Blue mussel (*Mytilus* spp.) cultivation in mesohaline eutrophied inner coastal waters: mitigation potential, threats and cost effectiveness

4 Lukas Ritzenhofen[1,2], Anna-Lucia Buer[1], Greta Gyraite[1,2], Sven Dahlke[3], Annemarie Klemmstein[1], Gerald

5 Schernewski[1,2]

6 [1] Leibniz-Institute for Baltic Sea Research Warnemünde, Rostock, Germany
7 [2] Marine Research Institute, Klaipeda University, Klaipeda, Lithuania
8 [3] Biological Station Hiddensee, University of Greifswald, Greifswald, Germany
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11 Corresponding Author:

12 Lukas Ritzenhofen[1]

13 Seestraße 15, Rostock, 18119, Germany

14 Email address: lukas.ritzenhofen@io-warnemuende.de

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Abstract

40 The EU-water framework directive (WFD) focuses on nutrient reductions to return coastal
41 waters to the good ecological status. As of today, many coastal waters have reached a steady
42 state of insufficient water quality due to continuous external nutrient inputs and internal loadings.
43 This study focuses first on the current environmental status of mesohaline inner coastal waters to
44 illustrate their needs of internal measures to reach demanded nutrient reductions and secondly, if
45 mussel cultivation can be a suitable strategy to improve water quality. Therefore, nitrogen,
46 phosphorus, chlorophyll a, and Secchi depth of nine mesohaline inner coastal waters in north east
47 Germany were analyzed from 1990 to 2018. Two pilot mussel farms were used to evaluate their
48 effectiveness as a mitigation measure and to estimate potential environmental risks, including the
49 interactions with pathogenic Vibrio bacteria. Further, estimated production and mitigation
50 potential were used to assess economic profitability based on the sale of small sized mussels for
51 animal feed and a compensation for nutrient mitigation. The compensation costs were derived
52 from nutrient removal costs of a waste water treatment plant (WWTP). Results show that
53 currently all nine water bodies do not reach the nutrient thresholds demanded by the WFD.
54 However, coastal waters differ in nutrient pollution, indicating that some can reach the desired
55 threshold values if internal measures are applied. The mitigation potential of mussel cultivation
56 depends on the amount of biomass that is cultivated and harvested. However, since mussel
57 growth is closely coupled to the salinity level, mussel cultivation in low saline environments
58 leads to lower biomass production and inevitably to larger cultivation areas. If 50% of the case
59 study area Greifswald Bay was covered with mussel farms the resulting nitrogen reduction
60 would increase Secchi depth by 7.8 cm. However, high chlorophyll a values can hamper
61 clearance rates (< 20 mg m^{-3}$= 0.43$ l h^{-1}dry weight g^{-1}) and therefore the mitigation potential.
62 Also the risk of mussel stock loss due to high summer water temperatures might affect the
63 mitigation potential. The pilot farms had no significant effect on the total organic content of
64 sediments beneath. However, increased values of Vibrio spp. in bio deposits within the pilot
65 farm (1.43 10^6± 1.10 10^{6}CFU 100 ml^{-1}(reference site: 1.04 10^6± 1.45 10^6 CFU 100 ml^{-1}) were
66 measured with sediment traps. Hence, mussel farms might act as a sink for Vibrio spp. in
67 systems with already high vibrio concentrations. However, more research is required to
68 investigate the risks of Vibrio occurrence coupled to mussel farming. The economic model
69 showed that mussel cultivation in environments below 12 PSU cannot be economic at current
70 market prices for small size mussels and compensations based on nutrient removal cost of
71 WWTPs.
72
Introduction
74 Globally, water quality of coastal ecosystems has deteriorated because of anthropogenic
75 eutrophication. The European Water Framework Directive (WFD, 2000/60/EC) and the
76 European Marine Strategy Framework Directive (MSFD, 2008/56/EC) were implemented to
77 reduce eutrophication, and the Baltic Sea Action Plan (BSAP) expanded and implemented the
78 WFD in the Baltic Sea (Schernewski et al., 2015). The overall aim is to restore the good

79 ecological status (GES) of aquatic systems by 2027 (WFD, 2000/60/EC). Indicators of the
80 ecological status are submersed macrophytes, zoobenthos, and phytoplankton; nutrient
81 concentrations and water transparency serve as supporting parameters (WFD, 2000/60/EC).
82 In the Baltic Sea, approximately 86% of coastal waters are below a good trophic status
83 (HELCOM, 2016). In Germany, the water quality of shallow, enclosed, and semi enclosed water
84 bodies are currently rated unsatisfactory or poor (UBA, 2017). However, semi enclosed systems
85 could still reach the turning point and return to a mesotrophic state, if nutrient loads and internal
86 nutrient concentrations are reduced substantially (Berthold et al., 2018; Friedland et al., 2019a).
87 Several internal mitigation measures are already under discussion for the Baltic Sea, including
88 geoengineering approaches like large scale oxygen ventilation (Stigebrandt et al., 2014) and P-
89 precipitation (Rydin et al., 2017), as well as biomass harvesting in terms of commercial and non-
90 commercial fish, bivalves, or water plants (Lindahl, 2012; Petersen et al., 2014; Karstens et al.,
91 2018). Nevertheless, many internal measures are controversially discussed. While some have
92 been associated with high costs and lack feasibility, others are accompanied with undesirable
93 side effects to the aquatic environment, such as damage to benthic habitats or substantial changes
94 in food webs (Naylor, Williams & Strong, 2001; Stadmark & Conley, 2011).
95 According to many authors, mussel cultivation seems to be one of the most promising
96 measures(Lindahl, 2012; Petersen et al., 2014; Holbach et al., 2020; Kotta et al., 2020a,b;
97 Wikström et al., 2020). Besides removing nutrients through biomass harvest, mussels can benefit
98 the water transparency as a result of their filter feeding activity (Nielsen et al., 2016, Schröder et
99 al., 2014) and can provide an economically interesting product. Longlines are the common
100 practice of mussel cultivation in the Baltic (Taylor et al., 2019) and, compared to bottom culture,
101 they are most promising for nutrient removal (Buer et al., 2020; Wiles et al., 2006; Filgueira et
102 al., 2018).
103 Mussel mitigation has its limitations though, due mainly to the physiology of mussels. Within the
104 Baltic Sea, only *Mytilus* spp. and *Dreissena* spp. are suitable for longline cultivation, as they use
105 byssus threads to attach to the provided collector material (Stybel, Fenske & Schernewski, 2009;
106 Friedland et al., 2019b).
107 While *Mytilus* spp. is distributed from full marine conditions to a salinity minimum of 4.5 PSU
108 (Darr, Gogina & Zettler, 2014; Schiele, Darr & Zettler, 2014; Schiele et al., 2015; Larsson et al.,
109 2017), *Dreissena* spp. occurs in Baltic lagoons and bays with up to 5.0 PSU (Ackerman et al.,
110 1994; Fenske, 2005; Stybel, Fenske & Schernewski, 2009).
111 Even though mussel cultivation has a relatively small negative environmental impact when
112 compared with coastal fin fish aquaculture (Newell, 2004; Dumbauld, Ruesink & Rumrill, 2009),
113 it is still associated with negative effects on the environment when one looks at intensive
114 production units and the resulting bio deposition (Weise et al., 2009). Increased bio deposition
115 from suspended mussel cultivation can result in organic enrichment of the sediments below
116 mussel farms, increasing benthic mineralization rates and sediment oxygen demands, as well as
117 the release of sediment bound nutrients (Giles, Pilditch & Bell, 2006; Richard et al., 2007).

118   These environmental pressures are expected to be stronger in shallow eutrophic coastal waters
119   due to the limited dispersal of bio active material and preloaded sediments.
120   Another threat posed by mussels is the spread of pathogens (Potasman et al., 2002).
121   Most cultivation sides and consumption-mussels are monitored for fecal indicator bacteria
122   (*Escherichia coli* & *Enterococci*), but neglect the risk of other associated bacteria, such as *Vibrio*
123   (Rincé et al., 2018). The increasing appearance of the pathogenic *Vibrio* spp. bacteria in
124   eutrophic coastal waters has led to a strong public reaction (Ruppert et al., 2004; Gyraite,
125   Katarzyte & Schernewski, 2019; Metelmann et al., 2020). Moreover, previous studies show that
126   filter feeders can accumulate bacterial pathogens and act as a reservoir of *Vibrio* bacteria
127   (Cavallo & Stabili, 2002; Stabili, Acquaviva & Cavallo, 2005); thus, mussel cultivation in
128   eutrophic environments may promote *Vibrio* abundancy and increase the risk for humans and
129   other marine species (Callol et al., 2015; Ina-Salwany et al., 2019).
130
131   This study investigates the ecological status of inner coastal waters and their demands to reduce
132   nutrients to reach the target values required to ensure the GES, and if blue mussel cultivation can
133   be a suitable mitigation tool for this purpose.
134   The objectives of this study are to (a) document the long term development of nutrients,
135   chlorophyll *a* concentrations, and water transparencies in mesohaline inner coastal waters of the
136   south western Baltic, to identify quantitative needs of nutrient and phytoplankton removal; (b)
137   present the ecological results of a test mussel farm in Greifswald Bay; (c) calculate and assesses
138   costs associated with mussel cultivation as a mitigation measure; and (d) discuss the quantitative
139   potential and cost-effectiveness of blue mussel cultivation as a means to reach GES within the
140   WFD and the potential of farming in other mesohaline inner coastal waters.
141

Methods & study site

Study site

144   The coast of the federal state Mecklenburg-Vorpommern is characterized by several bays,
145   backwaters (Haffe), estuaries and lagoons embedded by islands and peninsulas that form the
146   inner coastal waters (Fig.1). Salinity classifies two types of inner coastal waters for the German
147   Baltic coast: oligohaline (0.5 to 5-6 PSU) and mesohaline inner coastal waters (5-6 to 18-20
148   PSU) (Schernewski et al., 2004).
149   Wismar Bay and Salzhaff in the west are both part of the Bay of Mecklenburg with an intense
150   water exchange with the open Baltic Sea (Schlungbaum & Baulder, 2001).
151   The Warnow Estuary, surrounded by the city of Rostock, is the transition zone between the river
152   Warnow and the Baltic Sea. Salinity levels in the Warnow Estuary are strongly influenced by
153   stratification caused by river water and Baltic water inflow.
154   The Barther Bodden is part of the Darß-Zingst Bodden chain. Its salinity level is indirectly
155   influenced by water exchange from the open Baltic Sea and the oligohaline Bodstedter and
156   Saaler Bodden (Schumann et al., 2006). The Strelasund is a strait that separates the Island of
157   Rügen from the German mainland. The Westrügensche Bodden, Greifswalder Bodden (GWB),

