in the inner section of region Southeast was not detected in this study.

**Main conclusions:**

The baseline of *Mytilus spp.* in the Northeast Atlantic (58 – 70° N) is now available for future reference. The baseline, compared to surveys conducted 60 years ago, points to awareness of the population situated in the southeast section of the investigated region. Continued monitoring and modelling are needed to clarify drivers of temporal and spatial variation in the mussel populations along the Northeastern Atlantic coast.

Keywords

Abundance, baseline, bivalve, distribution, intertidal, method, monitoring,

SIGNIFICANCE STATEMENT

Mussels (*Mytilus spp*.) are abundant in the North Atlantic, sessile, and sensitive to environmental change, and suitable as sentinels of environment and climate change of costal ecosystems. During the last decades mussels have shown a poleward shift in the distribution along the Atlantic coast conceivably driven by elevated sea-surface temperatures. We have determined the baseline for mussels in the Northeast Atlantic, representing a geographical scale and habitat diversity previously not surveyed. The baseline has been compared with two surveys conducted 60 years ago, and it points to awareness of the population situated in the southeast section of the investigated region.

1. Introduction

Mussels (*Mytilus spp*.) are key species, ecosystem engineers and provide many ecosystem services in intertidal and shallow coastal ecosystems (Smaal et al., 2019). During the last decades mussels have shown a geographic contraction in its southern, equatorward range edge on the west Atlantic coast, shifting the range edge approximately 350 km north of its previous limit (Jones et al., 2010). The disappearance (i.e. mortality) of mussels along the southern portion of its range is associated with summer high temperatures. On the north east Atlantic coast mussels has reappeared in Svalbard (Leopold et al., 2019) after 1000 years of absence. This has also been linked to elevated sea-surface temperatures (Berge et al., 2005). In sum this indicates a northward shift in the distribution of mussels in the North Atlantic, conceivably driven by elevated sea-surface temperatures.

Within Atlantic Europe there are increasing numbers of reports of declining mussel populations in coastal waters, which have been reviewed by Baden et al. (2021). Massive mussel die-off was observed along the Netherlands (Capelle et al., 2021) and Adriatic coast (Bracchetti et al., 2023). In Norway the Institute of Marine Research (IMR) has received an increasing number of notices from the public on observations of absence of local mussel populations during the last decade (Andersen et al., 2017). Based on a general concern for the disappearances and population changes of a key intertidal species, the IMR established a monitoring program for the mussel populations along the Norwegian coast.

The Norwegian coastline, including the mainland, fjords and the islands is roughly 100 000 km long. Mussels are present along the entire coast (https://www.artsdatabanken.no/). Across the Trans-Atlantic distribution, *Mytilus* species show interregional separation, with hybrid zones and mixed populations in the contact area (Wenne et al. 2020). The *Mytilus* species complex along the Norwegian coast comprises *M. edulis*, *M. trossulus*, *M. galloprovincialis* and their hybrids (Brooks & Farmen, 2013; Mathiesen et al., 2017; Wenne et al., 2020), yet their detailed geographical distribution along the Norwegian coast is not well known. Salinity and temperature are typically the main drivers for the distribution of the species on a large geographical scale (Gosling, 2021). Numerous abiotic (ice cover, substrate, turbidity, wave action, current speed, etc) and biotic factors (predators, disease, food availability, competitors, fouling organisms, etc) may influence population structure, abundance and local distribution patterns. Predation is often considered the single most important source for mortality and may influence local distribution pattern (Gosling, 2003).

The vast coastal area entails a method that can monitor environmental gradients from head of fjord to coast (i.e. up to several 100 km) and concurrently identify local changes in abundance. This called for an elementary and rapid categorization of mussel abundance and metadata (associated flora and fauna and habitat description), that would enable large spatial coverage.

In this letter we present the baseline for the North Atlantic intertidal mussel populations (58 – 70° N) and compare the baseline with data from two separate surveys conducted 60 years ago. The objective of the monitoring is to elucidate if the abundance of intertidal mussels is changing over time beyond the natural variation, i.e. beyond the inherent randomness in the ecosystems. Collection of additional metadata is included to describe the ecosystem and to assess potential cause(s) to change and will be presented when the monitoring has accrued enough data.

1. Material and methods

Based on the distribution of observations from the public on the absence of mussels (*Mytilus spp*.) (Andersen et al., 2017) we monitor four regions in Norway (west, south, east and north, Fig. 1). In addition to the latitudinal and longitudinal gradient represented by the different regions we investigated the regional gradient from the head of fjord to exposed coast within the different regions. As it is not possible to visually distinguish between the different species (or hybrids) *in situ*, this monitoring program reports the *Mytilus* species complex.

