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Monitoring regional benthic environment of Norwegian salmon cage farms

Chun-Deng Wang*, **Yngvar Olsen**

Department of Biology, Norwegian University of Science and Technology (NTNU), Bynesveien 46, 7018 Trondheim, Norway

ABSTRACT: The influence of cage aquaculture on the benthic environment is a crucial concern for sustainable development. The impacts are affected by multiple environmental factors and aquaculture operations. Our main objective was to comprehensively analyze the interaction between Norwegian salmon aquaculture and the benthic environment, involving prolonged temporal observations and wide-ranging spatial assessments, achieved through reviewing government-regulated environmental assessment reports. A total of 3480 reports from 759 farms operating between 2016 and 2022 were analyzed. Our main finding was that the impact of Norwegian salmon cage aquaculture on the benthic environment varied significantly across the Northern, Central, and Southern regions ($p < 0.001$). This variability was significantly associated with factors such as water depth ($p < 0.05$), maximum allowable biomass density ($p < 0.001$), and length of the production cycle ($p < 0.001$), and was slightly correlated with current velocity ($p = 0.067$). Additionally, we observed that the most severe environmental degradation often occurred during the summer—autumn period under maximal annual feeding rates. Further, we traced 2922 reports to investigate the changes in the state of the benthic ecosystem over multiple production cycles. We found that the environmental impact of seafloor ecosystems was recoverable, with more effective recovery rates in the early stages of degradation compared to the later stages. We suggested that the optimal biomass levels, production cycle arrangement, and farming practices should differ depending on specific environmental factors. It is imperative to consider these factors for adapting farming operations and take early action when the benthic environment shows signs of degradation.

KEY WORDS: Aquaculture · Atlantic salmon · Organic enrichment · Benthic environment · Environmental assessment · Seabed monitoring

1. INTRODUCTION

Faced with increasing demand for seafood products and stagnant growth in capture fisheries, aquaculture has become the fastest-growing seafood industry and is predicted to play a critical role in fulfilling the human need for food in the foreseeable future (Olsen 2011, Food and Agriculture Organization of the United Nations [FAO] 2020). Like other food industries, aquaculture is transforming towards more intensified production systems, and guiding toward environmentally sustainable development has become a pressing issue. This development should be based on an Ecosystem Approach (EA), where aquaculture is treated as a component of the ecosystem (FAO 2010, Boyd et al. 2020, Dong et al. 2022). The concept of EA takes account of the interaction between aquaculture operations and their ecosystems to ensure ecological resilience (FAO 2010). This approach is embodied in EU legislation such as the Marine Strategy Framework Directive and the Water Framework Directive, which aim to achieve a 'good environmental status' (EU-COM 2008, Lambert et al. 2017). As a major producer of Atlantic salmon (*Salmo salar* Linnaeus, 1758), Norway has adopted the EA for marine management, and further regulations and action plans have been implemented for the aquaculture industry to support responsible environmental

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*Corresponding author: chun-deng.wang@ntnu.no

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stewardship of the industry (Bailey & Eggereide 2020).

Organic enrichment of the seafloor ecosystem is one of the most critical concerns regarding the impact of cage aquaculture on the ecosystem (Hargrave et al. 1993, 1997, Cromey et al. 2002, Carroll et al. 2003, Bannister et al. 2014). Of the feed given to farmed salmon, around 42% of the carbon (C), 40% of the nitrogen (N), and 20% of the phosphorus (P) is retained in salmon meat, while the remainder is released as either inorganic nutrients to surface water or particulate organic waste that mainly sinks to the seabed. More precisely, 47 and 19% of feed N and feed P, respectively, is released as inorganic nutrients, and 18, 13, and 61% of feed C, feed N, and feed P, respectively, is released as organic particulate waste (Hall et al. 1990, 1992, Holby & Hall 1991, Hargrave et al. 1993, Wang et al. 2013, Wang & Olsen 2023). Particulate organic matter may result in potentially harmful organic enrichment if the accumulation on the seafloor near the farm site exceeds the environmental carrying capacity (Ross et al. 2013). This may negatively impact the ecological state of the seafloor ecosystem, resulting in a reduction in species richness and abundance of benthic organisms, as well as impaired ecosystem functioning, including the ability to mineralize organic matter (Hargrave 2003, 2005, Edgar et al. 2010, Sanz-Lázaro & Marín 2011, Riera et al. 2013, 2017, Ross et al. 2013, Salvo et al. 2017). Therefore, evaluating the interaction between environmental conditions and organic enrichment is crucial for environmental sustainability and farming performance (Johnsen et al. 1993, Kalantzi & Karakassis 2006, Kutti et al. 2007, Sanz-Lázaro et al. 2011).

The dispersal of organic waste and severity of organic enrichment have been found to be influenced by biophysical conditions and farming practices, including water depth, water current velocity, production intensity, assimilation efficiency with feed, and production cycle, as well as complex interactions between the above factors (Holmer et al. 2005, Kalantzi & Karakassis 2006, Bannister et al. 2014, Wang & Olsen 2023). The water depth may influence biogeochemical processes leading to a change in benthic chemistry and fauna (Holmer & Kristensen 1994, Holmer et al. 2003, Valdemarsen et al. 2009). Additionally, studies have estimated that the majority of organic waste exhibits dispersion within 500 m of the farm location, while the inorganic nutrients can reach distances of more than 1 km when the salmon biomass is high (Bannister et al. 2016, Jansen et al. 2018). Other factors that may interact include distance between farms, proximity of a farm to land, geographical position, water current speeds, flushing rates in specific system or aquatic environments, length of the production cycle, and production density, all of which are reported to affect the benthic environment (Kalantzi & Karakassis 2006, Brager et al. 2016, Wang & Olsen 2023).

According to Norwegian national aquaculture regulations, salmon farms must conduct regular seafloor ecosystem monitoring surveys as specified in Norwegian standard NS 9410, known earlier as the Modelling-Ongrowing fish farms-Monitoring (MOM), and now referred to as b- and c-assessments. b-assessment is conducted once per production cycle during the maximum biomass period on the seabed directly under the salmon cages, whereas c-assessment is conducted every 3 production cycles and focuses on evaluating the seabed in the intermediate zone, typically located 30 to 500 m away from the sea cages. b-assessment includes measurements of pH, redox potential (Eh), presence of benthos, gas bubbles, color, smell, consistency, and thickness of organic matter deposits (Hansen et al. 2001, Stigebrandt et al. 2004, Bannister et al. 2014, 2016, Standards Norway 2016, Broch et al. 2017). The result of the b-assessment is classified into 4 states: 1 (Very good), 2 (Good), 3 (Bad), and 4 (Very bad), in general agreement with the ecosystem state categories of the Water Framework Directive (EU Water Framework Directive 2000). However, the 2 systems differ in their categorization of environmental states, with b-assessment using 4 distinct categories while the Water Framework Directive employs 5: High, Good, Moderate, Bad, and Poor. The category of an assessment will determine the different frequencies of future assessments required. Although the normal b-assessment frequency is once per production cycle during the maximum biomass period, if the assessment state is equal to or worse than 2, 1 or 2 additional assessments during a production cycle will be requested. Further action plans will be required if the environmental state is assessed as 3 or 4 for 2 consecutive assessments.

Norwegian salmon aquaculture occurs along a lengthy coastline, covering a straight-line distance of 2750 km from north to south, and the biophysical environment and farming performance are significantly different among regions (Thyholdt 2014, Forbord et al. 2020). Wang & Olsen (2023) showed that the annual salmon production has increased by about 80% in the Northern region over the past decade, while an approximate increase of only 20% has occurred in the Central and Southern regions (Directorate of Fisheries 2019). Different factors may contribute to explaining this fundamental difference, including water depth, water current velocity, production intensity, and length of the production cycle. A better understanding of the interactions among these factors across different regions can be advantageous for optimizing aquaculture operations and identifying new potential sites.

Although previous studies have revealed a correlation between the influence on the benthic environment and the biophysical conditions of farming locations (Carroll et al. 2003, Kalantzi & Karakassis 2006), few studies have investigated the long-term effects of salmon farming on the benthic ecosystem at large spatial and temporal scales. The objective of this study was to explore how strongly the benthic ecosystem is affected by nation-wide commercial salmon cage farms. We analyze the specific parameters used in the b-assessment and the spatiotemporal changes in the benthic ecosystem along with salmon production cycles. We also examine the correlation between the benthic environment and the environmental variables. The variables were categorized into 2 groups for analysis: biophysical conditions and farming factors. The biophysical conditions include sea surface temperature (SST), water current velocity, and water depth. The farming factors include farm size, maximum allowable biomass, and production cycles. All data were obtained from government institutions.

2. MATERIALS AND METHODS

2.1. Data

2.1.1. Geospatial data. Geospatial data on Norwegian salmon farms were obtained from the Norwegian Directorate of Fisheries (https://open-data-fiskeridirektoratet-fiskeridir.hub.arcgis.com). Geospatial data on water depth and coastline boundary were obtained from the Norwegian Mapping Authority (www.kartverket.no).

2.1.2. Sea surface temperature. SST data were obtained from the NOAA (National Oceanic and Atmospheric Administration) Satellite database and the NOAA Advanced Clear-Sky Processor for Ocean (ACSPO). This database provides daily temporal resolution and 0.02 degree spatial resolution from Low-Earth-Orbiting Platforms (L3S-LEO) (NOAA/STAR 2012). The SST was collected at points closest to salmon farms in this study.

2.1.3. Current velocity. Data on water current velocity were obtained directly from the Norwegian Directorate of Fisheries. Measurement was carried out by certified companies following Norwegian regulation NS 9415, which is the Norwegian standard for site survey of floating aquaculture farms, design, execution, and use (Standards Norway 2021). Water current velocity was measured in surface water, generally at 5 m depth. For some sites with missing values, we used data imputation matching to the closest farm or the average value for the farm's community.

2.1.4. Benthic environmental assessment. Benthic environmental assessments were obtained from the Norwegian Directorate of Fisheries. Assessment was conducted by certified companies following Norwegian regulation NS 9410 on environmental monitoring of benthic impact from marine fish farms (Standards Norway 2016).