158   Kleiner Jasmunder Bodden, and Nordrügensche Bodden all form the coastal lagoons around the
159   Island of Rügen. Salinity levels of coastal lagoons vary according to direct or indirect water
160   exchange with the Baltic Sea (Fig. 1, Tab.1).
161   The GWB is the biggest inshore basin located in north east Germany, limited by the mainland to
162   the south and the Island of Rügen to the West. The average water depth is 5.8 m, with a
163   maximum depth of 13.6 m. Sediment types consist mostly of mud, sand, and clay gravel-
164   mixture. Based on the lack of hard substrate (Kanstinger et al., 2018), only a limiting and or
165   fluctuating) Mytilus *spp*. stock can be expected. It is most likely that mussel larvae enter GWB
166   from mussel beds outside, which can be found on reef structures around Rügen Island (Darr,
167   Gogina & Zettler, 2014). Salinity levels range from 6 – 8 PSU. Water temperatures are highly
168   influenced by seasonal atmospheric temperature regimes.
169   The GWB plays an important role, both ecologically and economically. While tourism and
170   coastal fishing are essential for local employment (Obernaus & Köhn 2002; www.statistik-
171   mv.de), the GWB serves also as an important spawning ground of the herring stock in the
172   western Baltic Sea (Kanstinger et al., 2018). High nutrient inputs in the past have led to heavy
173   eutrophication (Munkes, 2005). As a result, submersed macrophyte cover declined from 90% to
174   15% and the GWB turned into a phytoplankton-dominated ecosystem (Munkes, 2005).
175   Altogether, it seems that present mitigation measures in the catchment area are not sufficient to
176   return to a GES and supporting internal measures are needed.
177
178   **Hydro-chemical and biological data analysis**
179   The hydro-chemical and biological data were provided by the State Agency for Environment,
180   Nature Conservation and Geology Mecklenburg-Vorpommern (LUNG). Monitoring stations
181   provide monthly data for total nitrogen (TN) and phosphorus (TP), dissolved inorganic nitrogen
182   and phosphorus, Chl. *a* concentration, and Secchi-depth for the period from 1990-2018.
183   Dissolved inorganic nitrogen (DIN) is the sum of nitrate, nitrite, and ammonium. Samples for
184   dissolved nutrients were stored dark until filtration through cellulose-acetate filters (pore size
185   0.45 µm) followed by freezing. Dissolved inorganic phosphorus (DIP) was determined as soluble
186   reactive phosphorus by using the molybdenum blue method (Strickland and Parsons, 1972). The
187   percentage share of non-bioavailable DIP was not determined. TP and TN were digested in a
188   microwave with peroxodisulfate (DIN11905-1 1998). Total and dissolved nutrients were
189   measured in a continuous flow analyser (Skalar Inc., later Alliance Instruments (Malcolm-Lawes
190   and Wong 1990; DIN13395 1996; DIN11905- 1 1998; DIN11732 2005). Chl. *a* was determined
191   fluorometrically (665 nm) after filtration (GF/F, 0.7 µm), extraction with ethanol, and
192   acidification (ISO 10260:19922).
193
194   To evaluate whether internal mitigation measures are suitable, time series analysis of total
195   nutrients (TN & TP), Chl. *a* concentration, and Secchi depth were conducted for the period
196   between 1990 and 2018. The data was split into three periods and average annual concentrations
197   from 1990-1999, 2000-2009, and 2010-2018 were compared. The time series were analyzed
198   using the Mann-Kendall test to identify whether the measured values of the time series are

199 randomly distributed or if trends occur in the data. The level of significance was set to 0.05.
200 Afterwards, values were compared with new WFD target concentrations (Schernewski et al.,
201 2015).
202
203 A general approach to managing eutrophication is the control of nutrient loads (N, P) essential
204 for primary production. It has to be known weather phytoplankton biomass responds to changes
205 in nitrogen or phosphorous in the water column. To investigate this, monthly DIN/DIP ratios and
206 Chl. *a* concentration for all water bodies were compared. Simple linear regression was used to
207 describe the monthly relationship between TN or TP to Chl. *a* concentration. To investigate how
208 nutrient reduction potentially improves water transparency, simple linear regression models were
209 used as well. Data was ln-transformed when necessary.
210

211 **Pilot blue mussel farms setup**
212 Pilot farm 1 is located in the Hagensche Wiek, a bay in the north eastern part of GWB (Fig. 1).
213 The cultivation unit consisted of 5 parallel longlines (Fig. 2). Each longline moored in a depth
214 between 5.0 and 6.0 m using dead weight anchors of 250 kg. Every longline was attached with
215 50 m collector material, consisting of 1 mm thick and 50 mm wide polypropylene bands reaching
216 up to 3.5 m water depth. Pilot farm 1 was deployed in April 2017 and was operated until October
217 2019. During the operating period, the collector material was used for spat collection and mussel
218 grow out.
219 A smaller test farm (pilot farm 2) was located in the Wieker Bay (WB) (Fig. 1). The setup
220 consists only of two longlines, each 10 m long (Fig. 2). The collector band material matches the
221 one of pilot farm 1 and the loops extended from 1 m to 1,5 m. Pilot farm 2 was deployed in June
222 2017.
223

224 **Field and laboratory experiments**
225 Mesocosm experiments were carried out at GWB and WB to estimate the individual clearance
226 rate at high Chl. *a* concentrations of *Mytilus* spp. The reduction of Chl. *a* was measured using an
227 in vivo fluorometer (Algae Torch, bbe-Moldaenke, Germany).
228 Additional laboratory experiments tested different Chl. *a* concentrations and their effect on the
229 clearance rate (CR) of *Mytilus* spp. During the laboratory experiments, different concentrations
230 of *Rhodomonas* spp. were added to a well-mixed and aerated aquarium with defined volume of
231 artificial seawater and a group of mussels (n = 20). The reduction of Chl. *a* concentration was
232 measured using a handheld fluorometer (AquaFluor, Turner Designs, USA). The clearance rate
233 was determined by the exponential decrease in Chl. *a* concentration as a function of time using
234 the equation $CI = a*(V/n)$, where V = volume of water, n = number of filtering mussels, and a =
235 slope of the regression line in a semi-ln plot of the reduction of Chl. *a*. Measurements were
236 repeated three times. Control runs without mussels were conducted to evaluate possible
237 sedimentation. Mesocosm and laboratory experiments were conducted at water temperatures of
238 20°C.

239   Nutrient harvest yields were estimated by the nitrogen and phosphorus content of cultivated blue
240   mussels. Mussel tissue and shells of all individuals were pooled, freeze- dried, and ground prior
241   to analyzing carbon and nitrogen with an auto-analyzer (Elementaranalysator EA 3000).
242   Phosphorous was determined in mussel ash using an alkaline persulfate oxidation after Hansen
243   and Koroleff (1999).
244
245   The bio deposition of faeces and pseudo-faeces was measured with sediment traps. The traps
246   were deployed within the GWB farm and at a reference point 100 m SW (N54°18,839;
247   E13°40,728) in May 2018. Additionally, sediment traps were deployed at a commercial mussel
248   farm (Farm size = 1ha) in the Kiel Fjord. Trap contents, including all suspended particles, were
249   filtered onto Whatman GF/F filters, dried, and weighed. Total organic content (TOC) was
250   measured as loss on ignition. Furthermore, sediment samples were taken within GWB farm and
251   the reference point. Subsequently, TOC was measured as loss on ignition of dry matter.
252   To measure the *Vibrio* spp. abundance within the pilot mussel farm in GWB and the reference
253   location, samples were taken of surface water, sediments, sediment traps and mussels.
254   The total number of *Vibrio* spp. from water samples was determined by filtering water volumes
255   of 10 and 50 mL through 0.45 μm-pore-size mixed cellulose ester filters (MontaMil® Membrane
256   Filters, Frisenette ApS, Knebel, DK). All filters were placed onto thiosulphate-citrate-bilesalts-
257   sucrose agar plates (TCBS agar) (SIGMA-ALDRICH, Missouri, US1A) and incubated for 24 h
258   at 37 °C. Sediment and sediment trap samples were serially diluted and plated on TCBS agar.
259   Fresh mussel samples collected at the mussel farm were transported in cooling boxes and
260   processed within 8 hours of collection. Sample preparation and homogenization was done
261   according to the CEFAS Standard Operating Procedure – Detection of *Vibrio parahaemolyticus*
262   in Bivalve Molluscan Shellfish (www.crlcefas.org). Serially diluted sample homogenate was
263   plated on TCBS agar. After 24 h of incubation, colonies were counted and the number of total
264   *Vibrio* determined as colony forming unit (CFU) 100 mL^{-1} for water, CFU 100g^{-1} for sediment
265   samples and CFU g^{-1} mussel tissue.
266
267   **Economic calculations**
268   Data for the economic calculations are based on the investment and maintenance costs of pilot
269   farm 1 in GWB. Since pilot farm 1 was a scientific mussel farm and therefore without annual
270   running cost (that would otherwise be faced by a commercial business), supplementary data were
271   derived from a commercial mussel farm in Kiel Fjord (Krost et al., 2011).
272   Krost et al. (2011) predicted annual yields of 25 t and 100 t of mussels for human consumption
273   after 18 months. Annual running costs include anchoring and foundation, longlines, buoys,
274   floaters, socks, collectors, and staff. The economic lifetime varied between 1 and 5 years.
275   Investment costs covering a boat and machinery (both with an assumed lifetime of 5 years), as
276   well as a land station, were summarized under annual investment costs. Since staff is the
277   dominating cost factor, the salaries from the year 2010 (Krost et al. 2011) were recalculated for
278   the year 2020 assuming an increase of 30% (the statistical average salary increase in Germany).

