



Field assessment of the potential for small scale co-cultivation of seaweed and shellfish to regulate nutrients and plankton dynamics

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ABSTRACT

The co-cultivation of seaweed alongside shellfish has the potential to regulate local dissolved nutrient concentrations and consequently affect plankton dynamics. Evidence for this has until now come largely from computational modelling and laboratory studies, rather than field studies. Here we report on weekly/bi-weekly profiling of inorganic nutrient concentrations (nitrate, nitrite, ammonium, phosphate, and silicate) over two years (2019–2020) at three sampling stations across a small-scale (16 ha) kelp and mussel farm in Porthallow Bay, Cornwall, UK. Nutrient concentrations were measured in conjunction with a range of related environmental variables, including water temperature, salinity, clarity, and phyto- and zoo- plankton abundance, biomass and community composition. These environmental data were also supplemented with river discharge data. Our results indicate typical seasonal variations in chemical (nutrient), physical (hydrographic), and biological (plankton) parameters across all three sampling stations and no significant reductions in inorganic nutrient concentrations in the water column downstream from the integrated kelp and shellfish farm. We conclude that the effectiveness of nutrient regulation by integrating seaweed and shellfish aquaculture will depend on local climatic and hydro-geochemical conditions (affecting background nutrient inputs), as well as the design and scale of integrated multi-trophic aquaculture (IMTA) systems.

1. Introduction

Global aquaculture production of finfish and shellfish has risen to 87.5 million tonnes, with a value at first point of sale in 2020 of US\$264 billion (compared to 90.3 million tonnes and US\$141 billion from capture fisheries) (FAO, 2022). Growth of marine bivalve shellfish aquaculture (amounting to 17.7 million tonnes (US\$29 billion) globally in 2020) is particularly promising in terms of sustainability, since filter feeding shellfish derive their food from freely available and often abundant marine planktonic microalgae (Costello et al., 2020; FAO, 2020), as well as detrital particulates, including from macroalgal sources (Stuart et al., 1982; Duggins et al., 1989; Hyndes et al., 2014). At the same time, filter feeding shellfish provide valuable ecosystem services, including direct regulation of particulate nutrients (plankton and

detritus) and indirect regulation of dissolved nutrients (taken up by phytoplankton) (Stadmark & Conley 2011; Petersen et al., 2014; Smaal et al., 2019). Nutrient removal by shellfish marine aquaculture (mariculture) and curbing of eutrophication in EU coastal waters has been modelled and valued at €11–17 billion per year (Ferreira et al., 2009). Since shellfish are such efficient regulators, marine spatial planning and ecosystem modelling (Ferreira et al., 2014) are required to ensure that cultivation activities do not result in the depletion of local primary and secondary production, with ramifications for wider ecosystem processes and/or other marine economic uses, including other aquaculture or fishing operations (Smaal et al., 1997, 2019).

Co-cultivation of seaweeds (macroalgae) with shellfish has the potential to further regulate local nutrient concentrations, including from shellfish faeces and pseudo-faeces (Chopin et al., 2001). Farmed

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seaweeds also compete with phytoplankton by: scavenging background nutrients, including marine and riverine derived nitrogen and phosphate (Harrison and Hurd, 2001); shading phytoplankton; stabilizing the water column, disadvantaging some less motile phytoplankton (Rosman et al., 2010) and by allelochemical interaction/competition (Tang and Gobler, 2011; Yang et al., 2015; Gharbia et al., 2017). Some modelling and experimental studies have also demonstrated the potential for mitigating Harmful Algal Blooms (HABs) through seaweed cultivation (Gharbia et al., 2017; Aldridge et al., 2021). However, few field studies have examined phytoplankton dynamics in and around operational seaweed farms or Integrated Multi-Trophic Aquaculture (IMTA) sites, including in temperate regions such as the northeast European coastline (Hossain et al., 2022).