The samples for b-assessment were collected from the seabed directly beneath the cages, using a grab conducted from the boat or cage facility. The minimum number of sampling stations, determined by the mean maximum allowable biomass (MAB), ranged from 8 to 20 per salmon farm. Samples should only be collected from cages that contain fish production. Each grab sample was used to measure the environmental parameters of the sediments, including pH, Eh, benthos, gas bubbles, color, smell, consistency, and thickness of organic matter deposits, and macrofauna. Each sediment sample was collected from the surface layer of the sediment, with a minimum area of 250 cm^2, and was sealed to prevent any water and sediment leakage during transport to the surface. The field measurement of Eh was conducted on board using platinum electrodes, while the pH was measured using either glass electrodes or ISFET (Ion Sensitive Field Effect Transistor) devices. Macrofauna was separated and retained using sieves with round holes ranging in size from 0.5 to 1.0 mm (Standards Norway 2016). As shown in Table 1, each parameter was assigned a score ranging from 0 to 4, and the collective average of these scores determines the environmental state, categorized into 4 levels: 1 (Very good), 2 (Good), 3 (Bad), and 4 (Very bad). Additionally, each b-assessment involved around 10 sampling stations, all located directly under the salmon cage site, and the overall result was determined from the mean scores derived from these stations, enhancing the reliability.

The survey frequency of b-assessment was determined by the result of previous assessments. The fundamental frequency is 1 assessment per production cycle during the maximum production period. An additional 1 to 2 surveys were required if the assessment revealed that the state was equal to or worse than 2.

Table 1. Scoring criteria of b-assessment (Standards Norway 2016)

Variables	Scoring
pH and Eh	0–4
Benthic macrofauna	Presence (0), absence (1) of any macrofauna
Gas bubbles	Absence (0), presence (4)
Color	Grey (0), black (2)
Smell	No (0), light (2), strong (4)
Consistency of sludge	Firm (0), soft (2), loose (4)
Grab volume	<¼ (0), ¼–¾ (1), >¾ (2)
Thickness of organic matter deposits	0–2 cm (0), 2–8 cm (1), >8 cm (2)
Mean of above variables	<1.1 (State 1, Very good) 1.1–2.1 (State 2, Good) 2.1–3.1 (State 3, Bad) >3.1 (State 4, Very bad)

2.1.5. Length of the production cycle. We used the frequency of b-assessment made at maximum biomass to estimate the length of the production cycle of individual farms, with a temporal resolution of 1 d. The time gap between 2 production cycles is included in the production cycle. For some sites with missing values, we used data imputation by matching the average value of the farm's community.

2.2. Study area

Our study involved 2 levels: the national level among the Northern, Central and Southern regions, and the fjord region level of Hardangerfjorden in the south. Our study conducted a comprehensive analysis of all salmon cage farms operating in Norway between 2016 and 2022. To ensure data adequacy, we included only those farms with sufficient information, resulting in a total of 759 salmon cage farms and 3480 b-assessment reports for national-level analysis. These farms were grouped into 3 regions based on their local county to analyze regional differences. Vestland and Rogaland og Agder were grouped into the Southern region, Trøndelag and Møre og Romsdal were grouped into the Central region, and Troms og Finnmark and Nordland were grouped into the Northern region (Fig. 1).

To conduct a comprehensive analysis of b-assessment performance and its correlation with the state of the benthic ecosystem, we selected a study area in the Kvam and Ullensvang municipalities of Hardangerfjorden, which is recognized as one of Norway's largest salmon-farming areas in the south (Husa et al. 2014). Various parameters, such as pH, Eh, presence of benthos, gas bubbles, color, smell, consistency, and thickness of organic matter deposits, were measured to evaluate their association with the different states of the b-assessment present in the study area. A total of 21 salmon farms were operating in this region from 2016 to 2020 (Fig. 2). In this study, we only analyzed 12 of them, specifically those with sampling stations located on soft bottom and with available data on monthly feed input. These farms had 69 b-assessment reports. Each report contained approximately 10 sampling stations, with the exception of a few on hard bottom, as our study included only farm sites with a soft bottom.

2.3. Statistics and data processing

All spatial and statistical analyses were performed in the Python 3.9 programming environment (Van Rossum & Drake 2009), using the Pandas (McKinney 2010), GeoPandas (Jordahl 2014), SciPy (Virtanen et al. 2020), and Statsmodels (Seabold & Perktold 2010) software libraries. The plots were performed using MATLAB (release 2022), ArcGIS Pro (Version 2.7, release 2021), Python Matplotlib (Hunter 2007), seaborn (Waskom 2021), and PCA (Taskesen 2020) software libraries. The results for the variables are reported as means ± 1 standard error (SE). To compare variables and the environmental state of the benthic environment among different regions, the Kruskal-Wallis (*H*) test with Dunn's post-hoc test was conducted because normal distribution could not be verified.

We use regression to assess the correlation between the state of the benthic environment and biophysical conditions (including SST, water depth, current velocity, distance to land, distance to closest salmon) and farming factors (including the size of farm area, maximum allowable biomass, maximum allowable density, and length of production cycle). The regression curves were determined by choosing the best R^2 value. The significance limits were set at 0.05. Principal component analysis (PCA) was performed to enable a more integrated interpretation of biophysical conditions and farming factors among the different states of the benthic environment. In addition, we randomly selected an equal number of b-assessments from each region to observe the relationship between SST and environmental state across the regions. A total of 1500 reports from 624 farms were analyzed.

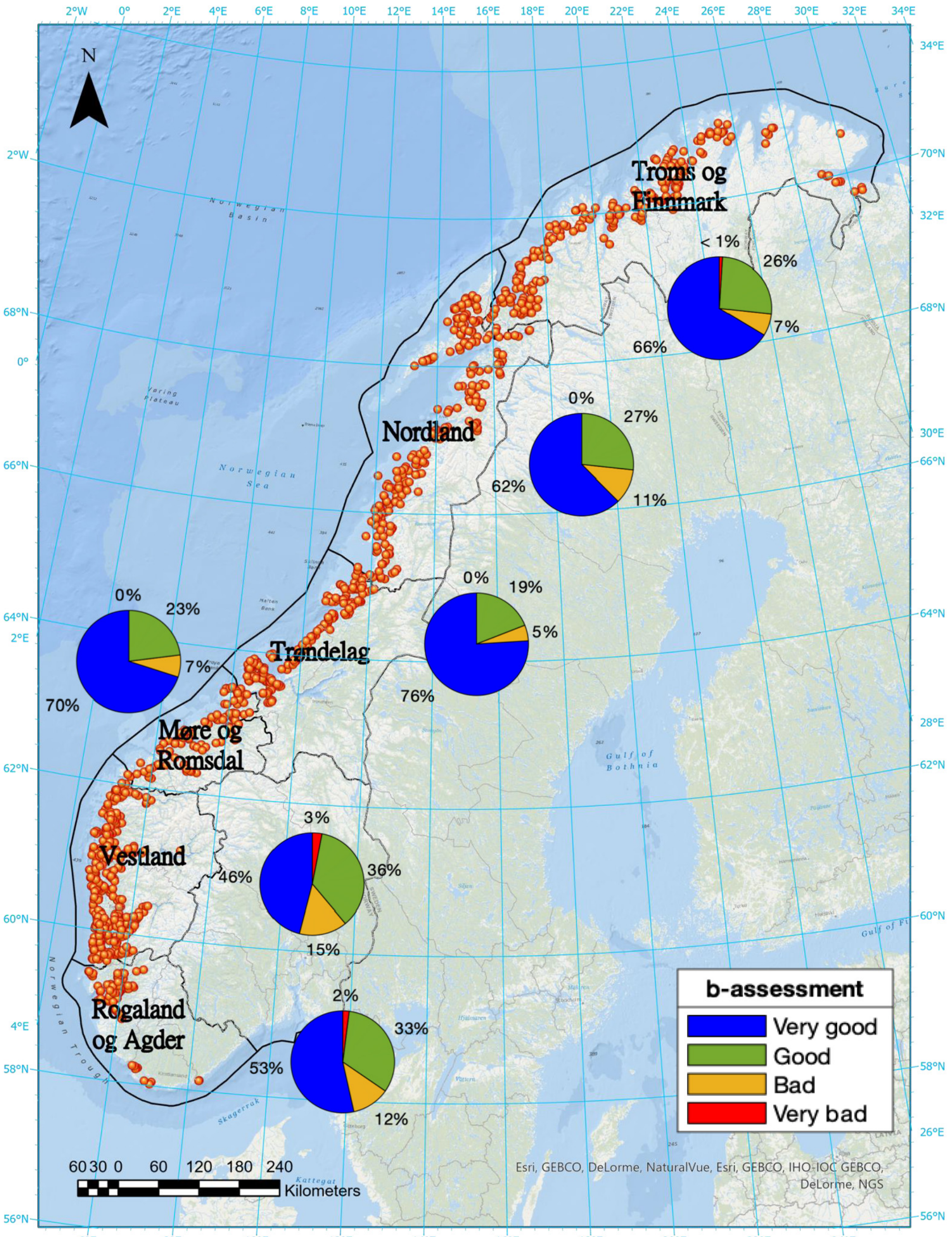

Fig. 1. Salmon aquaculture site distribution and b-assessment in Norway from 2020. Orange dots: locations of salmon farms. Pie charts indicate the environmental states at the county level, classified by b-assessment in 2020

3. RESULTS

3.1. Biophysical and farming conditions

The daily SST exhibited pronounced seasonal variation and steadily increasing values from the Northern to the Southern region (Fig. 3). The lowest SSTs occurred in March, while the highest occurred in August. The monthly mean SST from winter to summer during 2016 to 2022 ranged from 3.7 to 12.2°C in the Northern region, 5.3 to 14.5°C in the Central region, and 5.2 to 16.1°C in the Southern region (Fig. 3). Additionally, the Southern region showed a broader range of SST than the other regions.