279 With increasing farm size, we assumed that staff and investment costs decrease steadily per
280 produced ton of mussels; this decrease is relatively high in smaller farms and negligible in very
281 large units.
282 The salinity in GWB only allows for the production of mussels for mussel meal or feed,
283 harvested after about 12 months of cultivation time. As a consequence, we assumed lower
284 production costs with a reduced staff effort of 50% and 2% lower investment costs. These
285 numbers are based on our own experiences with our two small pilot farms and verified by
286 discussions with experts from the commercial mussel farm sector and literature.
287 The annual production of feed mussels in GWB is assumed to be 0.278 kg m^{-3} cultivation
288 volume. This data is based on a model simulation study in Buer et al. (2020) and verified by our
289 experimental farms. Assuming a cultivation volume from the surface to a depth of 3 m, and
290 taking into account the relatively low productivity, a farm producing 100 t mussels per year
291 would cover a surface area of about 120 ha. The nitrogen (phosphorus) content in mussels is
292 assumed to be 0.008 (0.0006) kg kg^{-1} fresh mussels, based on the cultivated mussels in GWB.
293 In addition to the production of feed mussels, we assumed a compensation for nutrient extraction
294 based on the removal costs of a wastewater treatment plant (WWTP). The revenue for nitrogen
295 and phosphorus removal is set at 30,000 € t^{-1} and 80,000 € t^{-1} (COWI 2007; Gren, Jonzon &
296 Lindqvist, 2008; Hautakangas et al., 2014).
297

Results

Bio-chemical status of coastal waters

300 Although all nine study sites were similar, their ecological status and its temporal development
301 differed strongly (Fig. 3). The majority had average annual TN concentrations between 20-50
302 μmol l^{-1}, TP concentrations between 1-2 μmol l^{-1}, and Chl. *a* concentrations between 5-20 mg m^{-3}
303 . Consequently, all coastal waters were regarded as eutrophic, their ecological status was
304 classified as unsatisfactory (LUNG 2013), and a need for measures to improve water quality was
305 apparent. During the 1990s, the technical improvement of WWTPs caused a strong reduction of
306 nutrient loads to coastal waters in the Federal State of Mecklenburg-Vorpommern, Germany.
307 The largest five WWTPs reduced TP loads by more than 95% and TN loads by over 80%
308 (LUNG 2013). As a result, the riverine loads declined by about 70% (TP). A significant decline
309 in TN loads did not take place during the last 30 years. The riverine loads closely correlate with
310 the river discharge. This is true for the TP loads after 1996, as well (LUNG 2013). In seven of
311 the coastal waters, the load reductions during the 1990s caused a decline in TN and TP annual
312 concentrations (Fig.3), but only two showed reductions in Chl. *a* concentrations and only three
313 increased water transparency. After 2000, the nutrient concentrations in the coastal waters did
314 not indicate significant changes. Since the riverine loads were largely stable during the past
315 decades, it can't be expected that a reduction in nutrients in coastal waters will take place in the
316 future without new, additional measures. Further, it seems unrealistic that additional external
317 load reductions will be implemented

318   After 2000, the Chl. *a* concentrations did not show a significant decline. In most coastal waters,
319   positive effects on water transparency were not visible either. Exceptions were the Barther
320   Bodden, the Jasmunder Bodden, and the Warnow Estuary. It is very likely that the status of the
321   two Bodden waters improved as a result of reduced diffuse agricultural nutrient loads. The
322   Warnow Estuary, as a shipping channel, was subject to several dredging activities. This
323   increased the water exchange with the Baltic Sea and reduced the nutrient and Chl. *a* levels. In
324   general, the nutrient and Chl. a levels seem directly related to the water exchange time and the
325   shallowness of systems. A low water exchange time and a large euphotic zone (low average
326   water depth) are likely reasons for the very high nutrient and Chl. *a* concentrations in the Kleiner
327   Jasmunder and the Barther Bodden, as well. On the other hand, the relatively strong reductions in
328   nutrients and Chl. *a* concentrations in both water bodies over the last decades indicate a distinct
329   reaction to changes in loads. The water exchange time and the average depths are parameters that
330   determine the effectiveness of internal measures in coastal waters.
331   The sensitivity of aquatic systems is one factor that determines how promising a potential
332   internal measure will be. Another factor is the present state of pollution and its deviation from
333   the good ecological status. Figure 3 indicates the desired threshold values, according to the WFD
334   for each coastal water. Wismar Bay and Salzhaff are already close to a good status and efforts to
335   reduce diffuse loads might already be enough to meet the threshold. While for the Warnow
336   Estuary, the West/Nord Rügener Bodden, and Strelasund and Greifswalder Bodden it seems
337   possible to meet the good status, it would require additional internal measures. Thanks to its size
338   and importance for fishing and recreating, the Greifswalder Bodden is the best case study for
339   assessing the suitability of mussel farming to improve ecological status.

340   **Seasonal nutrient and chlorophyll relationships**
341   During the winter, primary production in Baltic coastal waters is limited by temperature and
342   light. The increase of Chl. *a* concentrations and decrease of dissolved inorganic nutrient
343   concentrations that takes place during the spring and summer indicates that nutrients become a
344   potentially limiting resource for phytoplankton biomass in most water bodies (Tab. 2.). In all
345   coastal waters, DIN concentrations strongly decline between late winter and summer. For DIP,
346   the decline takes place earlier and by March concentrations are low. The molar N/P ratio of 16
347   (according to Redfield) provides a rough estimate for which nutrient is limiting primary
348   production.
349   During March and April, high nitrogen discharges initiate blooms in coastal waters; the average
350   DIN:DIP ratio ranged from 26 to 720, indicating a P limitation (Tab.2). In May, most water
351   bodies show a shortage of DIP. In June, phytoplankton growth reliance begins to change towards
352   a shortage of N. During July, the majority of the waterbodies show an average DIN:DIP ratio
353   between 2-10, indicating an N shortage. In the Wismar Bay, Nord/West Rügener Bodden, and
354   Strelasund and Greifswalder Bodden, this situation remained the same through August and
355   September (Tab. 2.), whereas the Salzhaff and Warnow Estuary returned to an N/P ratio of close
356   to 16:1 during this time. Only the shallow Kleiner Jasmunder Bodden and the Barther Bodden
357   were exceptions. Here, the Chl. *a* concentrations decreased from May until July and absolute

358 dissolved inorganic nutrient concentrations fluctuated but were relatively high (Tab. 2.). Results
359 indicate that phytoplankton growth is not controlled by the availability of nutrients but rather by
360 other parameters, such as turbidity and light.
361 The GWB is representative of coastal waters due to its short availability of P in the spring and a
362 shortage of N between July and September.
363 This is shown for GWB in Fig. 4. Between March and September, the Chl. a concentration
364 shows a close positive correlation to TN and TP concentrations.
365 This has several implications: (1) nutrients have a controlling function for phytoplankton
366 biomass and as a consequence, measures that reduce nutrient concentrations in the water (such as
367 mussel farming) will cause a reduction in phytoplankton concentrations and have a positive
368 effect on water quality; (2) especially between July and September, the availability of N seems to
369 control the productivity; summer is exactly the time when mussels show the fastest growth and
370 are most efficient at removing nutrients from the water column via phytoplankton filtration and
371 uptake.
372
373 **Improvement of water quality during summer**
374 Chl. *a* concentration and Secchi depth are related during the summer (the main grow out season
375 for mussels) and therefore directly connected to the mitigation process of mussel farming. The
376 linear regression shows a strong negative relationship between total nitrogen and Chl. *a*
377 concentrations during July up until September (Fig. 5, A). Secchi depth can be better explained
378 by Chl. *a* than total suspended solid concentration (TSS) (Fig. 5, B & D). Autocorrelation
379 between TSS concentration and phytoplankton biomass results in a close regression coefficient
380 because biomass is a natural part of TSS. The stronger coefficient of determination, however,
381 affirms that Secchi depth can be better described by Chl. *a* concentration. Based on the prior
382 linear regression model between TN and Chl. *a* concentration, a regression model describing the
383 relationship between TN and Secchi depth was established to describe water quality
384 improvements when nitrogen is mitigated (Fig. 5, C).
385 According to linear regression model A (Fig. 5), Chl. *a* concentration can be reduced to approx.
386 1.4 mg m^{-3} if total nitrogen concentration is reduced to the threshold value of 16.9 µmol l^{-1}.
387 Based on the relationship between Secchi depth and TN concentration (C), Secchi depth would
388 increase by approx. 70 cm. Given that GWB has a monthly water exchange rate, the reduction
389 effort has to be accomplished on a monthly basis.
390 Monthly nitrogen reductions would result in annual values of 41.6 µmol l^{-1} TN and 10.6 mg m^{-3}
391 Chl. *a* concentration, accounting for a reduction of 15.5% TN and 29.8% Chl. *a* of the mean
392 annual concentration.
393
394 **Water quality improvement by mussel farming**
395 In situ investigations of clearance rates (CR) of blue mussels from the two pilot farms showed
396 overall low clearance rates compared to laboratory CR investigations. *Mytilus* spp. from the pilot
397 farm 2 showed slightly higher CRs at a lower ambient Chl. *a* concentration (15 mg m^{-3}) than

398   *Mytilus* spp. from pilot farm 1 with a higher ambient Chl. a concentration (22 mg m^{-3}).
399   Laboratory tests revealed a significant decrease in CR with increasing Chl. *a* concentration
400   exceeding 20 mg m^{-3} (Fig. 6, A.). Based on these results, Chl. *a* is an important driver effecting
401   blue mussel CRs.
402   Nutrient contents of the mussels (wet weight total) did not differ significantly between both pilot
403   farms, indicating that neither salinity nor Chl. *a* concentration influence the nutrient content (Fig.
404   6, B.).
405
406   Rapid growth rates in the first few months lead to high nutrient extraction capacities per month.
407   The first settling of mussel larvae at pilot farm 1 was recorded in July. During August, juvenile
408   mussels had an average total wet weight of 17.78 ± 5.44 mg per mussel, while in September the
409   average wet weight already reached 147.01 ± 28.40 mg per mussel. During August and
410   September, TN concentrations in GWB ranged between 41.5 to 40.0 µmol l^{-1} (equaling approx.
411   1700 t N within GWB).
412   Subsequently, if 50% of the GWB was covered with mussel farms, it would take up 257 t N and
413   reduce TN concentration to 34.6 µmol l^{-1} by September (Tab. 3). According to the linear
414   regression model (Tab. 3, C), reduced nitrogen would increase the Secchi depth by 7.83 cm. Our
415   results also show that if mussel farming is used locally in areas with a low water exchange rate,
416   the effect of mussel farming can be extended. Based on the other water bodies that have no direct
417   water exchange with the Baltic Sea (Tab. 1), we assumed that the Hagnesche Wiek (location of
418   pilot farm 1 (Fig. 1)) has a lower water exchange rate of approx. 6-7 a^{-1}. Here, the results show
419   that the TN concentration could be reduced to 32.1 µmol l^{-1} and Secchi depth would increase by
420   10.6 cm (Tab. 3).
421   In addition to water transparency improvements seen by reducing nitrogen concentration, the
422   mussels improve water transparency by removing phytoplankton. Taylor et al. (2020, in
423   submission) calculated an average depletion of 5% from autumn 2017 to summer 2018 for pilot
424   farm 1. According to the linear regression model (Fig. 5, B), the reduction of Chl. *a*
425   concentration from a mussel farm occupying 50% would increase Secchi depth by an additional
426   13.3 cm, resulting in a total improvement of ~ 20 cm.
427   Our results clearly show that the cultivation of small sized mussels in low salinity environments
428   must cover a substantial amount of surface area to have a severe impact on water quality. This,
429   however, can create a tradeoff between potential improvements in water quality and negative
430   effects emerging from the mussel farm.
431
432   **Potential negative ecological effects of mussel cultivation in GWB**
433   The primary negative effects of suspended mussel cultivation are nutrient enrichment of benthic
434   habitats and the spread of pathogens.
435   While sediment TOC was not significantly influenced by the mussel farm in GWB (Fig. 7),
436   during 2018 an increasing trend of TOC was indicated beneath the pilot farm. This might be
437   explained by the fact that during 2018, the mussel farm was fully stocked (resulting in a higher