We conducted a field study at a small-scale IMTA site in Porthallow Bay, Cornwall, UK, to examine the potential for co-cultivation of

seaweed and shellfish to affect local nutrient concentrations and plankton dynamics. Sugar kelp (*Saccharina latissima*) was co-located and cultivated on new ropes within a pre-existing blue mussel (*Mytilus edulis*) farm in Porthallow Bay in 2019. Successful cultivation led to an increase in *S. latissima* biomass, and naturally recruiting furbelows (*Saccorhiza polyschides*) to settle following rope deployments in November 2019 and 2020. Water and plankton sampling were conducted weekly/bi-weekly (May 2019 to August 2020), upstream and downstream of the IMTA site to quantify variations in inorganic nutrient concentrations (nitrate, nitrite, ammonium, phosphate, and silicate) in conjunction with changes in cultivated seaweed biomass and plankton community composition. Other environmental factors influencing local nutrient concentrations and plankton abundance and diversity, including seasonal variations in rainfall, local river discharges, wave height and thermal stratification of the water column were also quantified and

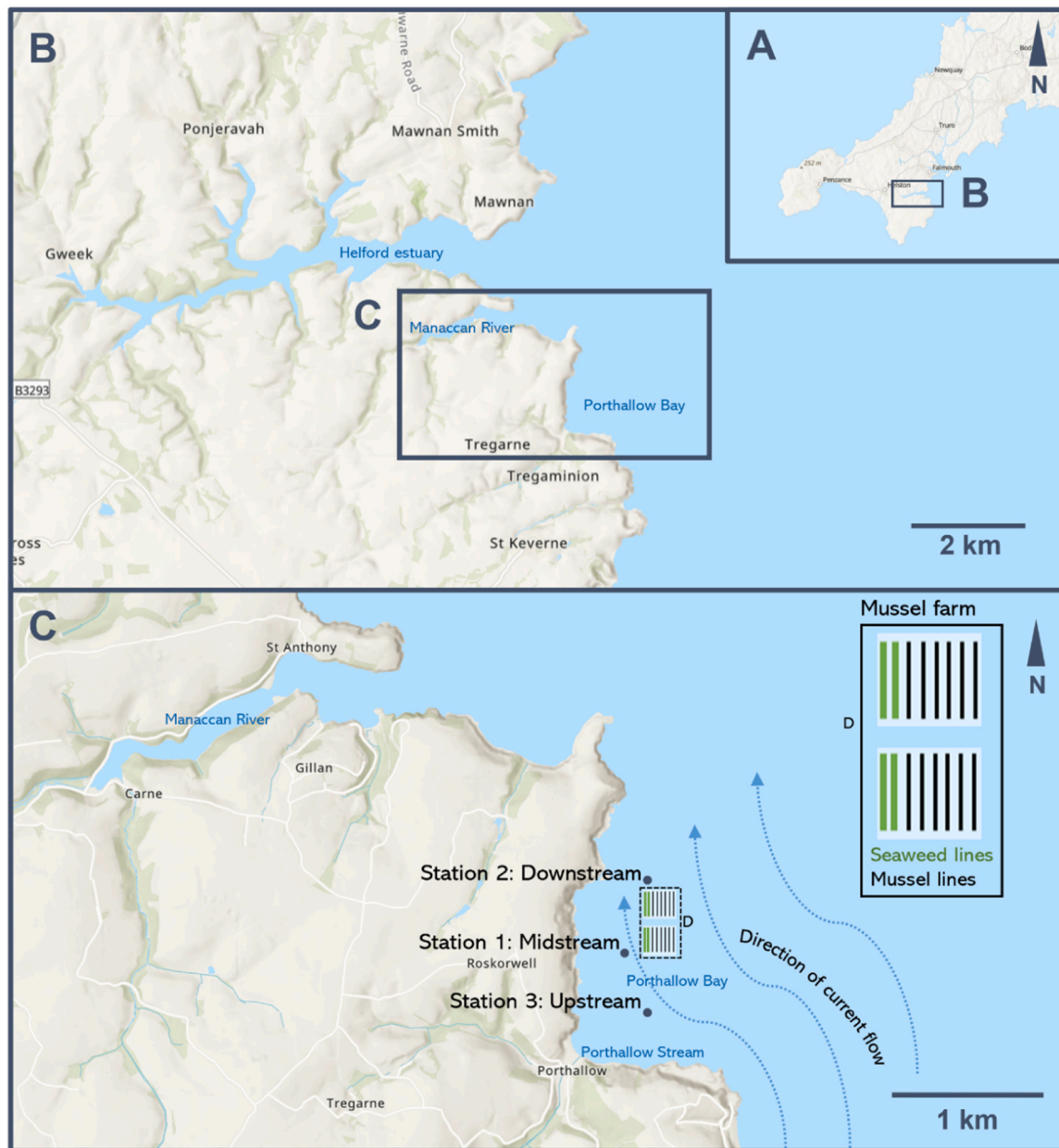


Fig. 1. Study site map with A) location in southwest UK; B) location on the Lizard, Cornwall; C) Map of Porthallow Bay integrated seaweed and mussel farm with the locations of water sampling stations (Station 1 corresponded with the Food Standards Agency's routine monitoring point for the Porthallow Bay Mussel Farm (Food Standards Agency (2021)), the direction of river discharge from the north, and the direction of the current around high water when sampling occurred; D) farm layout showing positions of seaweed and mussel lines (200 m each).

considered in the interpretation of the results.

2. Methodology

2.1. Farm characterization

The Porthallow Bay integrated seaweed and mussel farm is situated on the east coast of the Lizard Peninsula (Cornwall, UK; Fig. 1), and is therefore relatively sheltered from the prevailing southwesterly winds. Tidal inflow from the Atlantic, generates a consistent current flow (mean velocity of 0.5 m s^{-1}) from south to north from high water (HW) – 4 to + 2.5 h, which reverses and flows north to south thereafter (VisitMyHarbour, 2012). Wave action within the bay is relatively low amplitude, compared to the west coast of the Lizard (Corrigan et al., 2023). Porthallow Bay receives outflows from Porthallow Stream and lies close to the mouths of the Manaccan River (~3.5 km north) and Helford estuary (~5 km north). The farm covers approximately 16 ha, located approximately 500 m east of the coast, in