The mean water current velocity, which ranged from 1.1 to 21.1 cm s^{-1}, was significantly slower ($p < 0.05$) in the Northern region than in the Southern, but not significantly different between the Central and Southern regions and between the Northern and Central regions (both $p > 0.05$, Fig. 4A, Table 2). The

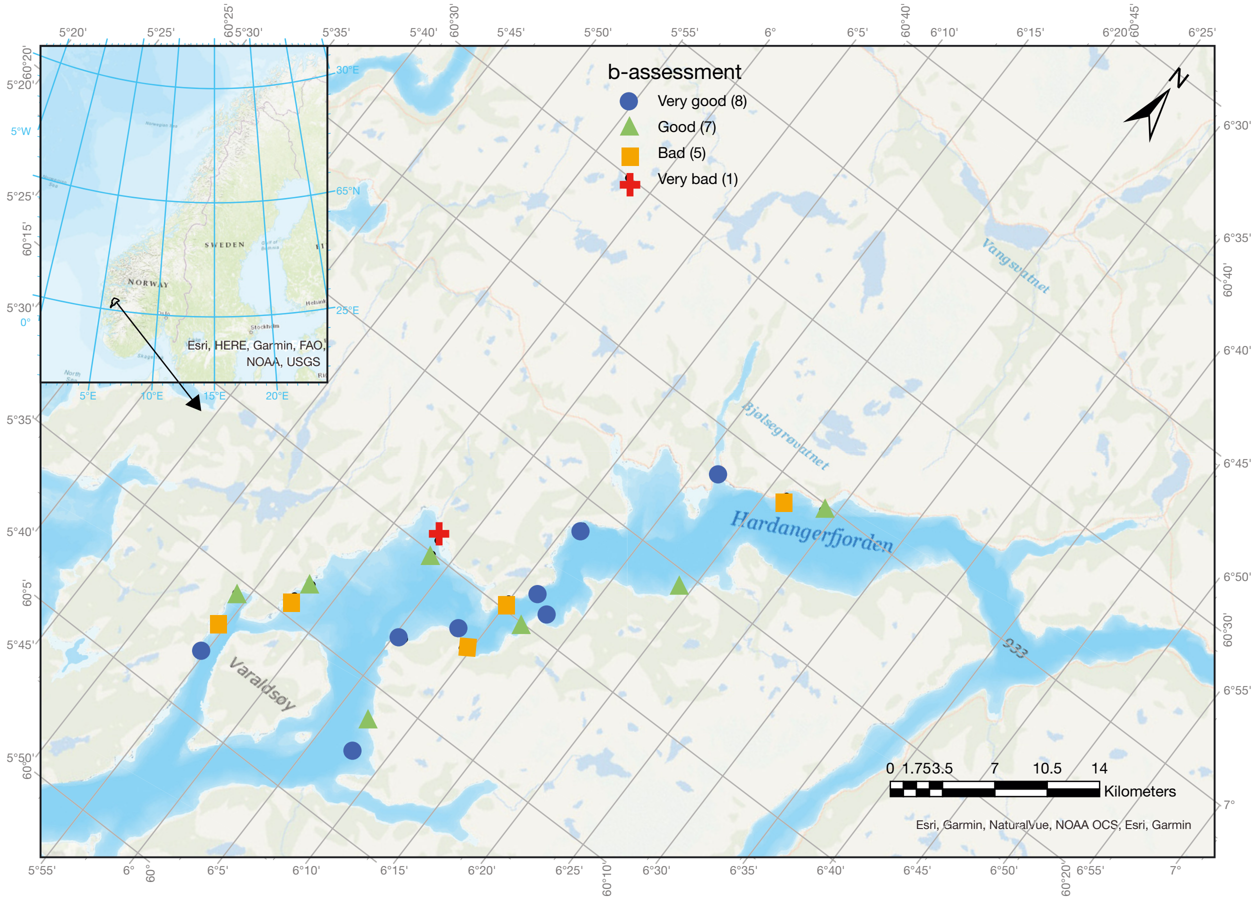

Fig. 2. Overview of the study area located in the Kvam and Ullensvang municipality of Hardangerfjorden in southern Norway

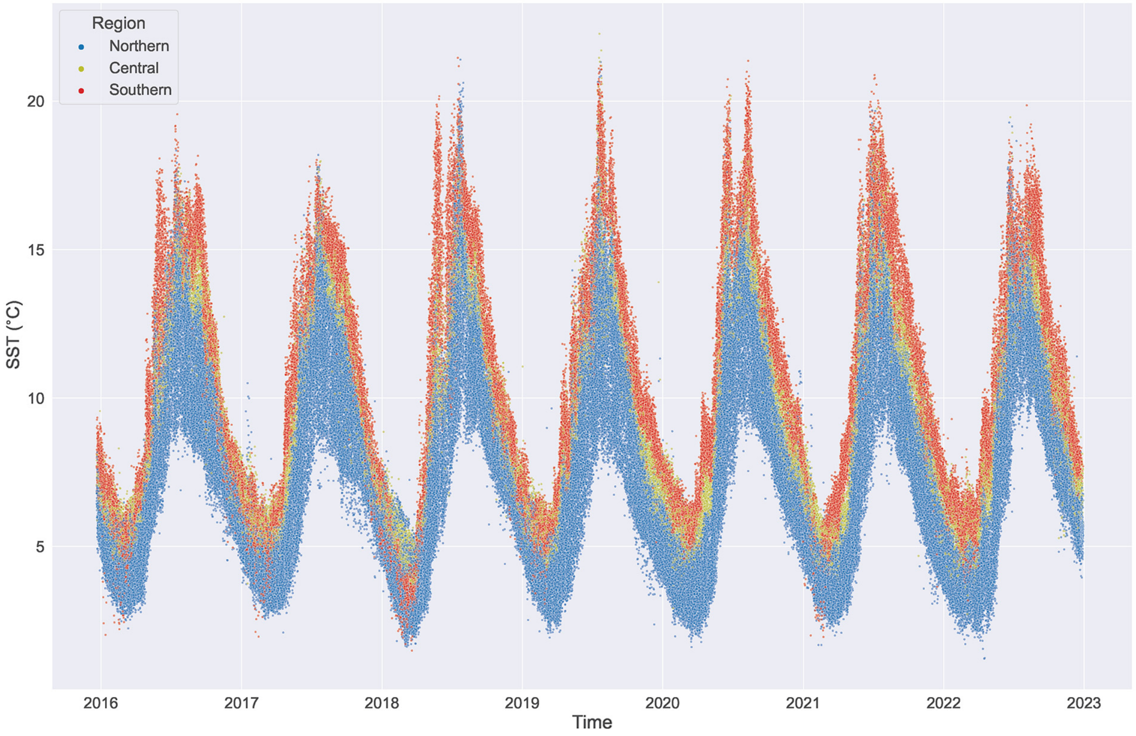

Fig. 3. Daily sea surface temperature (SST) of 759 Norwegian salmon cage farms from 2016 to 2022 (data from NOAA satellite database)

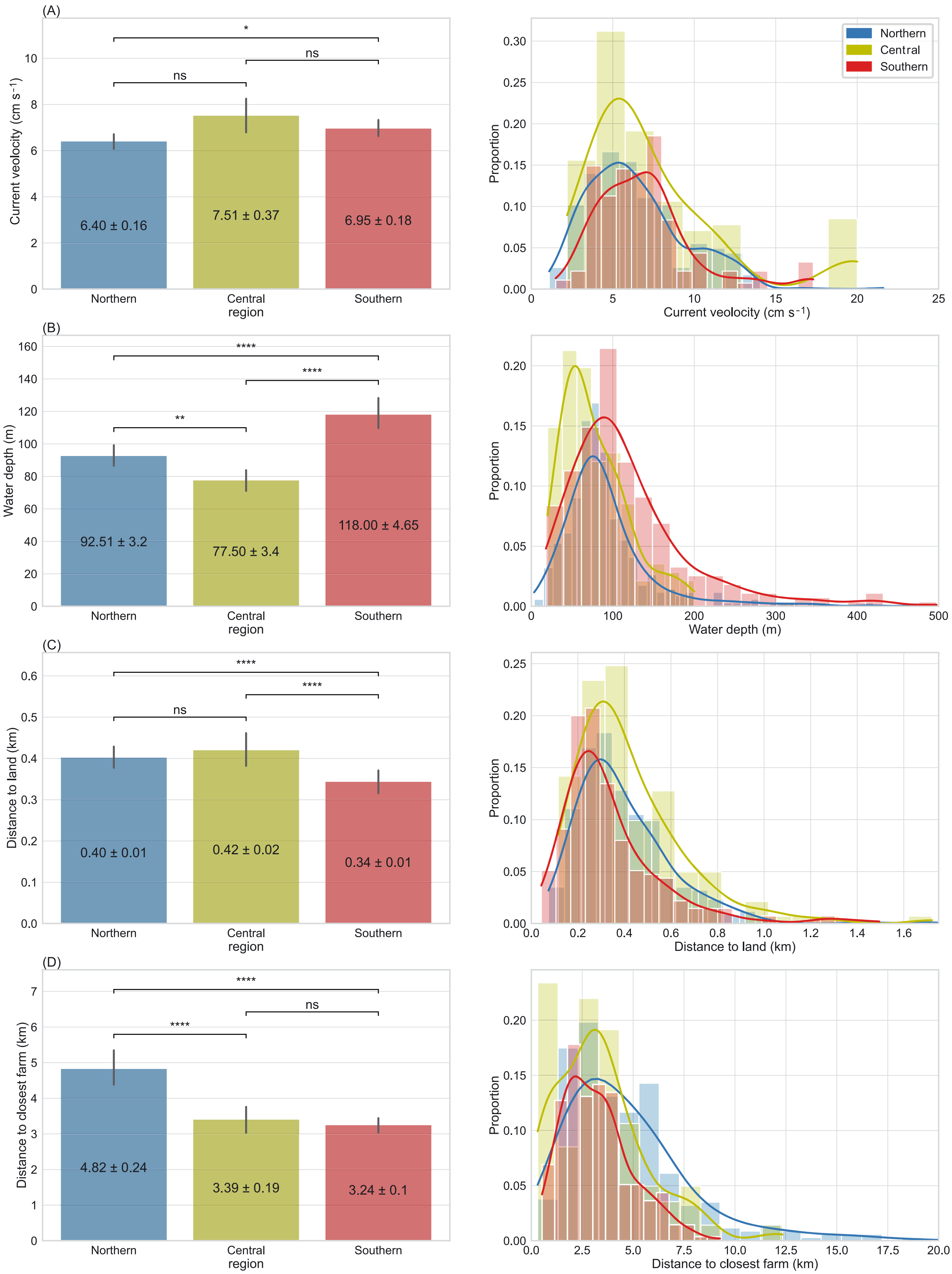

Fig. 4. Biophysical conditions of salmon farms. Mean ± 1 SE and frequency distribution of biophysical condition of 759 Norwegian salmon cage farms from 3 regions from 2016 to 2022. (A) Current velocity, (B) water depth, (C) distance to land, (D) distance to closest salmon farm. $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 1 \times 10^{-3}$, $^{****}p < 1 \times 10^{-4}$, ns: not significant

mean water depth was significantly different for each region (Fig. 4B, all $p < 0.01$, Table 2). The Southern region had a greater proportion of salmon farms located in water depths greater than 100 m (Fig. 4B). The mean distance from farm to land in the Southern region was significantly shorter compared to those in the Northern and Central regions (Fig. 4C, $p < 1 \times 10^{-4}$ for both). The mean distance between the farm and its closest neighbor farm was significantly longer in the Northern than in the Central and Southern regions (Fig. 4D, $p < 1 \times 10^{-4}$ for both). Additionally, as shown in Table 2 and Fig. 4D, the Northern region had a greater proportion of long distances between closest neighbor farms compared to the other regions.