438 bio deposition rate). Additionally, by the end of the summer, 80% of the mussel stock was lost
439 after mussels detached and sunk, inadvertently increasing overall organic content at the seafloor.
440 Bio deposition was higher over the summer at pilot farm 1 than at the reference site. This was
441 also confirmed by results from the Kiel Farm (Fig. 7). Results obtained from the commercial
442 farm, however, showed lower bio deposition compared to GWB, even though the commercial
443 farm was bigger in size and stock density. It has to be mentioned that measurements were not
444 obtained at the same time. While GWB measurements were taken in June, measurements at the
445 commercial farm were taken in October. Therefore, it can be assumed that in GWB the
446 sedimentation of phytoplankton adds to the content of bio deposition produced by mussels,
447 leading to significant increased values.
448 The *Vibrio* spp. concentration in cultivated blue mussels was $1.07 \ 10^4 \pm 1.75 \ 10^3$ CFU g^{-1} (Fig.
449 8). Higher concentrations of *Vibrio* spp. were found in the surface water and sediment at the
450 reference points. However, sediment trap samples showed increased *Vibrio* spp. concentrations
451 in the pilot farm 1 compared (Fig. 8).
452 The results show that *Vibrio* bacteria are concentrated in feces and pseudo feces in the water
453 column within the mussel farm, and concentrations in sediments are lower. This may be an
454 indication that bio deposits are further distributed and not concentrated directly beneath the
455 mussel farm.
456
457 **Economic assessment of mussel cultivation in GWB**
458 Based on the expected mussel yields in GWB, our results show that mussel mitigation with the
459 revenues from feed mussel sales and nutrient removal will not be profitable in GWB (Fig. 9).
460 Even though annual costs decreased with increasing production volume, the net balance
461 remained negative. Revenues from nutrient reduction can only narrow the gap towards cost
462 neutrality. In GWB, cost neutrality is not reached because the small sized mussels can only be
463 sold as feed mussels for a minor sales price of 0.06 € kg^{-1}. In comparison, fresh blue mussels for
464 human consumption could be sold for 11.0 € kg^{-1}. According to Buer et al. (2020a), mussel
465 cultivation for human consumption is only possible at a salinity threshold of 12 PSU, indicating
466 that mussel mitigation in Wismar Bay and Salzhaff and Warnow Estuary could be profitable if
467 mussels can be sold for human consumption instead of animal feed.
468 In GWB, a farm size of approx. 200 ha would reduce the cost gap to under 1,000 €. This gap
469 could be closed if water transparency improvements were compensated, as well.
470 Depending on the production volume, nutrient removal costs would range between 40 to 814 €
471 kg N^{-1} and 899 to 18,000 € kg P^{-1}. Even if mussel production volume increases, nitrogen
472 extraction by mussels is more expensive than other land-based measures (Fig.9 B). Mussel
473 mitigation becomes logical when nutrient pollution is caused by internal processes or when land-
474 based measures have reached their feasibility limit.
475
476 **Discussion**

477 During recent years, suspended mussel farming has progressed as a novel approach to mitigate
478 eutrophication and support underwater vegetation (Lindahl & Kollberg, 2008; Schernewski,
479 Stybel & Neumann, 2012; Friedland et al., 2019a; Petersen, Loo & Taylor, 2019; Timmermann
480 et al., 2019).
481 So far, reductions in nutrient inputs through the EU's Urban Waste Water Treatment Directive,
482 the modernization of WWTP, and changing agriculture practice (Munkes, 2005; Selig et al.,
483 2006; Boesch, 2019) have not been enough to improve the ecological status in regards to Chl. *a*
484 concentration and water transparency. Instead, after 2000 there was a stagnation in nutrient
485 reductions across most inner coastal waters of north east Germany and WFD targets were not
486 met.
487 Nevertheless, most water bodies could potentially reach the target values demanded by the WFD
488 if nutrient loads were further reduced and internal restoration measures implemented. This is
489 facilitated by the fact that climate change in north east Germany will most likely reduce diffuse
490 nutrient run off and nitrogen pollution further. Longer droughts and less rain in the summer
491 might limit crop production and the use of nitrogen fertilizer (Spekat, Enke & Kreienkamp,
492 2007; Jacob et al., 2008; Borken & Matzner, 2009). This could further shorten the gap to the
493 desired annual target values and make internal mitigation more effective (Williges et al., 2017).
494 Overall, the results show that in the summer, the availability of nitrogen controls phytoplankton
495 productivity. Therefore, by further shortening the nitrogen supply during the summer,
496 phytoplankton growth can be hampered and water transparency can be improved (Nielsen et al.,
497 2002).
498
499 Mussel farming as an internal mitigation measure is capable of reducing nutrients up to 0.6-3.01
500 t N ha-1 and 0.03-0.17 t P in Danish waters, depending on the farming strategy and harvesting
501 time (Petersen et al., 2014; Taylor et al., 2019). Timmermann et al. (2019) showed that blue
502 mussel farming in the eutrophied Danish Skive fjord decreased summer Chl. *a* concentration by
503 30% and light attenuation up to 14%. Improvements were also obtained in Sweden and Germany
504 (Lindahl et al., 2005; Schröder et al., 2014).
505 However, our results have shown that mussel cultivation in shallow coastal waters can be subject
506 to risks and success depends very much on the ecosystem and prevailing conditions.
507 The osmotic stress based on the salinity gradient in the Baltic has the most dominant effect on
508 blue mussel growth and health (Buer et al., 2020; Maar et al., 2015; Riisgård et al., 2012;
509 Westerbom et al., 2002) and therefore also on the mitigation effect.
510 Another factor which can affect the mitigation potential is the loss of mussel stock. Loss of
511 mussels can be caused by different events e.g. by predators such as eider ducks, damage or loss
512 of farm structures as well as changing environmental parameters such as high water temperatures
513 during summer (Varennes et al., 2013; Jones et al., 2010; Ross & Furnes 2000;). Especially, in
514 shallow coastal waters with limited water exchange rates high water temperatures can appear
515 during summer. Fly and Hilbish (2013) stated that the energetic balance of M. trossulus is
516 affected by water temperatures above 17 °C. Other studies have shown that byssus threads are up

517   to 60% weaker at water temperatures of 25 °C than at 10 °C (Newcomb et al., 2019).
518   Westerbrom et al. (2019) concluded that temperature stress coupled with continuous salinity
519   stress may also cause increased mortality. Therefore, there is an increased risk at low salinities
520   that mussels detach, die off and increase the organic pressure on the sediment below, while at the
521   same time decrease mussel harvest.
522
523   In addition, enclosed shallow coastal waters often suffer from internal loading and resuspension,
524   fuelling high phytoplankton biomass and particular matter (Schiewer, 1997; Selig et al., 2006)
525   which can also impact the effectiveness of mussel mitigation (Schulte, 1975; Riisgard, 1991).
526   Mesocosm and laboratory experiments showed lower CRs at high Chl. a concentrations (Fig.
527   6A), supporting previous studies (Clausen & Riisgård, 1996, Riisgård et al., 2003, Soon et al.,
528   2016). Clearance rates in mesocosm experiments were significantly lower than under laboratory
529   conditions, most likely because mussels under laboratory conditions were fed a Rhodomonas sp.
530   diet optimal for Mytilus spp. (Fernández-Reiriz et al. 2015). Three of the assessed water bodies
531   (Barther Bodden, Kleiner Jasmunder Bodden, Nord Rügener Bodden) exceed Chl. a
532   concentration of 20.0 mg m^{-3} throughout the entire summer, while others, e.g. Greifswalder
533   Bodden andf Strealsund, exceed these only at the end of summer (August, September).
534   Comparing results of the present study with available models, e.g. the Farm Aquaculture
535   Management System (FARM), it becomes apparent that the effectiveness of mussel mitigation is
536   hampered by Chl. a concentrations above 20 mg m^{-3}. For example, the FARM model calculates
537   an Assessment of Estuarine Trophic Status (ASSETS) score of "moderate" in regard of the late
538   summer Chl. a concentrations of GWB (> 20.0 mg m^{-3}). If the Chl. a concentration is set to 10.0
539   mg m^{-3} the calculate ASSETS score reaches "good".
540
541   Even though there was no significant difference in nutrient content (total DW was detected
542   between blue mussel samples from both pilot farms), mussel samples from pilot farm 1 had a
543   lower nutrient content in total WW. Mussels of this farm had a higher water content due to lower
544   salinity, supporting the results of Maar et al. (2015). With increasing salinity, the nutrient storage
545   capacity of blue mussels increases, improving the mitigation effect.
546
547   One of the greatest concerns regarding intense mussel farming is enhanced local bio deposition
548   beneath mussel farms (Nizzoli et al., 2005; Giles, Pilditch & Bell, 2006; Callier et al., 2009;
549   Giles et al., 2009). Surveys of benthic conditions beneath mussel cultivation sites in shallow
550   coastal embayment's (2m - 10 m water depth) in Canada revealed that after a production increase
551   of 43% (approx. 20 x10^3 t y^{-1} in 2001) organic matter (TOC) also increased significantly.
552   Furthermore, after a cultivation period of two years, approx. 50% of the sediment beneath the
553   cultivation site was permanently anoxic and dominated by white sulfur bacteria mats (Cranford
554   et al., 2009; Hargrave, 2015). Due to the small size and fluctuating stock density of the pilot
555   farms in this study, there was no significant enrichment of sediment TOC.

556 Increased bio deposition in GWB during the summer and at the larger farm in the Kiel Fjord,
557 however, support previous studies and point towards a risk of increased TOC if farm units
558 exceed a size specific for the ecosystem.
559
560 Filter feeders like blue mussel also accumulate pathogens from the surrounding water (Canesi et
561 al., 2002). Especially in the summer months, when water temperatures are high, Vibrio species
562 are highly abundant in coastal waters (Eiler et al., 2007; Baker-Austin et al., 2013). Collin et al.
563 (2012) stated that blue mussels are able to accumulate around 98% of marine Vibrio species
564 within a 24-hour period and, due to their robust immune systems, can eliminate these pathogens
565 (Balbi et al., 2013; Tanguy et al., 2013). However, our results show that *Vibrio* spp. are
566 concentrated by mussels and released into the water column through feces and pseudo feces,
567 indicating that the mussel immune system was not able to effectively erase Vibrio bacteria. In
568 this study, total *Vibrio* spp. abundance obtained from the mussel's tissue was approximately 2
569 times higher than $10^2 - 10^3$ of CFU per gram described in Huss (1997). High concentrations
570 paired with a reduced immune response caused by environmental stressors (Rahman et al., 2019)
571 might explain the release of viable bacteria. Pietrak et al. (2012) also argued that it is possible
572 that Vibrio bacteria are released in the form of pseudo feces production without passing through
573 the digestive system. In both cases, mussels and mussel farms could act as a sink of potentially
574 pathogenic Vibrio bacteria in the water column (Callol et al., 2015; Ina-Salwany et al., 2019).
575 Even though high concentrations were observed in the bio deposits in the water column, the
576 sediment concentrations did not increase compared to the reference site.
577 In both cases, when considering increased bio deposition and Vibrio concentration, the pilot farm
578 was too small to have an impact on the sediment beneath. Since it can be expected that bigger
579 farms in inner coastal waters will have a significant impact on the environment, more research
580 regarding ecological and pathological tradeoffs is needed.
581
582 The profitability of mussel cultivation can be an important factor in the selection and acceptance
583 of a mitigation measure. Buer et al. (2020a) described the effects of the salinity gradient along
584 the German Baltic coast on blue mussel farming and its economic implications. The authors state
585 that mussel farming here can be profitable only if blue mussels are sold for human consumption.
586 The threshold that this is still feasible is above 12 PSU, beyond which point mussel growth is too
587 slow to be profitable (Buer et al., 2020a). Beneath 12 PSU, alternative sale strategies, such as
588 animal feed (Schernewski, Stybel & Neumann, 2012) or compensation for nutrient removal are
589 proposed.
590 The results of this study show that even if mussel cultivation generates revenues from feed
591 mussel and nutrient extraction (based on the removal costs of a WWTP), the sales cost balance
592 remains negative and annual investment and running costs cannot be recovered. If blue mussels
593 cannot be sold for human consumption, nutrient mitigation will always be a no-income measure,
594 making it less attractive. Therefore, further funding schemes are necessary. Another option could
595 be a nutrient trading system where the polluter pays for the emission. This is easy to accomplish
596 for point source nutrient inputs, but becomes more challenging if diffuse sources are included