water depths ranging from 5 to 14 m at lowest astronomical tide. Seaweed (*Saccharina latissima* and *Saccorhiza polyschides*) covers approximately 2 ha, deployed on vertical dropper lines connected to two 200 m header long lines alongside fourteen 200 m blue mussel (*Mytilus edulis*) lines (Fig. 1) (Corrigan et al., 2023). Prior to first harvest in June 2019, total harvestable seaweed biomass was low (~200 kg), but in June 2020, seaweed biomass increased to ~2000 kg, while total harvestable mussel biomass remained comparable across both years, averaging ~100,000 kg (Corrigan et al., 2023).

2.2. Field data collection

Water sampling was conducted weekly during spring and summer and once every two weeks during autumn and winter from 28th May 2019 to 24th August 2020 at three survey stations around the farm within Porthallow Bay: Station 1 Midstream; Station 2 Downstream; Station 3 Upstream (Fig. 1). Corresponding environmental measurements of water temperature, salinity, water clarity (measured as Secchi depth) and dissolved nutrient concentrations (nitrate, nitrite, ammonium, phosphate, and silicate) were made, as detailed below. Timing of sampling coincided with tidal currents flowing from south to north (Fig. 1), meaning that the water measurements at the upstream station (Station 3) were not influenced by the farm and thereby provided background reference data. Station 1 corresponded with the Food Standards Agency's routine monitoring point for the Porthallow Bay Mussel Farm (Food Standards Agency, 2021).

Water samples were obtained from stations 1–3 (Fig. 1) at two depths: 2 m (representing surface waters) and 10 m (representing water below the seasonal thermocline). Water samples were collected using a 5 L Niskin bottle (General Oceanics, Miami, FL); they were transferred to 50 mL plastic bottles for nutrient analysis. For phytoplankton composition analysis, an additional 250 mL water sample was taken during May–August (pre- and post- achievement of maximum seaweed biomass) in both years at 2 m depth from Station 1 and preserved in 2 % acid Lugol's iodine solution in amber glass bottles. All water samples were stored in cool boxes before subsequent analysis at Plymouth Marine Laboratory (PML).

Samples for zooplankton community analysis were collected (Station 1 only) in June–August in both years using vertically hauled 500 mm diameter WP2-style ring net (200 μm mesh size) (NHBS, Totnes, UK) from approximately 2 m above the seabed to the surface. Zooplankton samples were washed off the 200 μm mesh collector with seawater and immediately preserved in 4 % formaldehyde (final concentration) in a 250 mL bottle.