Stations within each region were obtained using randomized line sections (python, 3.9 random library). Line sections were generated from all available coastline, including islands. Each station (line section) comprises 100 meters of coastline, horizontally in the intertidal zone. An example of a sampled line section is given in Figure S1. Line sections were randomly selected to be investigated (50-100 per region in 2021 and 2022). Stations falling within restricted and protected areas (nature reserves, bird nesting sites, military area, etc) and danger- or temporally non accessible areas (busy harbors, wind and waves action, etc) were ignored.

The abundance of mussels was determined by the degree of horizontal coverage along the generated line sections of the intertidal zone and as deep as the water visibility allowed for. Observations were acquired either by snorkeling or walking along the intertidal zone. Snorkeling has been preferred for the three southern regions where the tidal range is typically < 1 m. Snorkeling has also been preferred for habitats with abundant vegetation, boulders, cracks, steep inclination or else where it is difficult to walk in the intertidal zone. The observer is fitted with a GPS that logs geo-referenced positions at 0.2 Hz. The observer reports mussel abundance in three categories (see criteria below), assess the presence of age classes (spat, one year and two years or more), dominant substrate (rock, boulder, pebbles, sand or mud) and a species list of dominant flora and the most common mussel predators. Two online application packages have been developed to log (“shellfish monitoring tool”, <https://shellfish.shinyapps.io/monitoring_app/>) and explore (“mussel population survey”) the data.

The abundance of mussels is determined by the degree of horizontal coverage, using three categories:

**Category 1: Continuous abundance**: Continuous horizontal coverage of mussels in the habitat. Mussels are occupying 100 % of an imaginary horizontal line extending > 2 meters along the station. The imaginary horizontal line implies that mussels must not be situated next to each other as overlapping vertical spaced (patches of) mussels may fulfil the criteria. The width (i.e. the vertical height or “thickness”) of the horizontal line is not considered. Up to a two meters break in continuous cover is accepted before a shift in category is reported.

**Category 2: Patchy abundance:** Patchy horizontal coverage of mussels in the habitat. Patchy abundance of mussels includes continuous abundance of mussels extending < 2 meters in horizontal direction, groups of mussels and individual mussels. Patchy abundance allows a maximum horizontal distance between observations of mussels of five meters.

**Category 3: Non or very limited abundance of mussels**: Singular or groups comprising few mussels may appear on distances exceeding five meters, yet mussels are normally not observed.

1. Results

The baseline comprises 509 investigated stations obtained from the four regions sampled during 2021 and 2022 (Fig. 2). In average, 16-line sections were surveyed per day of field work. The mean length of all sampled stations was 133 meters and varied less than ± 5 m between regions (range 128 to 137 m). The total length of the coastline investigated was 60 km. The number of stations in West was 155, in East was 100, in North was 194 and South was 60. South was only monitored in 2022.

The baseline of abundance of mussels (*Mytilus spp*.) within the different regions is in Figure 2. We did not see a common clear pattern in mussel abundance over the environmental gradient from head of fjord to exposed coast. Continuous abundance of mussels (category 1) was present along 12 to 36 % of the total investigated coastline, where the western region had the highest percentage occurrence and the eastern region the lowest (Table 1). The range in percentage occurrence of patchy abundance of mussels (category 2) spans from 26 to 57 % between regions, where the eastern region shows the highest and the north region the lowest. No or very limited mussel abundance (category 3) ranged 26 to 46 % in occurrence, with the western region showing the lowest and the southern region having most observation of category 3.

1. Discussion

This baseline of intertidal mussel (*Mytilus spp*.) abundance comprises four investigated regions across latitudinal (58 to 70° N) and longitudinal (6 to19° E) gradients along the North Atlantic coastline. Mussel abundance was surveyed over the environmental gradient from protected head of fjord to fully exposed coast. We detected more continuous and patchy distribution than non or very limited mussels in all regions. We did not see a common clear pattern in mussel abundance over the environmental gradient from head of fjord to exposed coast. The baseline of *Mytilus spp.* in the Northeast Atlantic is now available for future reference and will be decisive for our future understanding of the temporal and spatial variation in the mussel populations.