597   (Ferreira & Bricker, 2016). Additionally, mussel farming could generate additional income
598   through the improvement of water transparency and its implications on ecosystem services. Tuya
599   et al. (2014) described the monetary values of seagrass meadows that act as nursery grounds for
600   commercially interesting fish species. The results of this study revealed an average monetary
601   value of seagrass meadows of 95.75 € ha^{-1} y^{-1}. The same approach could be applied for German
602   coastal waters and be used to compensate mussel cultivation for increasing water transparency.
603
604

Conclusion

606   This study showed that mussel cultivation in inner coastal waters can act as a nutrient and
607   phytoplankton sink during the summer and, potentially increase water transparency and light
608   availability for submerged macrophytes. However, depending on physical and biological
609   restrictions, mussel cultivation will have different improvement efficiencies mainly due to the
610   predominant salinity level. Estimations for the case study area GWB, which is with 6-7 PSU a
611   marginal cultivation site, have shown that if 50% of GWB are used for mussel cultivation, 257 t
612   TN can be bound in mussel biomass. This reduction could increase Secchi depth by 7.8 cm.
613   However, due to the limited mussel growth, this mitigation measure cannot be economic for this
614   site. Further, the mitigation potential can also be affected by unpredicted mussel loss caused by
615   high temperatures. Even though this study showed no negative environmental impacts by mussel
616   farming, it can be assumed that shallow eutrophic coastal waters are especially vulnerable if
617   production volumes were increased. For coastal waters with low salinity levels, a combination of
618   different internal mitigation measures would be recommended.
619   A higher concentration of *Vibrio* spp. was detected in bio deposits but not in the sediment below
620   the farm in GWB. Nonetheless, further research is needed to investigate if large mussel farms
621   can act as a sink for human pathogens like *Vibrio* spp. This is especially important for systems
622   that already suffer from high *Vibrio* spp. concentrations potentially causing a conflict for bathing
623   tourism. Mussel cultivation reaches highest mitigation potential at salinities above 12 PSU and
624   increase at Chl. a concentrations below 20 mg m^{-3}. However, including economic estimations,
625   mussel farming will not be cost neutral mitigation measure based on the current market prices for
626   feed mussels and compensation compared to nutrient removal cost of WWTP.
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886

Main characteristics of the investigated coastal water bodies.

Data for surface area, water depth, salinity and water exchange are extracted from Schiewer (2007) and Schlungbaum & Baulder (2001).

Water body	Area [km²]	Mean depth [m]	Salinity [PSU]	Water exchange rate [a⁻¹]
Wismar Bay	170	5.5	11	0.01
Salzhaff	21	2.3	11	0.01
Unterwarnow	12.5	4	12	0.03
Barther Bodden	19.4	1.6	7	0.13
Strelasund	64.4	3.9	10	0.04
Westrügenscher Bodden	171.3	1.8	10	0.14
Greifswalder Bodden	514	5.8	7.5	0.1
Kleiner Jasmunder Bodden	28.4	2.8	[<7]	0.14
Nordrügenscher Bodden	124	3.5	9	0.14

Seasonal dissolved inorganic nitrogen (DIN), phosphorus (DIP) and Chl.*a*. concentration in the different water bodies of the study site.

(A) Spring = March-April. (B) Summer = May-September. (C) Fall = October-November. DIN: DIP ratios indicate limitation of either nitrogen (bold numbers) or phosphorus (italic numbers).

A	Spring							
	March				April			
	DIN [μmol/l]	DIP [μmol/l]	DIN/ DIP	Chl.a [mg m⁻³]	DIN [μmol/l]	DIP [μmol/l]	DIN/ DIP	Chl.a [mg m⁻³]
Wismar Bay	9.94	0.36	*27*	8.39	2.28	0.15	16	1.49
Salzhaff	73.85	0.23	*325*	7.36	34.63	0.09	*391*	2.42
Warnow Estuary	117.36	0.60	*196*	6.63	40.70	0.35	*116*	7.16
Barther Bodden	92.87	0.13	*720*	36.19	26.44	0.12	*212*	77.68
West Ruegenscher Bodden	26.76	0.40	*68*	7.44	4.16	0.16	*26*	8.38
Strelasund	16.60	0.10	*159*	19.36	8.85	0.09	*93*	12.03
Greifswalder Bodden	26.70	0.11	*249*	39.59	10.24	0.10	*103*	18.97
Kleiner Jasmunder Bodden	40.88	0.20	*209*	76.49	9.34	0.26	*36*	111.44
Nord Ruegenscher Bodden	13.70	0.14	*101*	15.30	5.55	0.08	*67*	19.60

B	Summer																			
	May				June				July				August				September			
	DIN [μmol/l]	DIP [μmol/l]	DIN/ DIP	Chl.a [mg m⁻³]	DIN [μmol/l]	DIP [μmol/l]	DIN/ DIP	Chl.a [mg m⁻³]	DIN [μmol/l]	DIP [μmol/l]	DIN/ DIP	Chl.a [mg m⁻³]	DIN [μmol/l]	DIP [μmol/l]	DIN/ DIP	Chl.a [mg m⁻³]	DIN [μmol/l]	DIP [μmol/l]	DIN/ DIP	Chl.a [mg m⁻³]
Wismar Bay	1.07	0.10	**11**	1.31	0.79	0.23	**3**	2.18	0.71	0.28	**3**	4.68	1.12	0.54	**2**	4.68	2.11	0.57	**4**	5.86
Salzhaff	2.25	0.09	*26*	2.63	1.30	0.58	**2**	2.30	2.04	1.09	**2**	5.00	15.69	1.25	**13**	14.71	8.49	0.57	15	10.42
Warnow Estuary	9.41	0.18	*53*	9.17	3.52	0.47	**7**	14.01	7.06	0.65	**11**	13.18	12.66	0.91	**14**	7.50	10.24	1.14	**9**	7.11
Barther Bodden	4.15	0.16	*25*	69.53	1.35	0.14	**10**	51.42	1.46	0.13	**11**	37.11	5.91	0.17	*36*	56.34	2.56	0.12	*21*	59.31
West Ruegenscher Bodden	1.83	0.10	*19*	7.42	1.47	0.16	**9**	9.65	1.16	0.21	**5**	9.65	1.24	0.18	**7**	12.28	0.96	0.14	**7**	7.60
Strelasund	2.12	0.09	**23**	14.74	1.81	0.14	**13**	17.84	0.84	0.26	**3**	16.48	0.77	0.26	**3**	24.40	1.78	0.46	**4**	16.78
Greifswalder Bodden	4.79	0.09	**55**	14.00	2.23	0.14	16	14.80	1.39	0.24	**6**	16.71	1.19	0.70	**2**	23.59	1.75	0.50	**4**	20.37
Kleiner Jasmunder Bodden	2.07	0.34	*6*	111.44	4.13	0.31	**13**	90.81	1.85	0.18	**10**	67.27	2.00	0.15	**13**	70.08	4.41	0.31	**14**	83.21

| Nord Ruegenscher Bodden | 1.52 | 0.09 | 16 | 18.44 | 1.17 | 0.14 | 9 | 19.77 | 1.05 | 0.11 | 9 | 21.56 | 1.47 | 0.21 | 7 | 24.62 | 1.27 | 0.25 | 5 | 19.45 |

C	Fall							
	October				November			
	DIN [µmol/l]	DIP [µmol/l]	DIN/ DIP	Chl.a [mg m^{-3}]	DIN [µmol/l]	DIP [µmol/l]	DIN/ DIP	Chl.a [mg m^{-3}]
Wismar Bay	1.41	0.34	**4**	3.68	5.39	0.55	**10**	3.17
Salzhaff	8.59	0.20	*44*	6.13	30.67	0.19	*159*	4.73
Warnow Estuary	5.51	0.75	**7**	2.75	35.56	1.03	*34*	2.86
Barther Bodden	2.14	0.12	*18*	57.22	17.32	0.18	*96*	49.62
West Ruegenscher Bodden	2.27	0.25	**9**	6.33	4.16	0.21	*20*	9.40
Strelasund	3.13	0.30	**10**	15.36	5.81	0.32	*18*	19.13
Greifswalder Bodden	4.79	0.55	**9**	18.77	4.91	0.52	**9**	15.08
Kleiner Jasmunder Bodden	5.76	0.16	*36*	96.62	27.31	0.12	*219*	73.16
Nord Ruegenscher Bodden	2.34	0.16	**15**	15.51	3.62	0.16	*23*	11.63

Reduction of TN concentration by mussel farming and associated water transparency improvement in summer (Aug/Sept).

For the Hagensche Wiek, monthly reduction of nitrogen and increase in Secchi depth were

added together, because of its water exchange rate of 6-7 a^{-1}.

Water body	Farm size [% of the water body surface]	Nitrogen retention by mussel growth [t]		Reduction of TN concentration [μmol l⁻¹]		Secchi depth improvement by nitrogen retention [cm]	
		Aug.	Sept.	Aug.	Sept.	Aug.	Sept.
GWB	1	0.5	5.1	40.7	40.6	0.64	0.50
	10	5.1	51.4	40.6	39.5	0.71	1.18
	25	12.9	128.5	40.5	37.7	0.85	3.51
	50	25.7	257.0	40.2	34.6	1.13	7.83
Hagensche Wiek	1	0.0	0.1	39.8		0.8	
	10	0.1	1.3	38.4		1.66	
	25	0.3	3.1	36.1		5.9	
	50	0.6	6.3	32.1		10.6	

Figure 1

Map of the study site.