The mean size of farm area was significantly smaller in the Southern region compared to that in the Northern and the Central regions ($p < 0.01$ and 0.001, respectively, Fig. 5A, Table 2). A relatively higher proportion of farms in the Southern region were smaller than ~7 ha (Fig. 5A, Table 2).

The MAB and MAB density (kg m^{-3}) were significantly different among the regions (Fig. 5B,C, all $p < 0.05$). The Southern region had clearly the lowest MAB but the highest MAB density among the regions.

As shown in Fig. 5C and Table 2, the Southern region has a relatively higher proportion of farms with a MAB density above ~5 kg m^{-3} compared to the other regions. This could potentially be influenced by the higher proportion of smaller farms in the Southern region, compared to the other 2 regions (Fig. 5A, Table 2).

The mean length of the production cycles was significantly longer in the Central region compared to the Northern and Southern regions (Fig. 5D, Table 2,

Table 2. Statistical values for biophysical condition and farming factors of 759 Norwegian salmon cage farms from 3 regions from 2016 to 2022, shown in Figs. 4 & 5. MAB: maximum allowable biomass; IQR: interquartile range; CV: coefficient of variation. Kurtosis is a measure of the relative peakedness of a distribution. Skew is a measure of the asymmetry of the probability distribution. Water volume (m^3) = water depth (m) × farm area (m^2); MAB density (kg m^{-3}) = MAB / water volume (m^3)

Variable	Region	Mean ± SEM	Percentile 25%	Percentile 50%	Percentile 75%	IQR	CV	Kurtosis	Skew
Biophysical conditions									
Current velocity (cm s^{-1})	Northern	6.40 ± 0.16	4.05	5.80	7.98	3.93	47%	1.36	0.96
	Central	7.51 ± 0.37	4.56	6.20	9.25	4.69	59%	2.14	1.63
	Southern	6.95 ± 0.18	4.90	6.90	8.00	3.10	44%	2.36	1.35
Water depth (m)	Northern	92.5 ± 3.2	62.58	80.00	103.93	41.35	64%	10.39	2.69
	Central	77.5 ± 3.4	50.00	67.65	100.00	50.00	52%	0.53	0.99
	Southern	118.0 ± 4.7	70.90	98.44	141.85	70.95	65%	4.75	1.91
Distance to land (km)	Northern	0.4 ± 0.01	0.26	0.35	0.50	0.24	61%	32.43	4.02
	Central	0.42 ± 0.02	0.26	0.35	0.52	0.26	57%	6.09	1.98
	Southern	0.34 ± 0.01	0.20	0.28	0.41	0.21	67%	6.49	2.21
Distance to the closest farm (km)	Northern	4.82 ± 0.24	2.55	3.93	6.04	3.49	93%	99.69	7.88
	Central	3.39 ± 0.19	1.77	3.07	4.38	2.62	67%	1.68	1.11
	Southern	3.24 ± 0.1	1.98	2.98	4.07	2.09	52%	0.29	0.78
Farming factors									
Water volume (m^3)	Northern	9.34 ± 0.34	5.52	8.27	12.16	6.65	68%	20.35	2.94
	Central	10.2 ± 0.52	6.07	8.74	13.67	7.60	60%	1.21	1.08
	Southern	7.97 ± 0.37	3.09	7.26	11.27	8.18	76%	1.54	1.10
MAB (1000 t)	Northern	3.76 ± 0.09	2.70	3.60	4.84	2.14	44%	−0.17	0.44
	Central	4.13 ± 0.14	3.12	3.90	5.46	2.34	40%	−0.79	0.11
	Southern	2.85 ± 0.08	2.18	3.12	3.60	1.42	44%	0.16	0.49
MAB density (kg m^{-3})	Northern	4.34 ± 0.16	2.47	3.64	5.56	3.09	66%	8.44	2.15
	Central	3.77 ± 0.24	2.09	2.92	4.23	2.14	76%	7.53	2.39
	Southern	6.78 ± 0.45	2.60	4.25	7.93	5.33	111%	11.20	3.06
Length of production cycle (mo)	Northern	21.13 ± 0.2	18.57	21.13	23.48	4.90	17%	−0.37	−0.24
	Central	22.98 ± 0.19	22.39	23.38	24.07	1.67	10%	4.70	−1.58
	Southern	21.77 ± 0.15	20.56	22.07	23.15	2.59	11%	1.05	−0.77

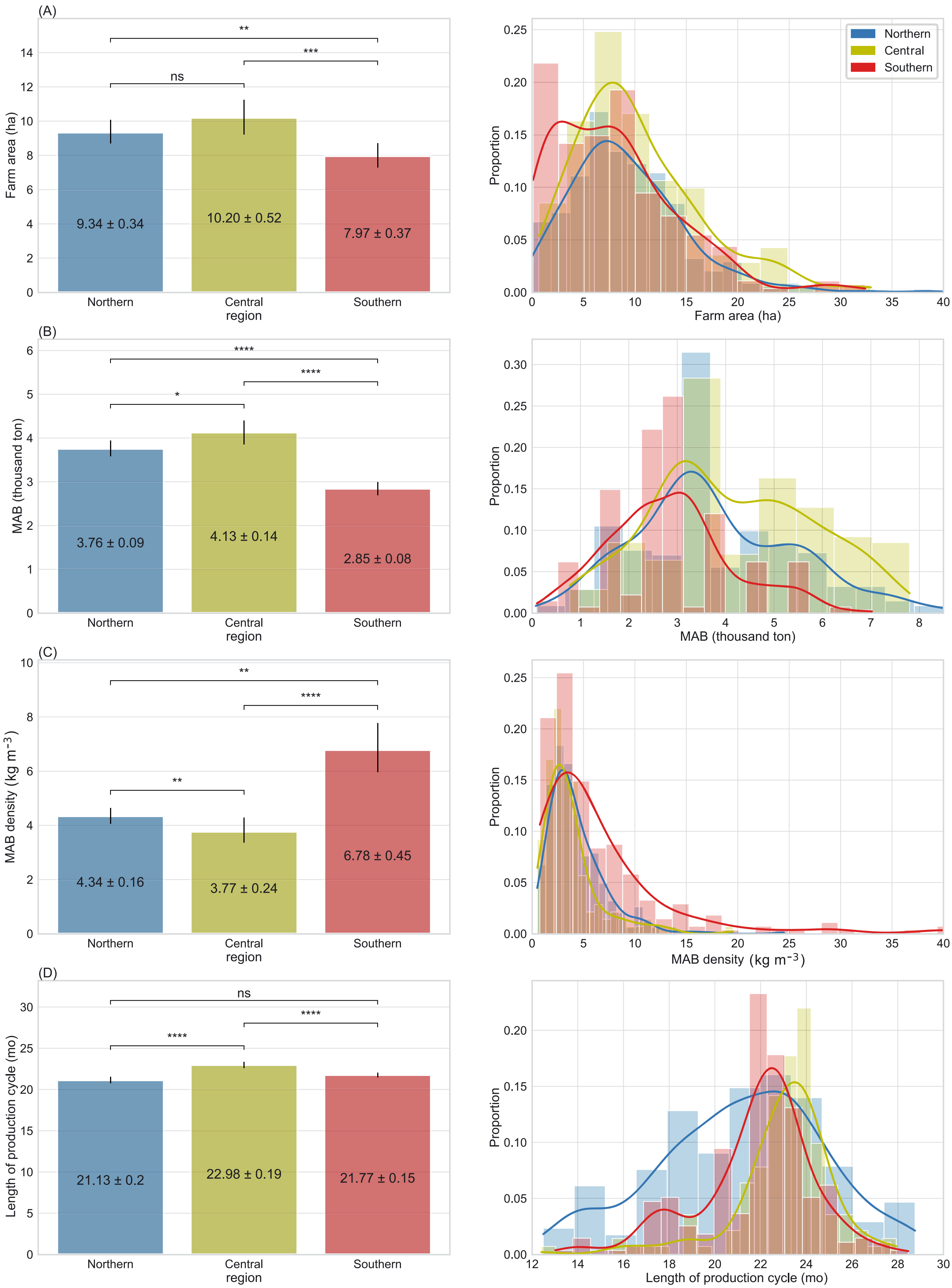

Fig. 5. Mean ± 1 SE and frequency distribution of farming factors of 759 Norwegian salmon cage farms from 3 regions from 2016 to 2022. (A) Size of farm area (ha), (B) maximum allowable biomass (MAB), (C) MAB density, (D) length of production cycle. $^*p < 0.05$, $^{**}p < 0.01$, $^{***}p < 1 \times 10^{-3}$, $^{****}p < 1 \times 10^{-4}$, ns: not significant

$p < 1 \times 10^{-4}$ for both). No significant difference was found for the Northern and Southern regions ($p > 0.05$). This suggests that farming operations may have a greater impact on the production cycle than biophysical conditions. The longer production cycles found for the Central region were likely due to a longer gap between consecutive production cycles. Additionally, the Northern region showed greater variability and a higher proportion of salmon farm sites with production cycles shorter than 22 mo compared to the other regions (Fig. 5D, Table 2). This suggests that the initial salmon size at the start of the production cycle may have been larger or more diverse, resulting in a shorter sea phase.