At each station, a Sontek CastAway™ conductivity, temperature, and depth profiler (CTD, Sontek, San Diego, CA) was lowered to the seabed and parameter values were recorded at 30 cm depth increments on ascent. A Secchi disk was then lowered into the water until not visible,

and the depth at which it became visible on ascent was recorded to the nearest 0.5 m. Before proceeding to the next station, metadata were collected including GPS location, time in relation to HW, sea state, weather, cloud cover and any unusual conditions.

Local river flow data for the Manaccan River (reference 19A03, 1.6 miles NW of the farm) were obtained from the Environment Agency, to indicate periods of intense rainfall, from 28th May 2019 – 24th August 2020. River flow data were averaged across the week prior to Porthallow Bay sampling to represent potential lag-time between rainfall, run-off, and river discharge. Significant wave height and mean wave period data were collected from the nearest operational wave buoy in Penzance Bay (with a similar aspect and wave exposure to Porthallow Bay) and were similarly averaged across each week prior to sampling (Channel coast, 2021).

2.3. Laboratory analysis

The frozen nutrient samples were defrosted and handled in the laboratory according to GO-SHIP protocols (Becker et al., 2020). Nutrient concentrations of nitrate, nitrite, ammonium, phosphate, and silicate were determined colourimetrically using a segmented flow SEAL nutrient autoanalyzer with analytical methods described in (Woodward and Rees, 2001). The limits of detection were: nitrate and phosphate, 0.02 μM ; nitrite, 0.01 μM ; ammonium, 0.05 μM ; silicate 0.02 μM .

Phytoplankton cell counts were performed using the Utermöhl technique following the British and European Standard protocol (BS EN 15204:2006), the guidance standard on the enumeration of phytoplankton using inverted microscopy (Utermöhl, 1958). Each sample was gently re-suspended to ensure homogeneity, and 50 mL sub-samples were taken and left to settle for 24hrs before being examined at between 200x and 400x magnification using a Leica DMI400B inverted microscope. Phytoplankton taxa were identified where possible to species level and their abundance was expressed in cell counts per mL of water. The cell counts of desired species or genera were then multiplied by 1000 to represent cells L^{-1} . Average cell dimensions (μm) of individual taxa were used to compute biovolume estimates, assuming appropriate geometric shapes (Olenina et al., 2006) and converted to carbon biomass according to the equations of Menden-Deuer and Lessard (2000). Individual taxa were grouped according to five functional groups: diatoms, dinoflagellates, flagellates, *Phaeocystis* and ciliates.

Zooplankton were identified by microscopy to the lowest practicable taxonomic resolution and enumerated under an inverted microscope (100x magnification). Subsamples were extracted with a Hensen-Stempel pipette achieving between 200 and 400 individuals. Larger subsamples were checked for larger and/or rarer species. Abundance was expressed as numbers of organisms per cubic meter (abundance m^{-3}).

2.4. Data analysis

Prior to data analysis, nutrient concentrations and plankton data were averaged per month of sampling. All statistical analysis was conducted using the PERMANOVA add on for Primer v7® software (Anderson et al., 2008; Clarke and Gorley, 2015). Differences for each nutrient concentration at depth, between stations and within months were examined using three-way univariate permutational analyses of variance (PERMANOVA). Models included “month”, “station” and “depth” as fixed factors, and permutations (999 under an unrestricted model) were based on Euclidean distances between normalised data. Differences for all normalised nutrient concentrations between stations at both depths and between months were visualised using Principal Component Analysis (PCA).