Mesohaline inner coastal water bodies (blue areas, labeled in red) including monitoring stations of the State Agency for Environment, Nature Conservation and Geology Mecklenburg-Vorpommern (LUNG) (red dots) providing environmental data for every water body in the study area (where multiple measuring stations occur, data of these stations are pooled (marked by a dotted line)). Green dots represent the two pilot mussel farms.
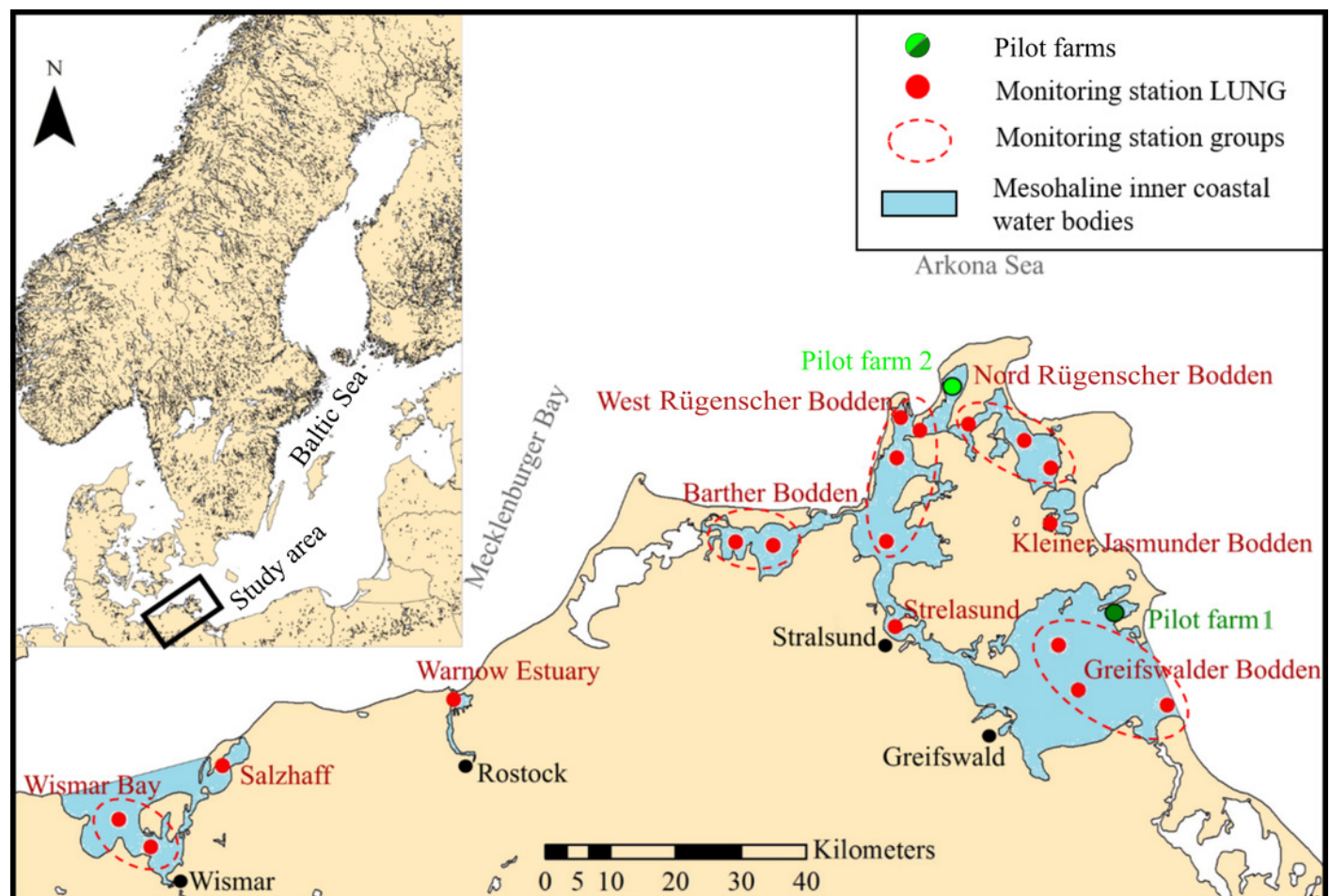
Figure 2

Design of the two pilot longline mussel farms located in GWB and Wieker Bay.

(A) Pilot farm 1 located in GWB. (B) Pilot farm 2 located in Wieker Bay. Credits: Lukas Ritzenhofen, Sven Dahlke
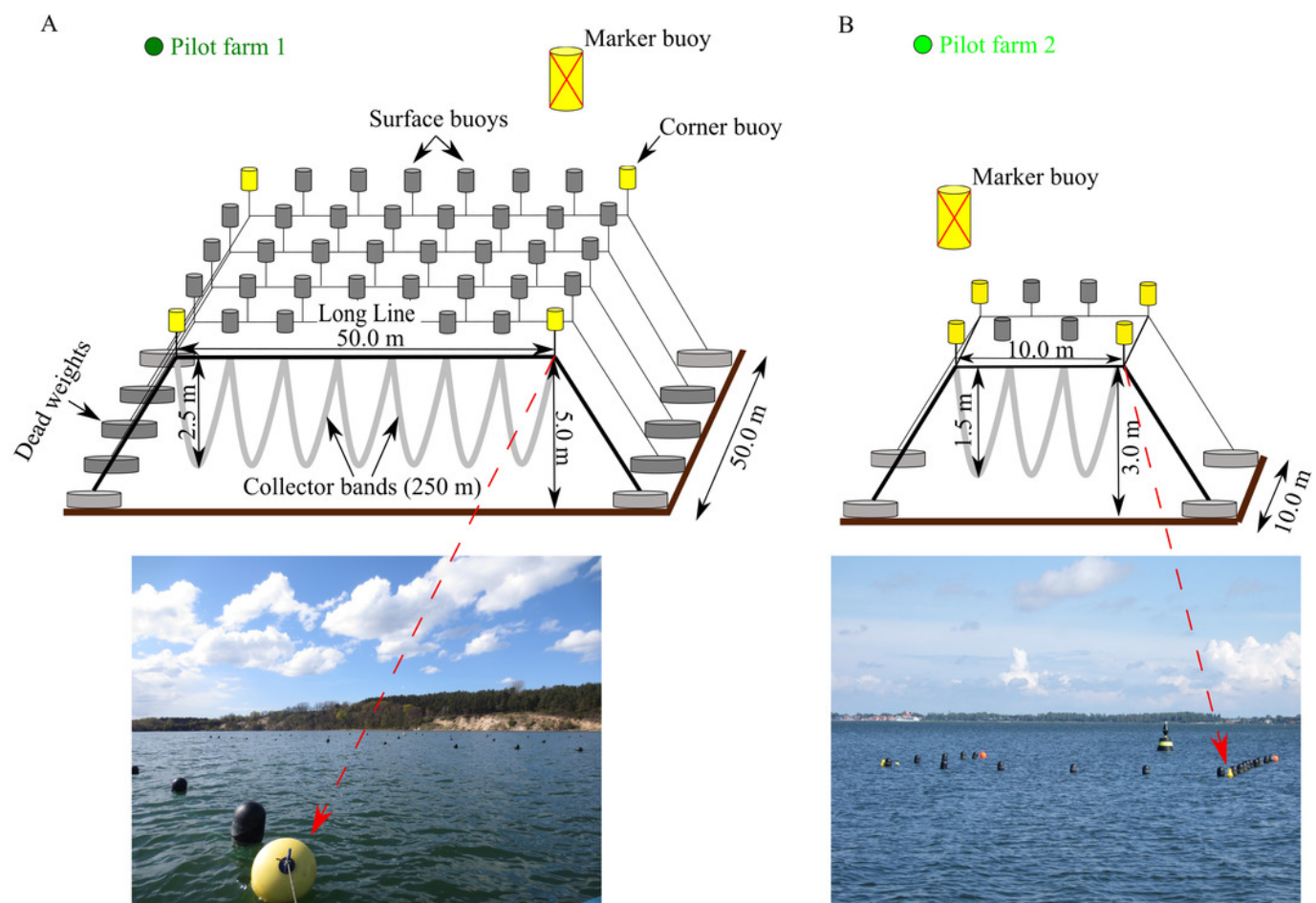
Figure 3

Development of total nutrients, Chl. *a* concentration and Secchi depth between 1990 and 2018 in the different water bodies of the study site.

Total nitrogen in red, total phosphorus in blue, Chl. *a* concentration in green and Secchi depth in grey. Deviation between the current status (2020-2018) (spacing and labeled deviation in red) and the target values demanded by the WFD (green lines).
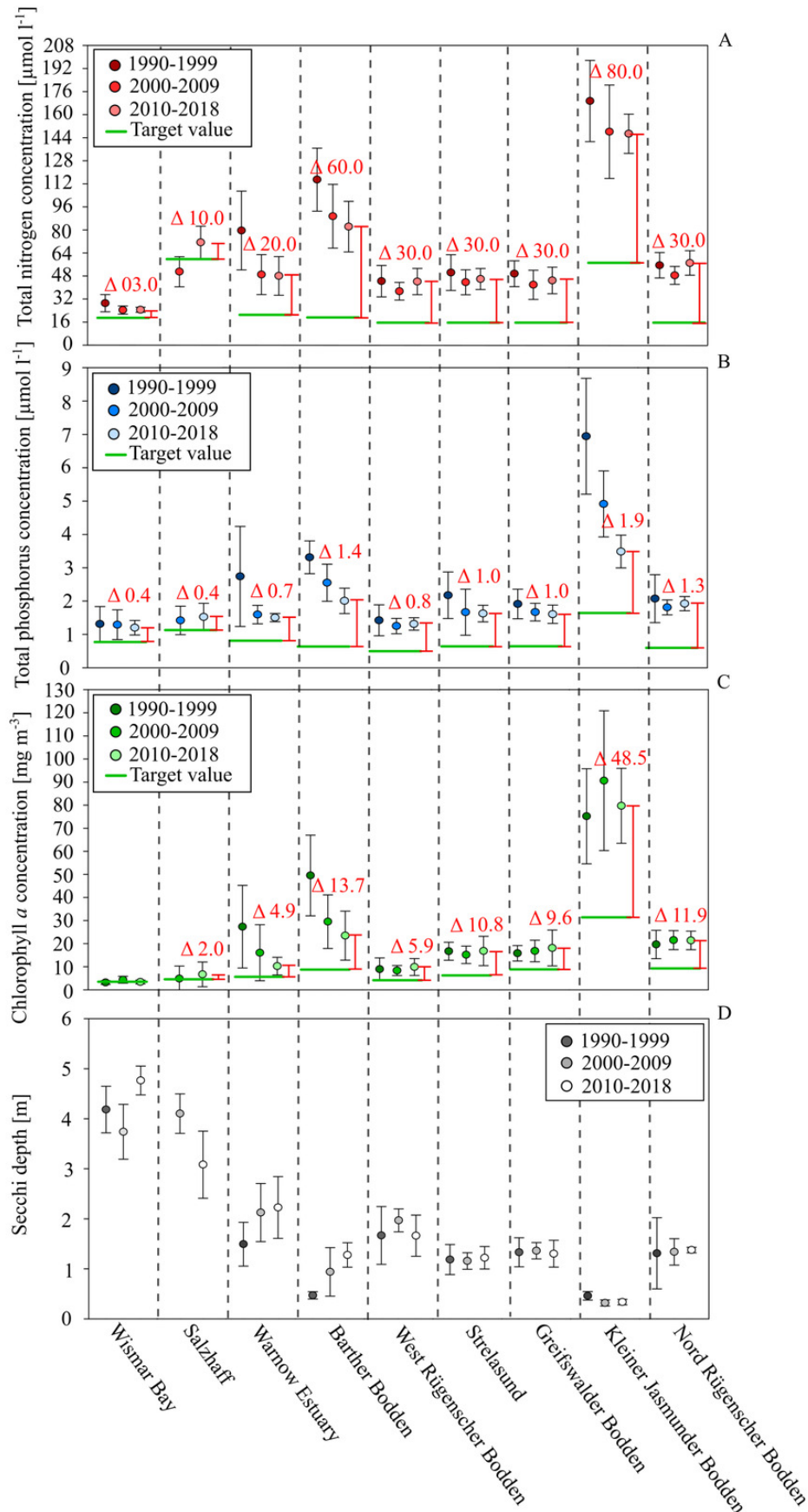
Figure 4