The results of our study show that the biophysical conditions of farms were often significantly different among regions (Table 2). The Northern region had the slowest current velocity and longest distance to the closest farm; the Central region had the shallowest water depth; the Southern region had the deepest water depth and the shortest distance to land. Additionally, several farming factors were also significantly different among regions (Table 2). MAB density showed the most noteworthy difference, with the highest values found in the Southern region and the lowest in the Central region (Fig. 5C)

3.2. Variables determining the state obtained in b-assessment

Various environmental factors were evaluated in the study area in Hardangerfjorden (Fig. 2), including pH, Eh, presence of benthos, presence of gas bubbles, color, smell, and consistency of the sludge, and thickness of organic matter deposits (e.g. uneaten feed and fish feces) in the benthic environment (Table 1). The results revealed that all sampling stations showed similar variation in most of the above variables and slight similarities were observed in organic matter deposit thickness and benthic macrofauna (Fig. 6). Both pH and Eh decreased with a reduced environmental state (Fig. 6A). Most cases of State 1 (Very good) and State 2 (Good) had alkaline pH (pH > 7) and positive Eh values. In contrast, those of State 3 (Bad) and State 4 (Very bad) tended to have acidic pH (pH < 7) and negative Eh values. Benthic macrofauna was present in all states, but when the benthic environment reached State 4, there was a higher likelihood of an absence of benthic macrofauna (Fig. 6A).

As the environmental state worsened, the sediment had a stronger odor, with a black or brown color appearing for states worse than 3 (Fig. 6B). With

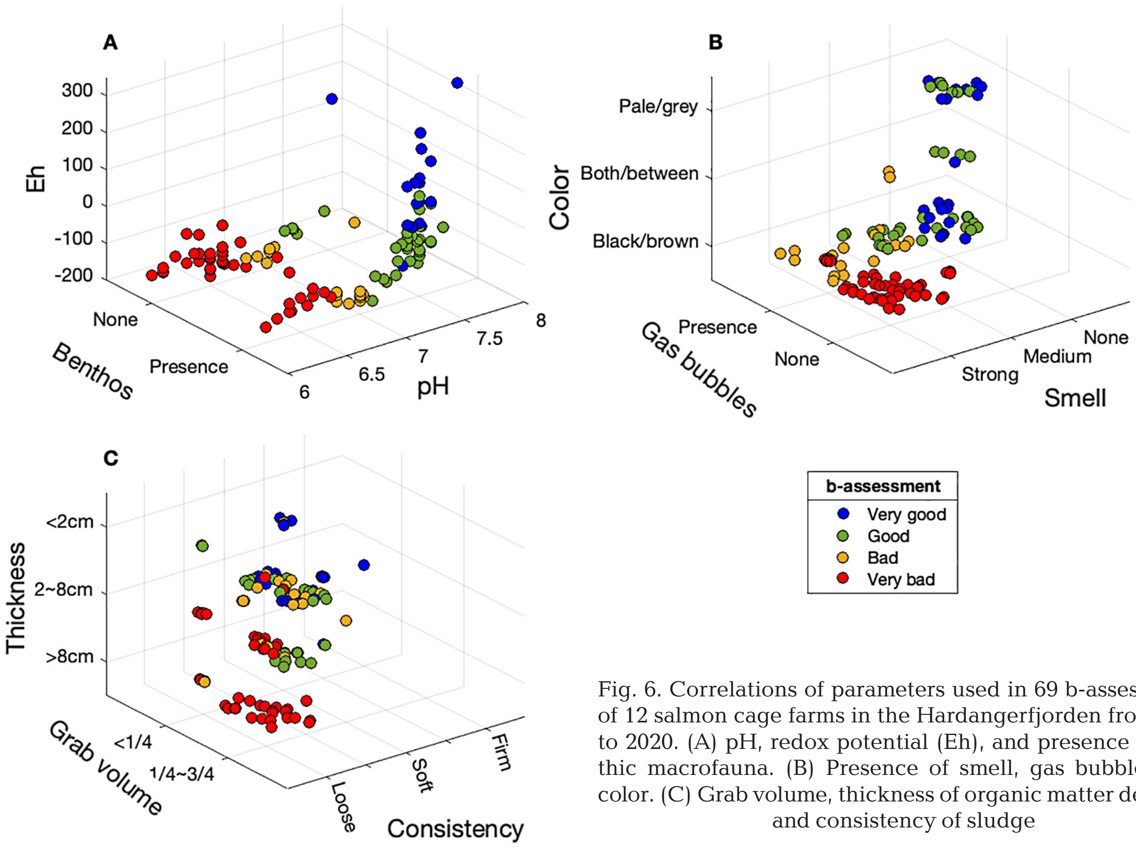

Fig. 6. Correlations of parameters used in 69 b-assessments of 12 salmon cage farms in the Hardangerfjorden from 2016 to 2020. (A) pH, redox potential (Eh), and presence of benthic macrofauna. (B) Presence of smell, gas bubbles, and color. (C) Grab volume, thickness of organic matter deposits, and consistency of sludge

deteriorating environmental conditions, organic matter deposits increased in volume and thickness, while sediment consistency decreased from firm to soft and loose. At environmental State 4, we observed a more apparent increase in the thickness of organic matter deposits, exceeding 8 cm, and a decrease in sediment consistency to a loose state (Fig. 6C).

Clear boundaries among the 4 different environmental states could be observed by combining all of the above variables, making this a suitable approach to monitoring changes in the benthic environment (cf. Table 1).

3.3. Influence of biophysical and farming conditions on the environmental state

The results of the benthic state assessment for 759 farms for 2016 to 2022 revealed noticeable seasonal fluctuations over the year (Fig. 7). The cases receiving State 4 and State 3 showed an annual peak during September and October (about 43% of annual cases, Fig. 7C,D). In contrast, the State 1 cases did not show such clear annual peaks; only 17% of annual cases occurred during September and October (Fig. 7A).

The relationship between SST, the environmental state, and spatial location of salmon farms, which were randomly selected from 500 reports out of 624 farms, is shown in Fig. 8. Most assessments resulting in States 1 to 2 were found around 6°C, while States 3 to 4 showed a pronounced peak at approximately 10 to 12°C (Fig. 8A). Fig. 8B–E shows the relationship between SST and the latitude of salmon farms for each state. The occurrence of States 1 and 2 was observed at lower SST compared to States 3 and 4. Additionally, slight regional variations were observed. The Central region had a higher probability density for the occurrence of State 1. Moreover, for the occurrence of State 4, the majority of cases in the Southern region occurred at approximately 13°C, while in the Northern region, they occurred at around 9°C (Fig. 8E).

The relationship between benthic environment state and biophysical conditions and farming factors, analyzed using linear regression, are presented in Table 3. Regression coefficients revealed that the state of the benthic environment was significantly correlated with water depth ($p < 0.05$), MAB ($p < 0.001$), size of farm area ($p < 0.001$), length of the production cycle ($p < 0.001$), and MAB density ($p < 0.001$), and only weakly correlated with current velocity ($p = 0.067$). This implies that the impact on the benthic environment increased with increasing water

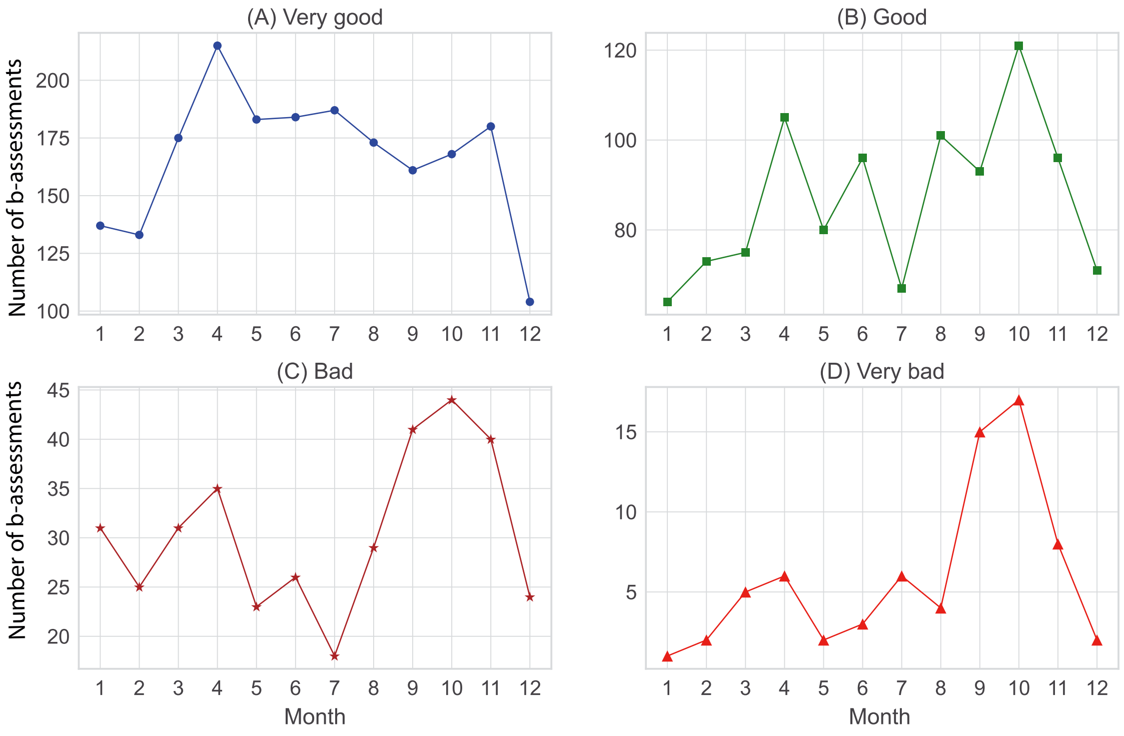

Fig. 7. Temporal variation of the benthic environment of 759 Norwegian salmon cage farms from 2016 to 2022. (A) State 1 (Very good), (B) State 2 (Good), (C) State 3 (Bad), (D) State 4 (Very bad)