Variability in phytoplankton and zooplankton samples between months sampled each year were examined separately using individual PERMANOVAs. Univariate tests for total zooplankton abundance and total phytoplankton abundance and biomass between months were

examined using two-way permutational analyses of variance (PERMANOVA). Models included “month” and “year” as fixed factors, and permutations (999 under an unrestricted model) were based on Euclidean distances between untransformed data. Multivariate phytoplankton and zooplankton assemblages were examined using the same model, but with permutations based on separate Bray-Curtis resemblance matrices constructed from the abundance of either zooplankton or phytoplankton taxa and the biomass of phytoplankton taxa and visualised using metric multidimensional scaling (mMDS) ordination. Fourth root transformation was chosen for abundance and biomass of phytoplankton and zooplankton taxa to down-weight the influence of highly abundant taxa. For both the univariate and multivariate analyses, pair-wise tests in PERMANOVA were conducted wherever the main effect was significant ($p < 0.05$) with Monte Carlo routine to mitigate for the small sample size. Differences in within-treatment variability between levels of factors were also examined using the permutational dispersion (PERMDISP) routine. Where within-treatment dispersion differed between groups, a more conservative p-value ($p < 0.01$) was adopted for the main PERMANOVA test for that given response variable (Anderson, 2017).

3. Results

3.1. Environmental conditions at the farm site

Environmental conditions monitored at the farm site varied across the time series in accordance with typical seasonal patterns (Fig. 2). Data analysis on Manaccan river flow across the time series, indicated an

expected seasonal relationship, with increased rainfall in the winter seasons, resulting in increased river discharge from October to March (Fig. 2). Secchi depth as a proxy for water clarity decreased from September to March, through the autumn and winter months, and then started to increase again, with the exception of May 2020, when a plankton bloom was observed. Secchi depth was generally less in summer 2020 compared to summer 2019 and this corresponded with higher flow rates for the Manaccan River in summer 2020. Temperature profiles also varied across the time series, from maximum values of $\sim 17^\circ\text{C}$ in July-September 2019 to minimum values of $\sim 10^\circ\text{C}$ in March 2020. Spring temperatures were warmer in 2020, reaching $\sim 15^\circ\text{C}$ in June, whereas in 2019 similar values were not observed until July.

3.2. Nutrient analysis

Results from the PCA and multivariate analysis revealed there were no significant differences in overall and individual nutrient concentrations between stations or depths (Fig. 3, Table 1). There were however, clear seasonal differences in overall and individual nutrient concentrations (and consequently nutrient ratios) between months at both water depths across sampling stations (Figs. 3 and 4, Table 1). During the autumn and winter seasons, there was a noticeable increase in nitrate, nitrite, silicate and phosphate i.e. from September 2019 to March 2020 (Fig. 4), which correlated with the increase in periods of high river discharge (Fig. 2).