Relationships between total nutrient concentration and Chl. *a* concentration on a monthly basis in GWB.
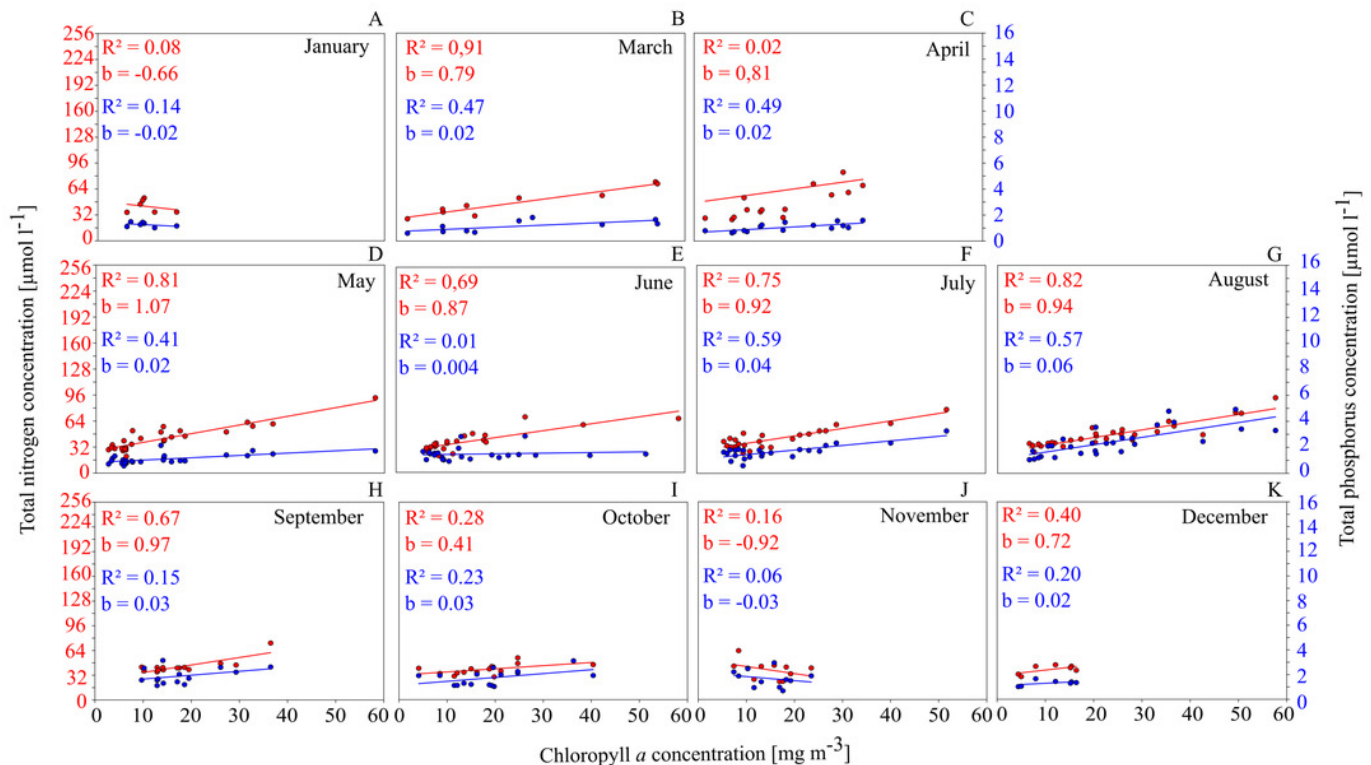
Figure 5

Linear relationships between Chl. *a*, total nitrogen concentration, total suspended solids and Secchi depth.

(A) Chl. *a* concentration (Y) as a function of total nitrogen concentration (X). (B) Secchi depth as a function of Chl. *a* concentration. (C) Secchi depth as a function of total nitrogen concentration. (D) Secchi depth as a function of total suspended solid concentration. Functions are found by single linear regression on logarithmically transformed data ($\ln(Y) = a + b \times \ln(X)$ for the summer months (July-September, 2010-2018) in Greifswald Bay.
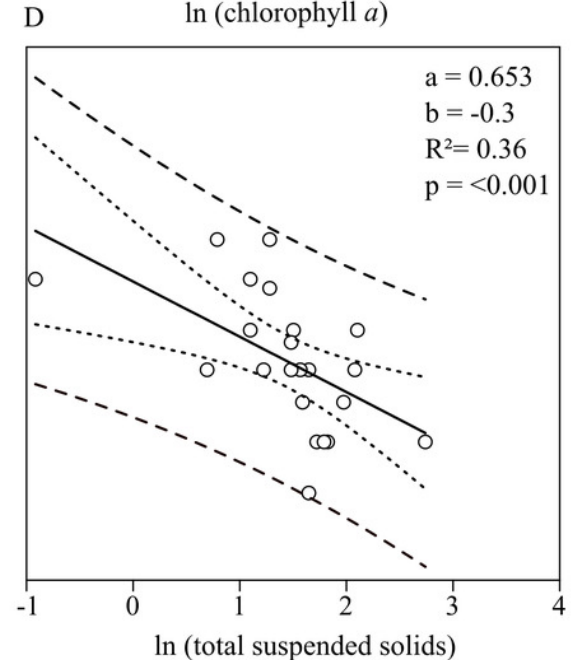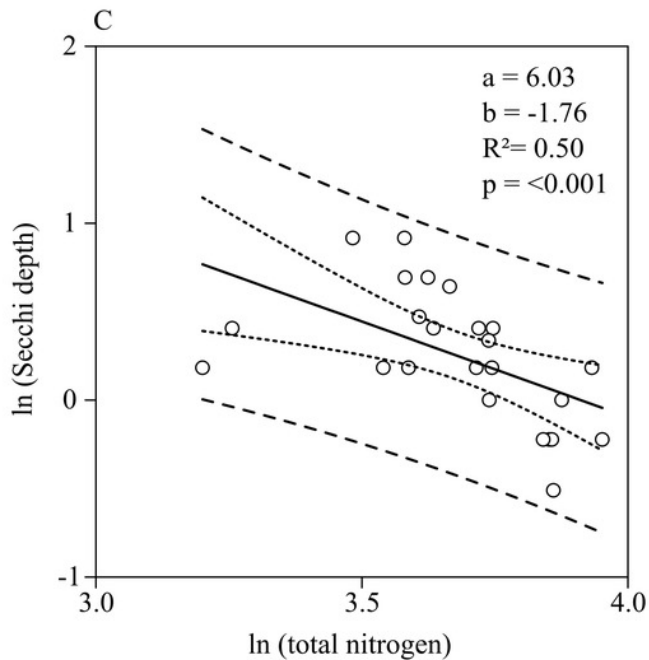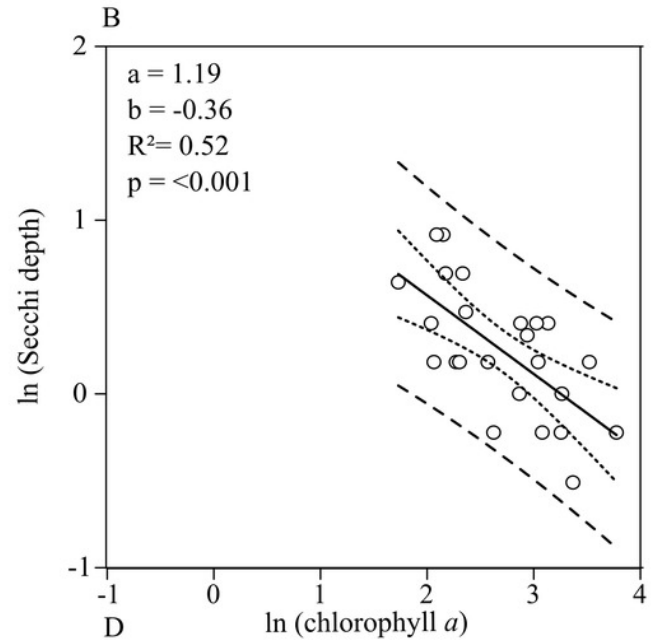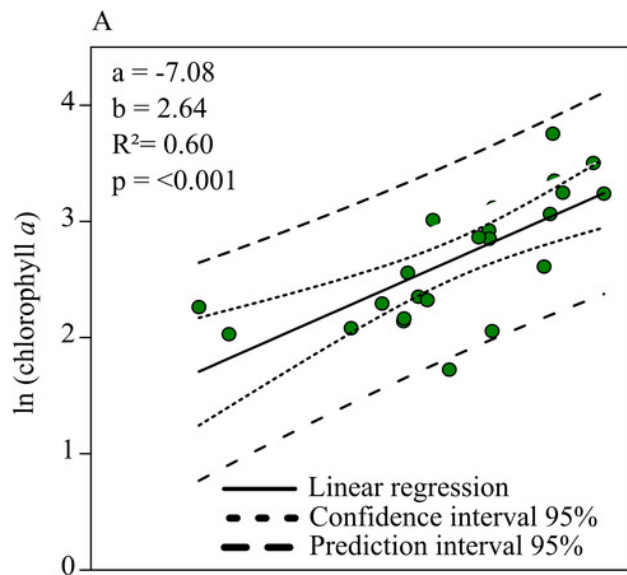
Figure 6

Clearance rates and nutrient content of cultivated blue mussels.