Mussel distribution was investigated in the southeastern and western regions approximately 60 years ago by Bøhle (1965) and Brattegard (1966). Bøhle (1965) surveyed the Oslofjord, corresponding with our southeastern region, with the purpose of identifying “mussel fields” from the intertidal zone and at least to 10 m depth. Bøhle’s sampling sites and mussel fields are visualized in his Figure 2, which corresponds to our Figure 2 (panel A). Bøhle (1965) reports the highest presence and abundance of mussels in the inner part of the Oslofjord (north from Drøbak), the southwestern part of the region (Tønsberg and Nøtterøy) as having “good mussel fields” and the mid part of the region (Hurumlandet to Holmestrandsfjorden) as having “good abundance” of mussel. His observations most often resemble our findings of presence for similar situated sampling stations, however major “mussel fields” in the inner Oslofjord (Nesodden and Sætre) and mussel abundance in the effluent area of the Drammen River was not detected in this survey. This points to awareness of these populations and continued monitoring should clarify if the populations are changing.

Brattegard (1966) described the horizontal distribution of the fauna of rocky shores in the Hardangerfjord, based on field work conducted during 1955-63. His study site overlaps with fjord branches, inner fjord, and intermediate fjord in the western region of our study (panel C in Figure 2 and see Figure S2 for the past distribution of mussels). The relative presence of mussels was determined by Brattegaard (1966) as the percentage of investigated locations and in the present study as the percentage of investigated shore length. We have compared the relative presence of mussels between these two surveys in Table 2.

The data show minor changes in relative presence but indicates that mussels currently are more present in the fjord branches and less present in the inner part and the intermediate section of the fjord. Brattegard’s study was designed to describe the fauna on rocky shores, and protruding headlands and rocky substrata were selected for the investigated stations. This survey should include all substrates and habitats in the region, also habitats where mussels may not thrive, such as sandy or pebble beaches, freshwater outlets, etc. It is therefore to be expected that our approach will detect lower relative presence. Given the minor differences in relative presence between the past and present survey and the different methodology employed, it appears inconclusive if the mussel presence in the Hardangerfjord has changed over the last 60 years.

The dataset presented here represents a baseline and a starting effort to compile knowledge on the habitat and biology and distribution of the *Mytilus* complex along the Northeastern Atlantic coast. The baseline and metadata are collected to assess the role of ecosystem interactions (predation, competition) and habitat characteristics (substrate, vegetation) in the distribution biology of the *Mytilus* complex. Our goal is to generate spatial distribution models and ecological niche time series for the mussels from the different regions by combining the baseline data with environmental variables generated from oceanographic models (NorKyst800, (Asplin et al., 2020)) and ecosystem models (Norwecom.e2e, (Skogen et al., 1995)). These models should aid to assess the role of changes in environmental forcing on the distribution of mussels in the studied areas.

Conflict of Interest

The authors have no conflict of interest to declare.

Data Availability

Distribution datasets of *Mytilus spp.* are archived where?

BIOSKETCH

The authors are an interdisciplinary team representing marine costal ecology, physiology, aquaculture, and modelling.

Author Contributions: TS and ØS conceived the project, all authors contributed to the fieldwork, AA made the monitoring- and exploration software, and TS led the writing with significant contribution from all authors.

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TABLES

Table 1. The length of coastline investigated (m) and the mean relative abundance of mussels (*Mytilus spp.*) in four regions (%) in Norway for 2021 and 2022. Category 1 = continuous abundance, category 2 = patchy abundance and category 3 = non or very limited abundance.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | West |  | East |  | North |  | South |  |
| Category | (m) | % | (m) | % | (m) | % | (m) | % |
| 1 | 7192 | 36 | 1622 | 12 | 8520 | 32 | 1887 | 24 |
| 2 | 7489 | 38 | 7544 | 57 | 6950 | 26 | 2438 | 31 |
| 3 | 5092 | 26 | 4173 | 31 | 11024 | 42 | 3649 | 46 |
| Sum | 19773 | 100 | 13339 | 100 | 26494 | 100 | 7974 | 100 |

Table 2. The relative (%) presence of mussels (*Mytilus spp.*) in three sections of the Hardangerfjord around 1960 and 2020 as estimated from Brattegard 1966 and this study.

|  |  |  |
| --- | --- | --- |
| Fjord area | 1955-63 | 2021-22 |
| Fjord branches | 71 | 76 |
| Inner | 98 | 90 |
| Intermediate | 86 | 68 |

FIGURES

A map of the northern hemisphere

Description automatically generated

Figure 1. Monitored regions along the Norwegian coast encircled.