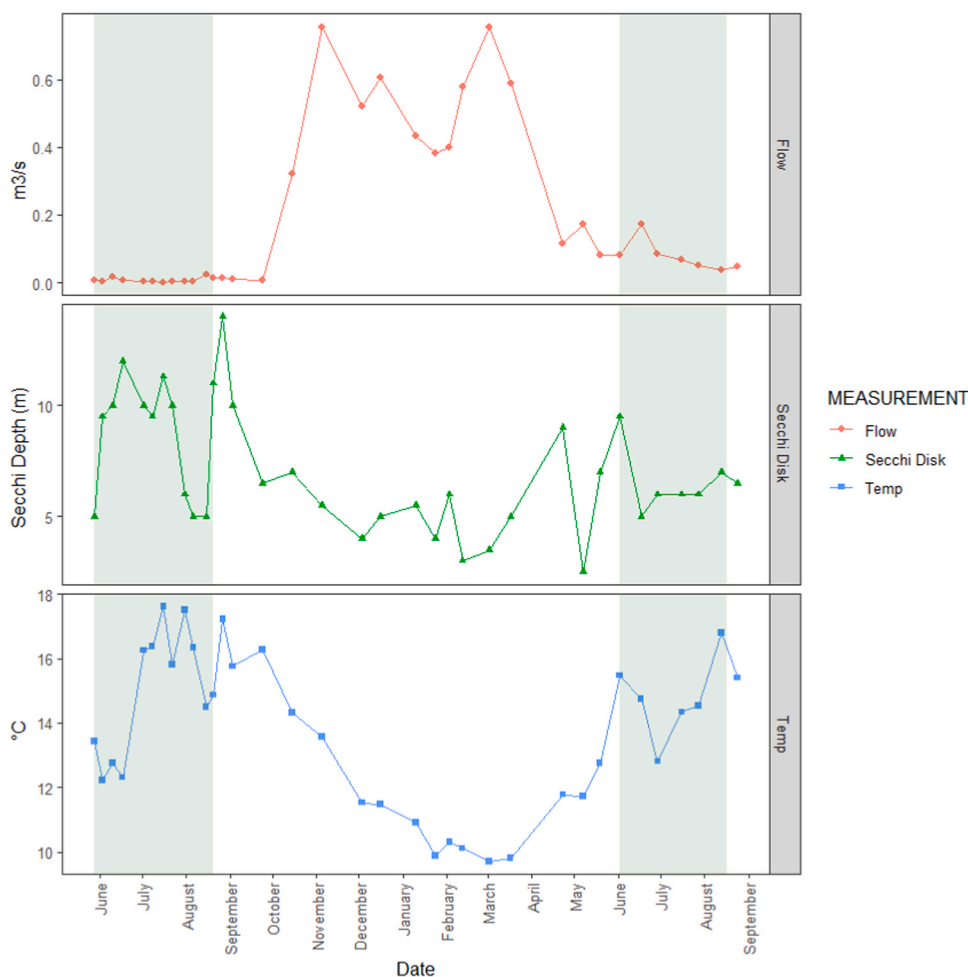


Fig. 2. Manaccan River flow (m^3/s), Secchi depth (m) and temperature ($^\circ\text{C}$) across the time series from May 2019 to August 2020. Secchi depth and temperature were measured at Station 1. Light green boxes indicate the time periods where phytoplankton and zooplankton data were collected from Station 1.

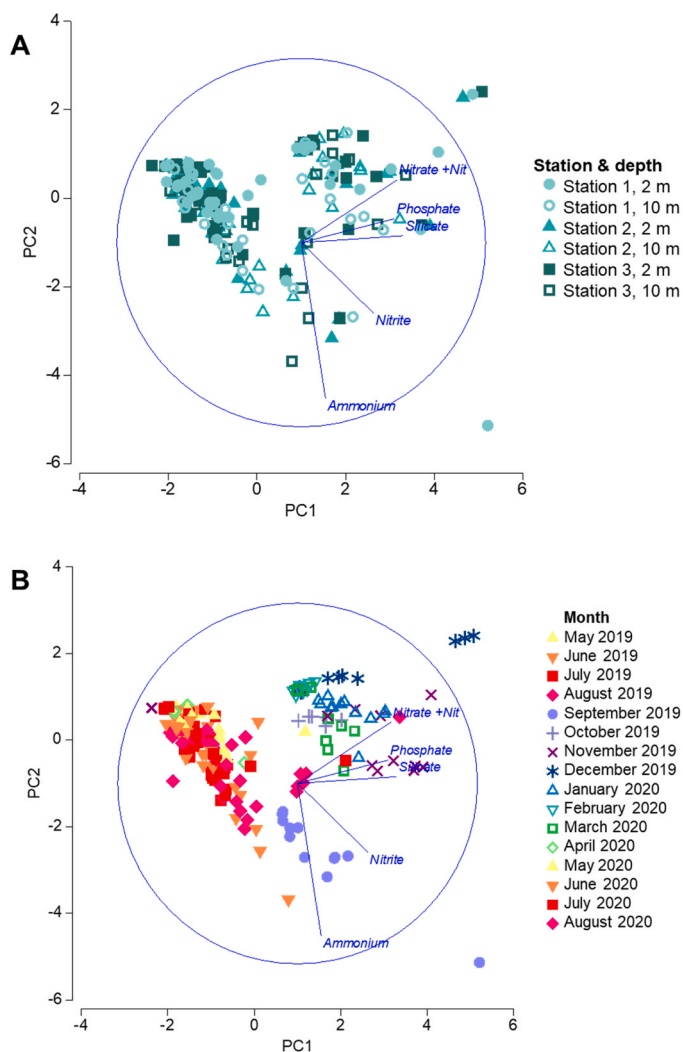


Fig. 3. Principal Component Analysis plots depicting multivariate analysis of normalised nutrient data collected around Porthallow farm between A) stations and depths, and B) months and years.