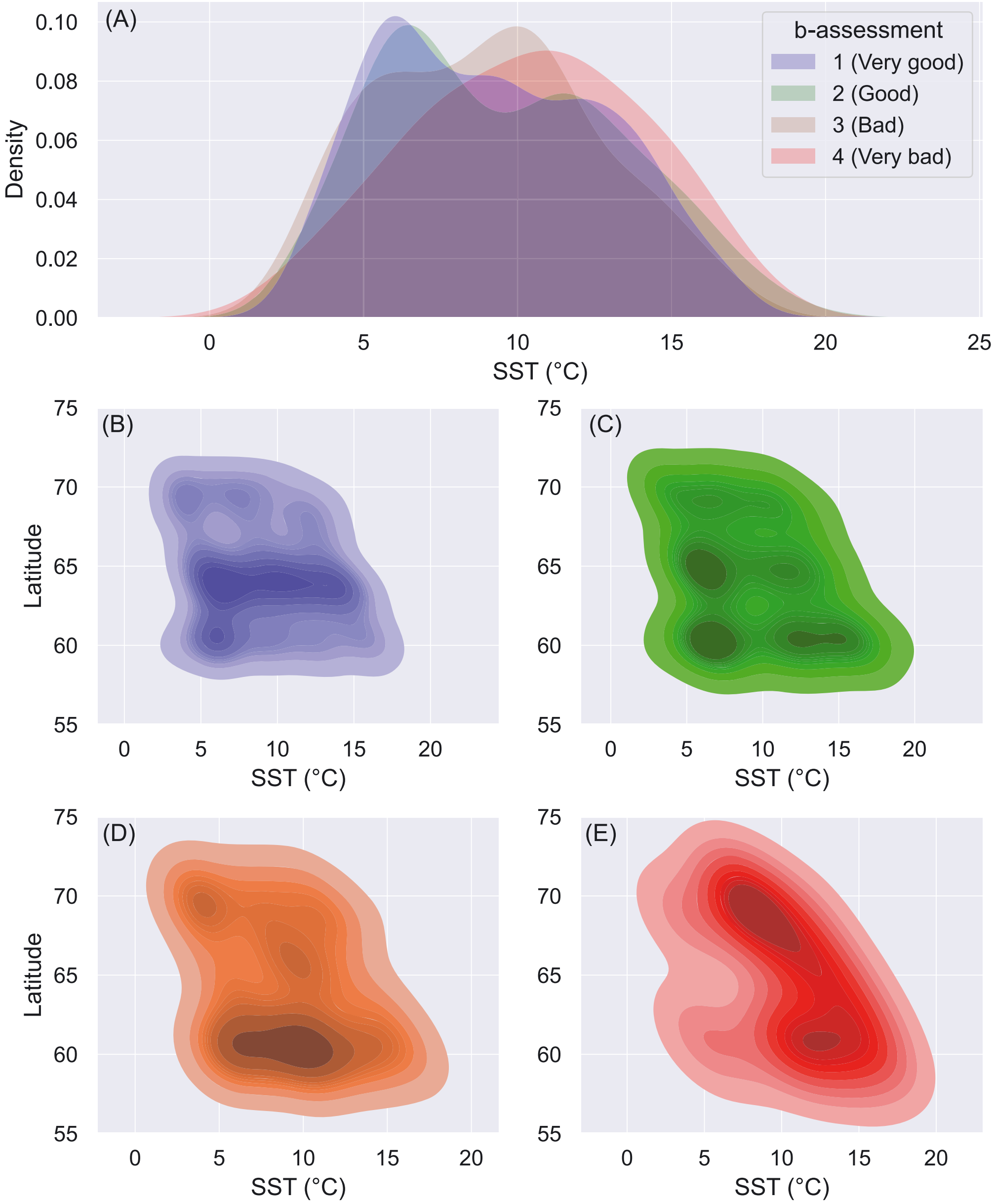

Fig. 8. Relationship between SST and b-assessment of 624 Norwegian salmon cage farms located at different latitudes from 2016 to 2022. (A) Probability density of the 4 different environmental states with respect to the variation in SST. Distribution of (B) State 1 (Very good), (C) State 2 (Good), (D) State 3 (Bad), and (E) State 4 (Very bad) with respect to SST and latitude variation. SST: sea surface temperature

depth (Fig. 9D) and MAB density (Fig. 9E), and decreased with increasing current velocity (Fig. 9G), length of the production cycle (Fig. 9H), MAB (Fig. 9A), and size of farm area (Fig. 9B).

The results of the PCA conducted to examine the relationship between the benthic environment and variables among 490 surveyed farms in 2022 showed that the first 4 principal components accounted for 85% of the total variance in the data, with 26, 21, 19, and 18% of the variance explained by PC1, PC2, PC3, and PC4, respectively. PC1 was primarily influenced by farm area, PC2 by water depth, PC3 by production cycle, and PC4 was dominated by a combination of SST (with a contribution of 0.89) and production cycle (with a contribution of 0.46, Fig. 10B). However, the scatterplot did not reveal apparent differences between the 4 environmental states. This suggests that there may be other potential factors that affect the state of the benthic environment that were not identified in the present study (Fig. 10A).

Table 3. Statistical coefficients for linear regression of the average b-assessment of 759 Norwegian salmon cage farms from 2016 to 2022 vs. variables from environment and farming operations. MAB: maximum allowable biomass; CI: confidence interval (2.5–97.5%). Significant values are given in **bold**: *p < 0.05, ***p < 0.001

Variable	Slope Mean [CI]	Intercept Mean [CI)]	R^2	p
Biophysical conditions				
Water depth (m)	6×10^{-4} $[9 \times 10^{-5} - 1 \times 10^{-3}]$	1.38 [1.32 – 1.44]	0.007	**$<$ 0.05***
Current velocity (mean)	−0.001 [−0.020 – −0.001]	1.51 [1.43 – 1.59]	0.004	0.067
Current velocity (max.)	−0.001 [−0.003 – 0.001]	1.48 [1.39 – 1.56]	0.001	0.40
Distance to land (km)	-2×10^{-6} $[-7 \times 10^{-5} - 6 \times 10^{-5}]$	1.44 [1.38 – 1.51]	0.001	0.98
Distance to closest farm (km)	-6×10^{-6} $[-2 \times 10^{-5} - 4 \times 10^{-6}]$	1.47 [1.42 – 1.52]	0.002	0.20
Farming factors				
MAB (t)	-7×10^{-5} $[-9 \times 10^{-5} - -5 \times 10^{-5}]$	1.67 [1.59 – 1.75]	0.047	**$<$ 0.001*****
Farm area (ha)	-1×10^{-6} $[-2 \times 10^{-6} - -5 \times 10^{-7}]$	1.53 [1.47 – 1.59]	0.017	**$<$ 0.001*****
Length of production cycle (mo)	−0.001 [−0.001 – −0.000]	1.89 [1.65 – 2.13]	0.017	**$<$ 0.001*****
Interactions and others				
Water volume (m^3)	-1×10^{-9} $[-4 \times 10^{-9} - 2 \times 10^{-9}]$	1.45 [1.41 – 1.50]	0.001	0.510
MAB density (kg m^{-3})	0.014 [0.007 – 0.021]	1.37 [1.32 – 1.42]	0.023	**$<$ 0.001*****
Max. b-assessment	0.476 [0.460 – 0.493]	0.53 [0.49 – 0.56]	0.814	**$<$ 0.001*****
Survey frequency (yr^{-1})	0.72 [0.65 – 0.79]	0.85 [0.79 – 0.92]	0.339	**$<$ 0.001*****

3.4. Recovery of the benthic environment

We traced all reports of b-assessment during 2016 to 2022 (a total of 2922 reports) to investigate development in the assessment state of the benthic ecosystem after an earlier assessment. The results revealed that about 57% of locations with a benthic environment of State 4 had recovered to State 2 or better at the following assessment (Fig. 11). For locations given State 3, about 75% of these had recovered to or better than State 2 (Fig. 11). For locations with State 2 or State 1, about 86% were equal to or better than State 2 in the following survey (Fig. 11).

The data for the selected study area in Hardangerfjorden (Fig. 2), in the Southern region, allowed further analysis of the correlation between the assessment state of the benthic ecosystem and the production cycle in the individual farm. The state of the benthic environment fluctuated greatly with the monthly feed input (Fig. 12), a proxy related to the biomass of the salmon. However, it is important to note that the feed input can be influenced by other factors, such as water temperature, and fish size and age, as well as their health and stress levels. Most cases of State 3 or State 4 occurred in months of high feed input, and most sites recovered just after the feed input was reduced.

Based on the above observation, we infer that aquaculture operations can negatively impact the benthic environment below the fish cages, but these impacts are also recoverable, and the recovery rate appears to be higher at earlier stages of environmental degradation. Therefore, the b-assessment provides a timely warning to fish farmers so that relevant action can be taken to alleviate the impact, making this a functional tool for maintaining good environmental conditions.