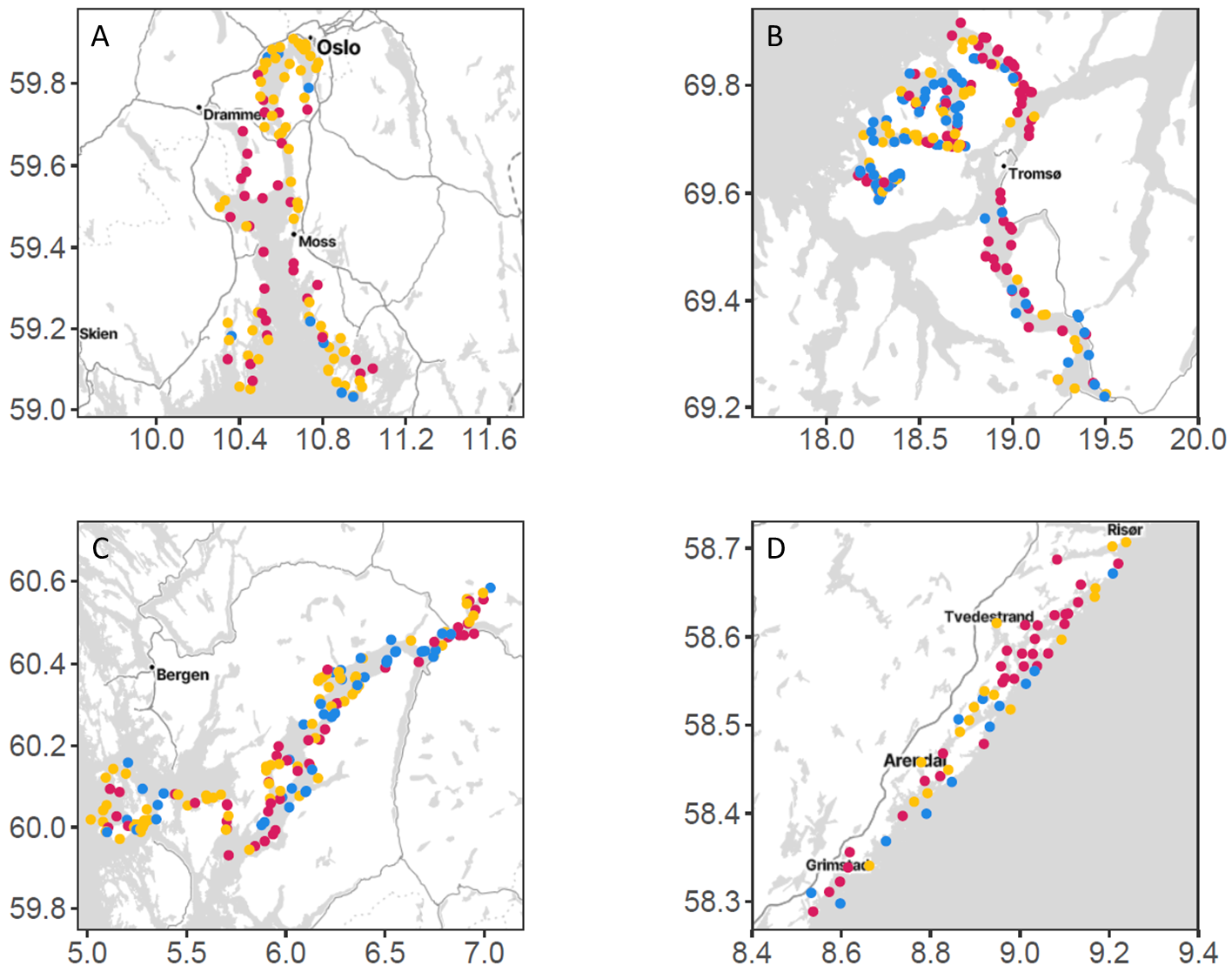


Figure 2. Baseline of mussel abundance (*Mytilus spp.*) in A =east, B =north , C = west and D = south in Norway during 2021 and 2022. Blue dots (i.e. line sections) indicate continuous abundance, yellow dots indicate patchy distribution and red dot indicate no or very limited abundance of mussels. Note to panel C (region west): The relative presence of mussels detected in this study is compared to the findings of Brattegard (1966) east of 5.7° E (Figure S2), matching his subdivision of the fjord (i.e. fjord branches (IV), inner fjord (III) and intermediate fjord (II)).