3.3. Plankton communities

Phytoplankton communities in Porthallow Bay (represented by Station 1: Midstream) did not significantly differ in total abundance or biomass in 2019 (low seaweed biomass) compared to 2020 (high seaweed biomass), however, total phytoplankton biomass did differ between months within years (Table 2, Fig. 5). The multivariate analysis revealed differences in species composition between months within years in terms of abundance and biomass – with flagellates being numerically dominant (particularly in May 2019), (Table 2, Fig. 5).

Zooplankton communities at the IMTA site in Porthallow Cove (represented by Station 1: Midstream) were not significantly different in total species abundance in 2019 (low seaweed biomass) compared to 2020 (high seaweed biomass) or between months within years (Table 2, Fig. 6). However, the multivariate analysis did reveal differences in species composition between years and between June and August in both years (Table 2, Fig. 6).

4. Discussion

We recorded no significant differences in nutrient concentrations in the water column (at both 2 m and 10 m depth) between stations sampled across the ~2 ha seaweed farm (integrated within the ~16 ha

Table 1

Nutrients: statistical results from PERMANOVA and PERMDISP analysis of normalised nutrient concentrations, between stations, depths, and months for each year, with post-hoc results within factors detailed. Results are for stations 1–3. Degrees of freedom (df) are reported within treatments. Significant P values are highlighted with *.

Nutrient	Factors	df	PERMANOVA		PERMDISP		
			F	P	F	P	
Nitrite	Depth	1	0.64352	0.436	0.15021	0.797	
	Station	2	0.13263	0.886	0.16099	0.92	
	Month	15	24.282	0.001*	53.227	0.001*	
	Depth × station	2	0.096221	0.89	N/A	N/A	
	Depth × month	15	0.42935	0.961	N/A	N/A	
	Station × month	30	0.14968	1	N/A	N/A	
	Depth × station × month	29	0.080272	1	N/A	N/A	
	Nitrate + Nitrite	Depth	1	5.8172	0.015	12.698	0.029*
		Station	2	0.42074	0.671	0.43729	0.833
Month		15	48.674	0.001*	14.593	0.001*	
Depth × station		2	0.10169	0.892	N/A	N/A	
Depth × month		15	2.8213	0.004*	N/A	N/A	
Station × month		30	0.88147	0.647	N/A	N/A	
Depth × station × month		29	0.22988	1	N/A	N/A	
Ammonium		Depth	1	1.1001	0.309	1.7277	0.272
		Station	2	0.045008	0.953	0.962	0.059914
	Month	15	6.1992	0.001*	5.3537	0.002*	
	Depth × station	2	0.12529	0.884	N/A	N/A	
	Depth × month	15	0.73169	0.734	N/A	N/A	
	Station × month	30	0.28645	1	N/A	N/A	
	Depth × station × month	29	0.26564	1	N/A	N/A	
	Silicate	Depth	1	3.59	0.06	9.8234	0.003*
		Station	2	1.184	0.297	0.75168	0.517
Month		15	16.649	0.001*	3.9675	0.003*	
Depth × station		2	0.98686	0.396	N/A	N/A	
Depth × month		15	1.3772	0.169	N/A	N/A	
Station × month		30	0.77475	0.788	N/A	N/A	
Depth × station × month		29	0.33124	1	N/A	N/A	
Phosphate		Depth	1	0.64701	0.421	< 0.001	0.994
		Station	2	0.037934	0.964	0.42683	0.784
	Month	15	13.943	0.001*	1.3255	0.789	
	Depth × station	2	0.07912	0.927	N/A	N/A	
	Depth × month	15	0.56062	0.875	N/A	N/A	
	Station × month	30	0.52262	0.962	N/A	N/A	
	Depth × station × month	29	0.34831	1	N/A	N/A	

mussel farm) in Porthallow Bay, in both 2019 (low seaweed biomass) and 2020 (high seaweed biomass). Seasonal changes in nutrient concentrations were mirrored at sampling stations both upstream and downstream from the cultivation site and corresponded with seasonal changes in phytoplankton and zooplankton assemblages. Ammonium was most variable in concentration at both up- and down- stream