4. DISCUSSION

The main finding of our study is that the environmental states of the benthic environment beneath salmon cage farms were significantly different among the Northern, Central, and Southern regions of Norway ($p < 0.001$). Such differences might be influenced by current velocity, water depth, size of farm area, and length of the production cycle. Moreover, the SST showed a distinct seasonal fluctuation and a gradual increase from the Northern to Southern regions. We observed that the state of the benthic environment promptly varied in response to changes in salmon biomass. The b-assessment method appeared to provide reliable and reproducible results among farms and seasons, which is essential for the sustainable environmental management of aquaculture. Environmental impacts were found to be recoverable within a production cycle, and the recovery capabilities were most efficient in the earlier stages of environmental degradation. This indicates that conducting regular and continuous environmental

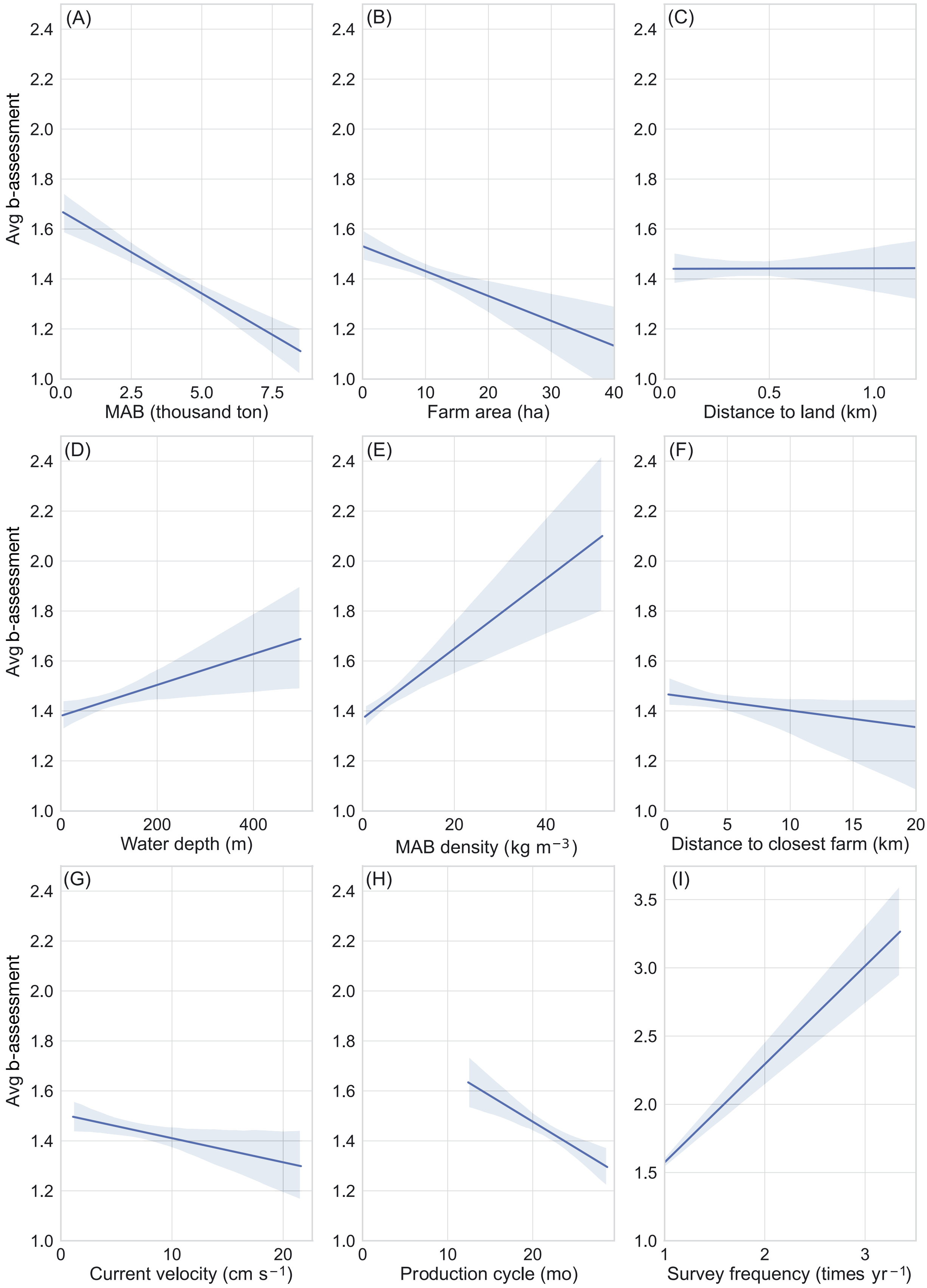

Fig. 9. Regression analysis illustrating the correlation between the average b-assessment result of 759 Norwegian salmon cage farms from 2016 to 2022 and biophysical condition and farming factors, with the shaded area representing the standard deviation of the error bounds. (A) Maximum allowable biomass (MAB), (B) size of farm area, (C) distance to land, (D) water depth, (E) MAB density, (F) distance to closest salmon farm, (G) current velocity, (H) length of production cycle, and (I) survey frequency

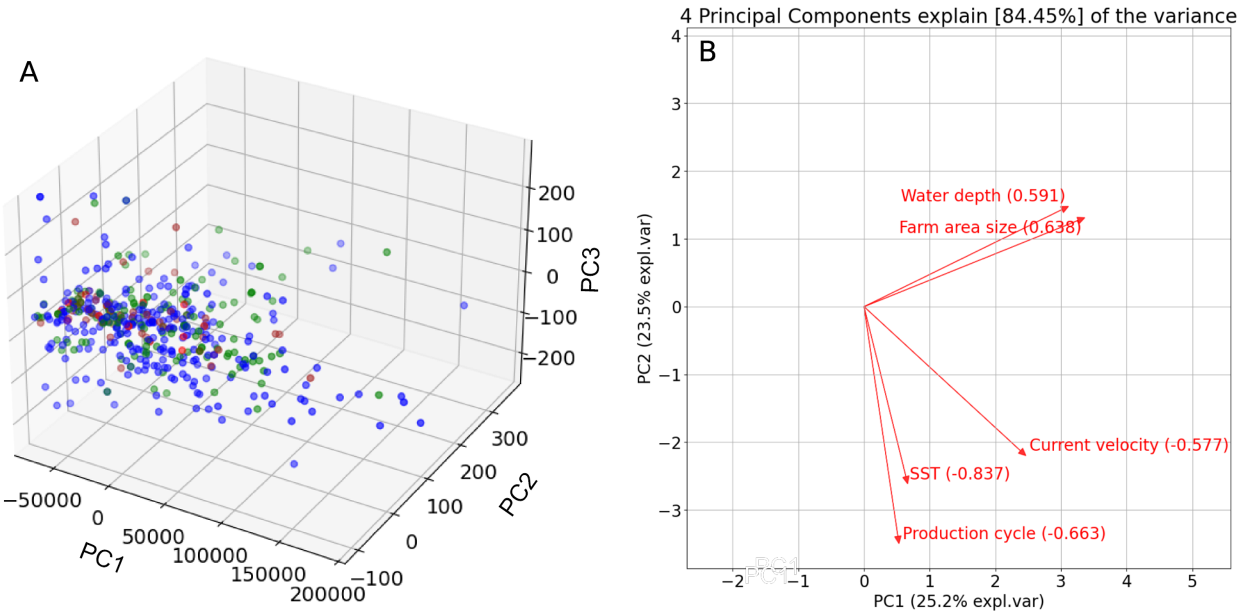

Fig. 10. Principal components analysis (PCA) with 3 principal components (PC1, PC2, and PC3) of 759 Norwegian salmon cage farms from 2016 to 2022. (A) The variation in the data is explained by PC1, accounting for 26%, followed by PC2, explaining 21% of the variation, and PC3, explaining 19%. (B) Contribution of the variables to the plot scores

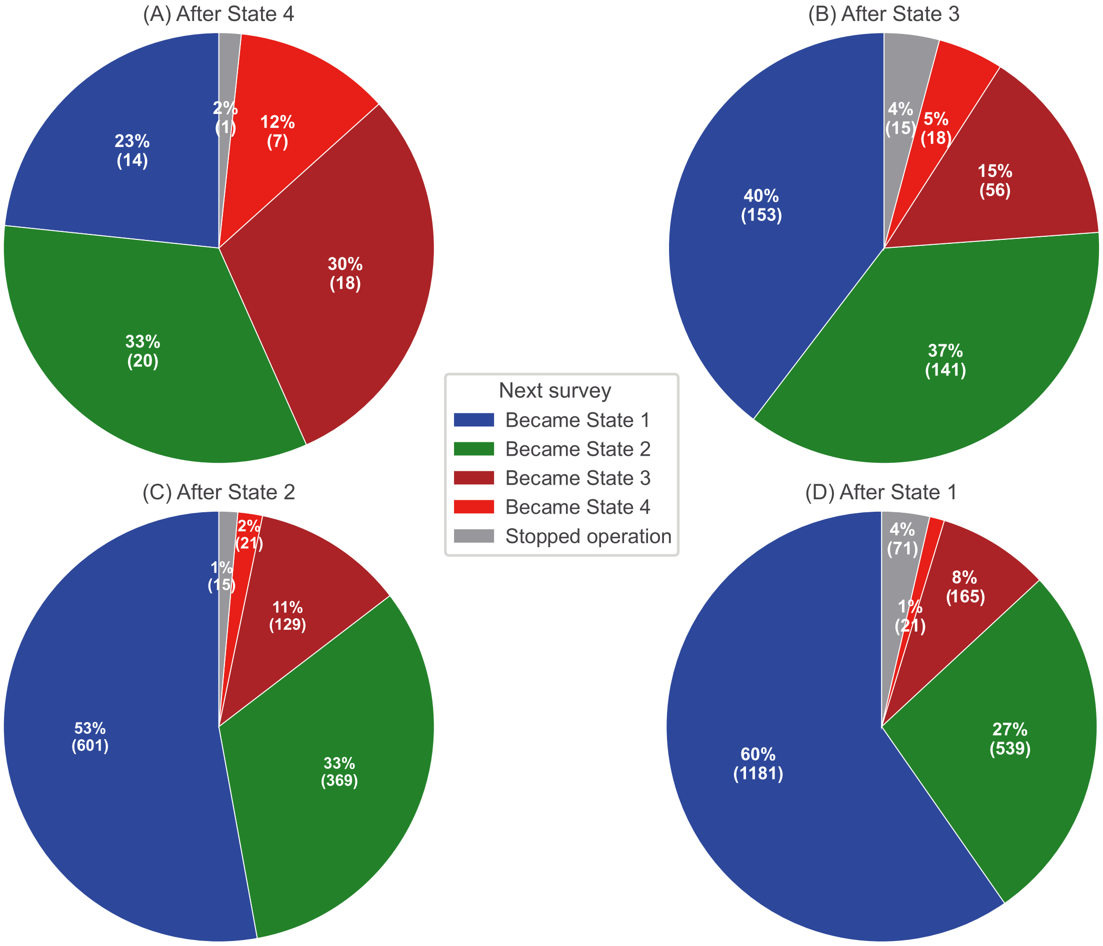

Fig. 11. Successive outcomes of b-assessments of the benthic environment of 759 Norwegian salmon cage farms from 2016 to 2022