APPENDICES

A map of land with a map of land and a map of land

Description automatically generated

Figure S1. Screen display from the online application packages “mussel population survey”. Panel A: Surveyed station in region east in 2021 and 2022. Dots indicate line sections, green = continuous abundance, yellow = patchy distribution and red dot = no or very limited abundance of mussels (*Mytilus spp.*). Panel B: Magnification of an investigated line section (total length 174 m). Line color indicate mussel abundance as given for dots.

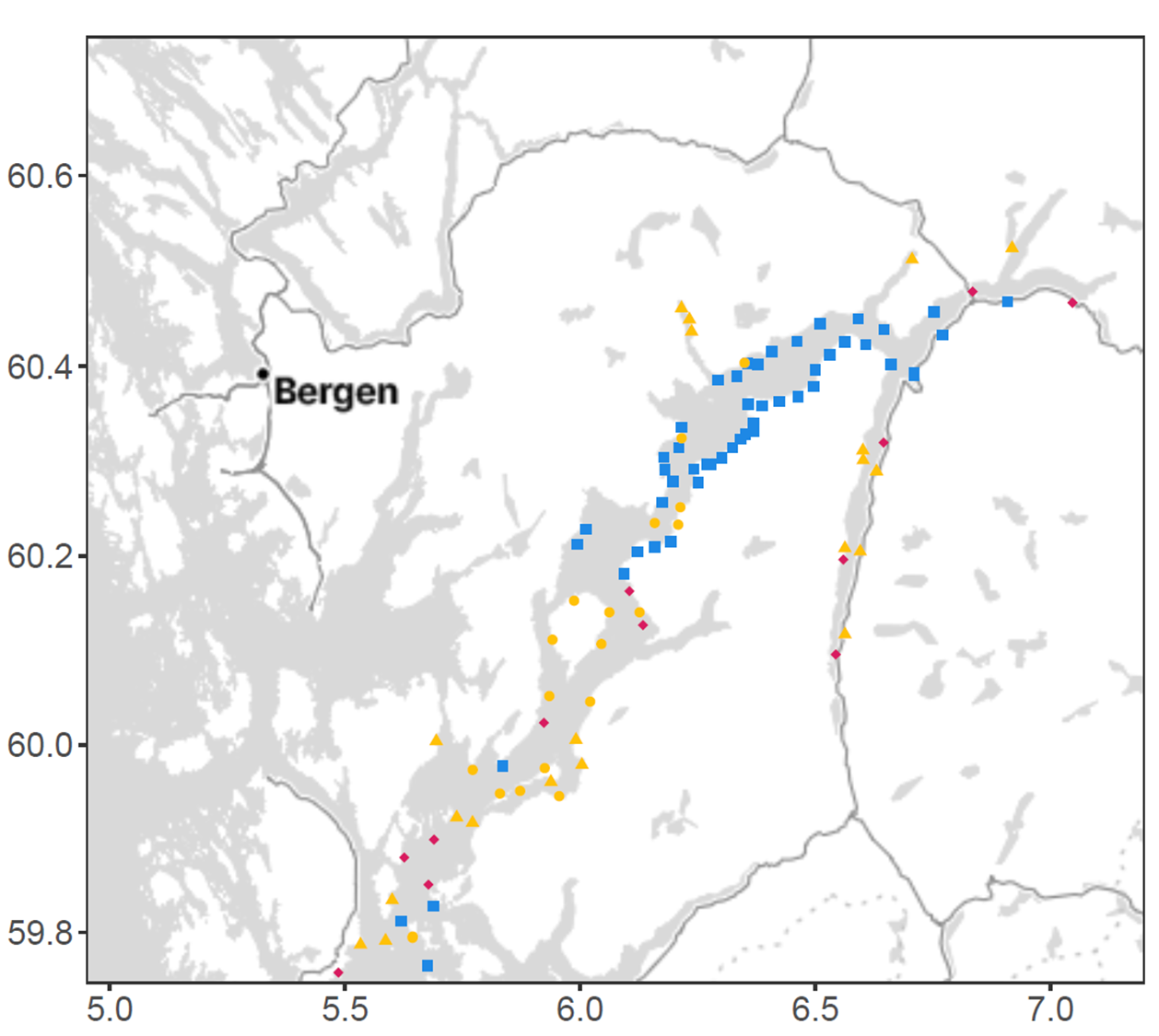


Figure S2. The relative presence of mussels reported by Brattegard 1966 east of 5.7° E. Blue markers indicate abundant, yellow markers indicate patchy distribution and red markers indicate not found.