(A) Clearance rates of*Mytilus* spp. within the pilot farms (pilot farm 1 = dark green; pilot farm 2 = light green) and under laboratory conditions (white) at different Chl.*a* concentrations. (B) Total nutrient content in percent of blue mussels

A

B
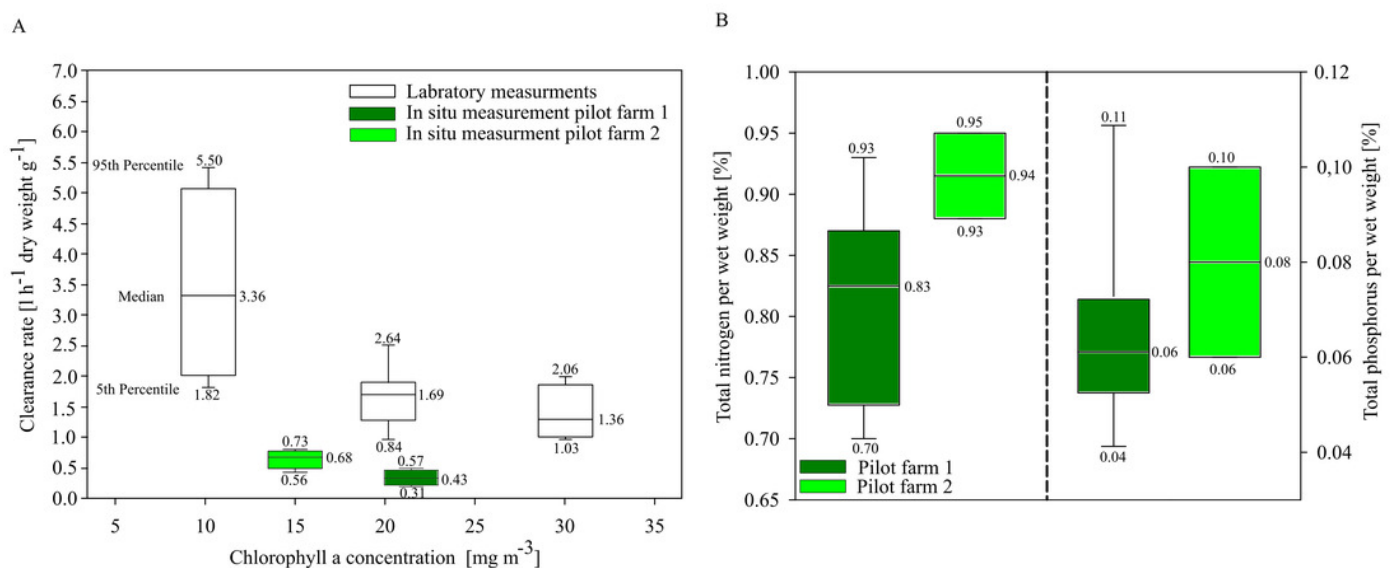
Figure 7

TOC of surface sediment and bio deposition rates within the pilot farm 1.

(A) Surface sediment TOC at the pilot farm 1 (green) compared to reference measurements (white) from 2017 to 2019 divided by seasons and presence of mussel stock. (B) TOC sedimentation rate in the water column in pilot farm 1 (green) and at a reference site (white). For comparison, results from the commercial mussel farm in Kiel are added.
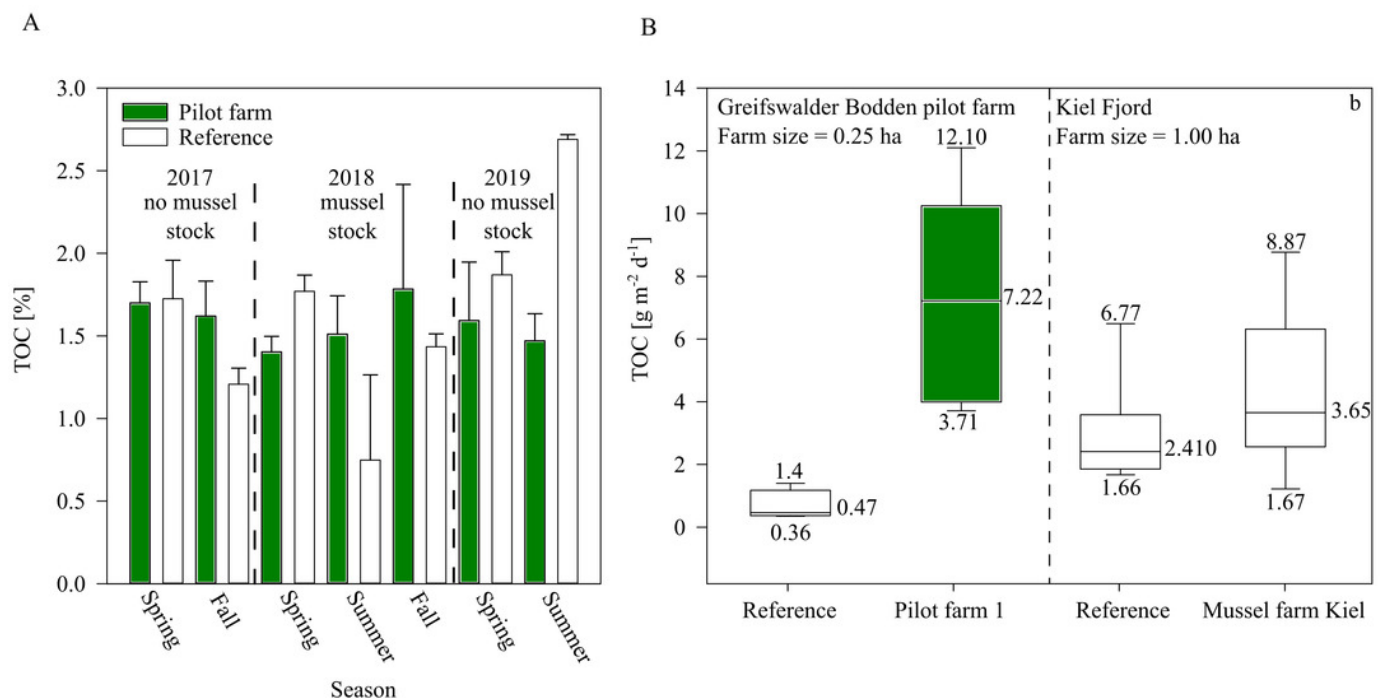
Figure 8

Vibrio spp. appearance within the pilot farm 1.

(A) *Vibrio* spp. concentration (CFU 100 ml^{-1}) at the surface water at the pilot farm 1 compared to a reference measurement. (B) *Vibrio* spp. concentration (CFU 100 ml^{-1}) in the water column. Samples were taken via a sediment trap located in the pilot farm and at a reference point. Labeled in red presents the *Vibrio* spp. concentration (CFU g^{-1}) detected in the cultivated blue mussels. (C) *Vibrio* spp. concentration (CFU 100 g^{-1}) measured in the surface sediments beneath the pilot farm compared to reference measurement.

A

CFU 100 ml^{-1}

Surface water samples

269.0

530.0

St. dev.— 95.0
Average — 170.0

B

Blue mussel = 1.07 10^4 ± 1.75 10^3 CFU g^{-1}

CFU 100 ml^{-1}

1.10e+6

1.43e+6

1.04e+5
1.45e+5

Sediment trap samples

Water column

C

CFU 100 g^{-1}

1.02e+5

2.28e+5

1.30e+5

1.04e+5

Sediment samples

Mussel farm   Reference
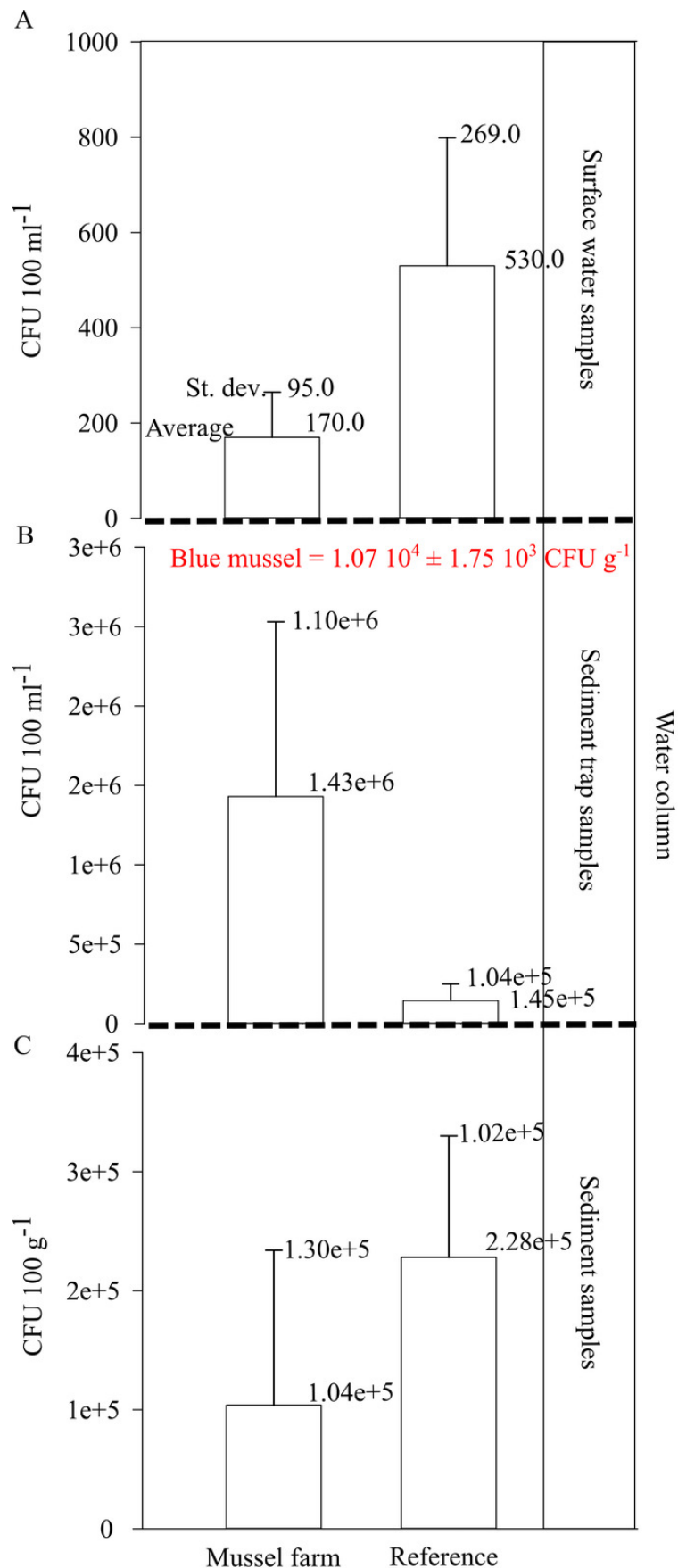
Figure 9

Annual sales cost assessment for mussel cultivation in GWB and its comparision with reduction costs of land based measures.

(A) Total annual costs per ha mussel farm (red line) and annual sale cost balance for two scenarios (black and black dotted line). Scenario I (black dotted) represents the annual sale cost balance if the mussel farm would generate income by selling feed mussels only. Scenario II represents the annual sales cost balance if the mussel farm generates income by feed mussel sales and nutrient removal derived by removal costs of a WWTP. (B) Nitrogen (red line) and phosphorus (blue line) reduction cost (€ kg^{-1}) per farm size compared to other mitigation measures (dotted box) derived from Gren et al., (2008).