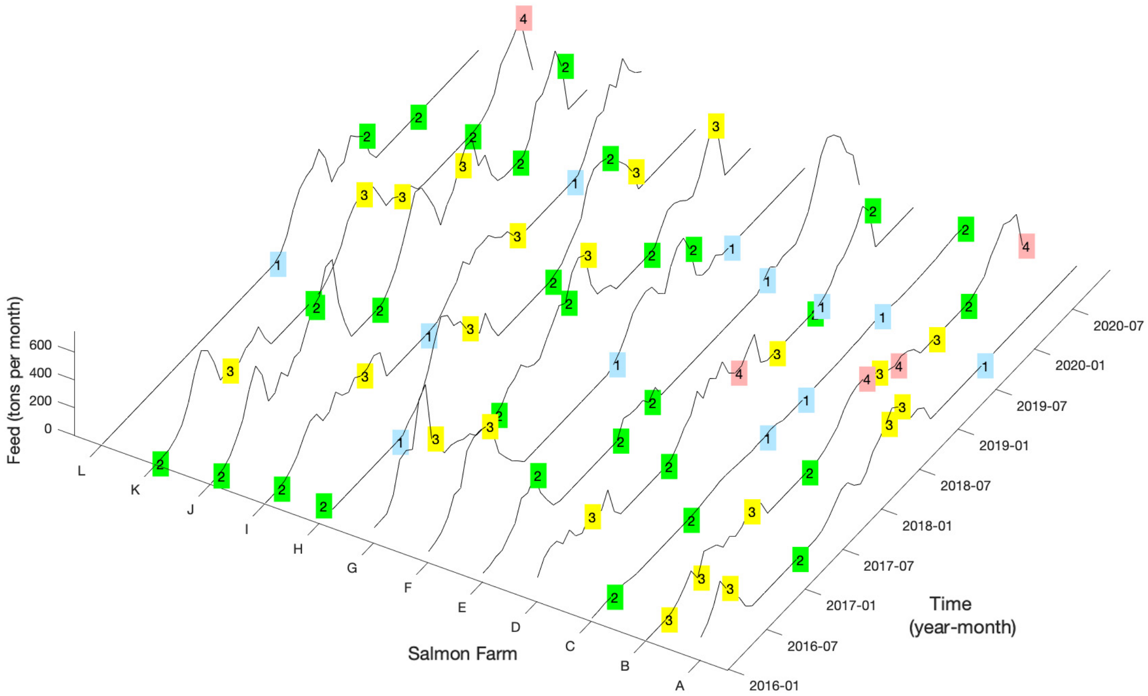

Fig. 12. Overview of the b-assessments of 12 salmon cage farms in Hardangerfjorden from 2016 to 2020. The numbers on the colored labels indicate the assigned environmental states: 1 (Very good), 2 (Good), 3 (Bad), and 4 (Very bad)

assessments is essential for evaluating environmental impacts for the sustainable management of the industry. Furthermore, studies on the correlation between environmental states and variables can also be meaningful and beneficial for site selection and methods of aquaculture operations.

4.1. Environmental cost

The Norwegian legal regulation NS 9410 requires that salmon farmers conduct benthic environmental assessments of farm locations for each production cycle, with a mandatory frequency and sampling time determined by the results of previous assessments. As explained in Sections 1 & 2.1.4, if the state is assessed as equal to or worse than 2 (Good), 1 to 2 additional assessments will be requested. Nevertheless, for some sensitive sites, we propose conducting triplicate sampling from each station and including additional parameters, such as sulfides, as suggested by Wildish et al. (2001), Hargrave et al. (2008), and Hamoutene (2014). This can provide a more comprehensive understanding of the sediment, particularly at the initial stages.

We found a significantly positive correlation between the average b-assessment and the frequency of assessments ($p < 0.001$, Table 3). This confirms that the regulation is effectively implemented and that farms with a more substantial environmental impact incur higher costs for multiple benthic assessments.

4.2. Reliability of b-assessment

Our study showed that the 4 designed classifications defined for environmental states have clear boundaries, which can be observed through various individual parameters, including pH, Eh, presence of benthic macrofauna, presence of smell, gas bubble, color, grab volume, thickness of organic matter deposits, and sludge consistency (Fig. 6). The b-assessment measures the above variables at about 10 sampling stations and allows the overall state of the benthic environment to be determined, as described in Section 2.1.4. We therefore suggest that this is a robust and reliable methodology to assess the quality and health of the benthic environment. The method requires verification of acceptable ecological and chemical states of the ecosystem, which is in fair agreement with the requirements set in the European Water Framework Directive, although the environmental states are categorized differently.

Our findings reveal that the state of the benthic environment is influenced by the amount of feed given during the salmon production cycle and that the ecosystem can recover relatively quickly, even within a single production cycle (Figs. 11 & 12). Therefore, we agree with the Norwegian regulations (NS 9410) that require a mandatory benthic assessment at maximum biomass for each production cycle as a critical measure to obtain reliable evaluation results.

4.3. Influence of biophysical conditions and farming operation

The b-assessment also provides temporal and spatial data that can be an essential source of information for large spatial scale and long-term observations of the interaction between aquaculture and the environment.

States 3 (Bad) and 4 (Very bad) were found mostly in September and October, while State 1 (Very good) was most typical for April (Fig. 7). This suggests that season is among the variables that reflect the strength of benthic environmental influence. Previous studies have reported that Norwegian farmed salmon consume more feed and grow faster during late summer and autumn, and the emission of biogenic waste is higher during this period (Wang et al. 2013, Brager et al. 2016). Our findings show that there are similar seasonal patterns of variation in feed consumption and seabed degradation, as indicated by environmental States 3 and 4 in Fig. 7C,D. This suggests that the increase in feed consumption during the summer and autumn months, when higher levels of biogenic waste are released, is associated with a greater impact on the seabed environment. However, this impact may be only temporary, as the occurrence of seabed degradation was found to decrease soon after the feed consumption decreased, as shown in Fig. 7C,D.

SST also plays a crucial role in the influence of the seabed environment due to its impact on the growth rate and feed consumption of salmon, which in turn results in increased waste generation (Wang & Olsen 2023). As shown in Fig. 8, State 4 occurred more frequently at higher SST compared to other states (Fig. 8A,E). While high growth rates during the summer and autumn may have economic benefits by shortening production cycles, this period is also associated with more severe environmental degradation. Therefore, we suggest that regulating stocking biomass density for future production cycles in areas known to have increased impacts on the environment might be a good approach to facilitate recovery of the benthic environment when signs of environmental degradation are detected.

Our results show that the average length of production cycles, including the time gap between consecutive production cycles, was less than 2 yr (Fig. 5D). This estimation aligns with findings from previous studies, such as Black et al. (2008), Asche & Bjorndal (2011), and Afewerki et al. (2023). However, our study provided an overall view of the relationship between salmon farming and the state of the benthic environment across a large geographical area and long time period. It is important to note that the results may not accurately reflect the specific conditions of individual farms. For instance, some farms may stock larger smolts or juvenile salmon to reduce the duration of their sea phase, thereby minimizing their impact on the sea floor.

4.4. Regional differences

Our results suggest that the regional differences in b-assessment are primarily influenced by variations in site characteristics and farming practices, while SST only partially contributes to this difference (Fig. 10). As mentioned in Section 3.1, the Central region had the shallowest water depth (Fig. 4B, Table 2), the fastest current velocity (Fig. 4A, Table 2), and the longest length of production cycles (Fig. 5D, Table 2) among the 3 regions, and this could contribute to enhanced environmental capacity to degrade organic wastes. Although the farm size (Fig. 5A, Table 2) and MAB (Fig. 5B, Table 2) were also highest in the Central region, these were not associated with environmental degradation.

A previous study found a noticeable difference in feed conversion rate (FCR) among regions, accompanied by a corresponding difference in the release rate of biogenic waste, with a gradual rise from the Northern to the Southern regions (Wang & Olsen 2023). Additionally, previous studies have also reported that the Central region exhibited apparent interannual variation in salmon production (Wang et al. 2013, Wang & Olsen 2023). The observed effect may be attributed to the longer time interval between successive production cycles in salmon farms located in the Central region, as supported by the longer production cycle reported in Fig. 5D and Table 2. As a result, unlike other regions, the amount of feed given in the Central region does not show a consistent increase year over year (Wang & Olsen 2023). The longer time gap between 2 successive production cycles is likely beneficial for benthic environmental recovery, which could explain why the environmental state in the Central region was generally better than that of the other 2 regions. Only about 4 to 6% of the cases of States 3 (Bad) and 4 (Very bad) were found in the Central region, while the other 94 to 96% occurred in the Northern and Southern regions in relatively similar proportions.

4.5. Suggestions

Our study indicates that environmental conditions can vary significantly from one site to another, highlighting the need for site-specific MAB limits that consider environmental capacity. The NS 9410 regulation also requires that salmon farms conduct additional benthic assessments before increasing their MAB, suggesting that the regulations for MAB and benthic assessment are well matched (Standards Norway 2016). As shown in Fig. 9A, the relationship between MAB and the state of the benthic environment differed from conventional expectations. This suggests that carrying capacity, which will vary from site to site, has most likely been taken into consideration in determining the current site-specific MAB limits. Therefore, the higher MAB limits did not lead to a higher likelihood of negative environmental impacts.

Previous studies have reported that among biogenic wastes, the fraction of particulate organic waste for carbon and nitrogen is about one-third, which mainly impacts the benthic environment; the other two-thirds is inorganic nutrient waste, which may influence the marine ecosystem of the surface water (Wang et al. 2013, Wang & Olsen 2023). The b-assessment method for seafloor ecosystems is inadequate for assessment of the environmental state of the surface water ecosystem, which must also fulfill the requirements of the Water Framework Directive (EU Water Framework Directive 2000). Thus, we suggest the establishment and implementation of an additional regulating assessment for the surface water and water column to provide a complete environmental assessment of the influence of aquaculture on the marine ecosystem.

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