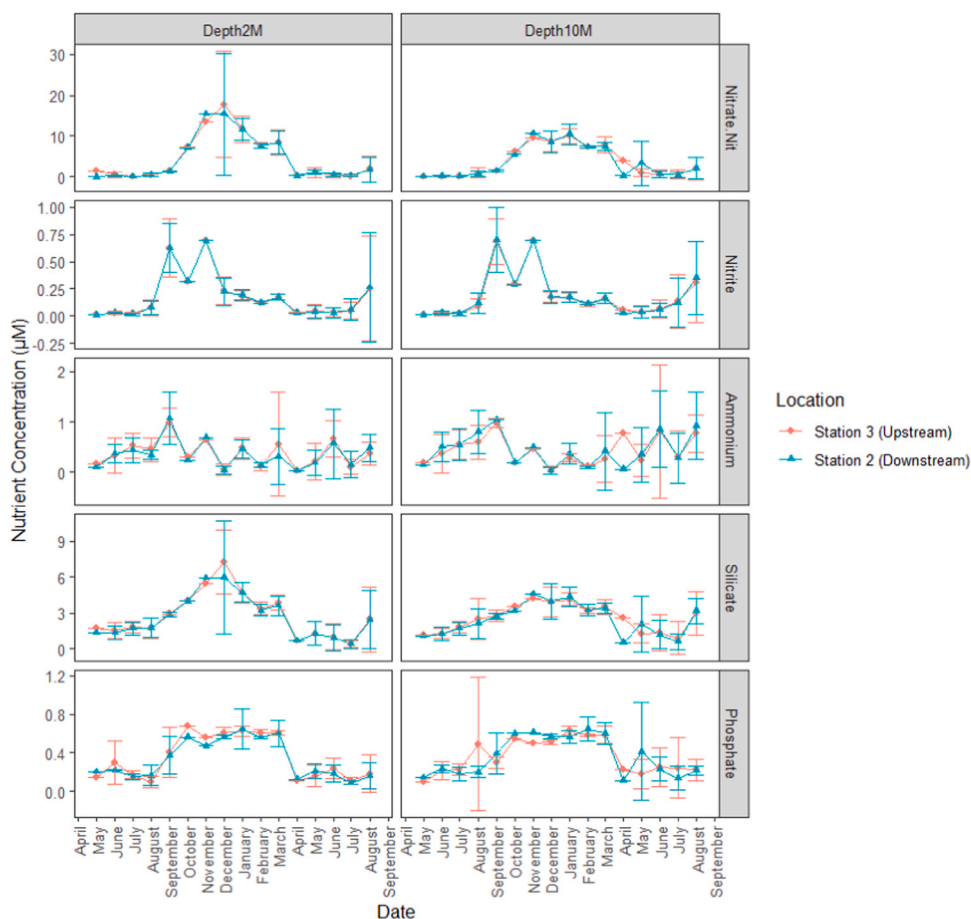


Fig. 4. Nutrients (μM) across the time series from May 2019 – August 2020, showing Nitrate + Nitrite, Nitrite, Ammonium, Silicate and Phosphate concentrations across 2 m and 10 m depth, with upstream measurements in red (diamond) and downstream measurements in blue (triangle). Error bars produced using 95 % confidence intervals.

Table 2

Plankton: statistical results from PERMANOVA and PERMDISP univariate (Uv) and multivariate (Mv) analysis of plankton assemblages, between months and years, with post-hoc results detailed. Results are for midstream Station 1. Degrees of freedom (df) are reported within metrics and significant P values are highlighted with *.

Response metric	Transformation	Factor	df	PERMANOVA		PERMDISP		Post-hoc significant differences
				F	P	F	P	
Phytoplankton abundance (Uv)	N/A	Month	2	2.0377	0.159	1.0237	0.496	N/A
		Year	1	3.0435	0.109	1.3037	0.271	N/A
		Month \times year	2	1.0721	0.379	N/A	N/A	N/A
Phytoplankton biomass (Uv)	N/A	Month	2	1.5684	0.225	0.71921	0.742	N/A
		Year	1	0.79263	0.406	0.84066	0.415	N/A
		Month \times year	2	6.6677	0.005*	N/A	N/A	2019: May > all 2020: May < August
Zooplankton abundance (Uv)	N/A	Month	2	0.82502	0.496	2.6304	0.337	N/A
		Year	1	0.23744	0.68	1.3596	0.578	N/A
		Month \times year	2	0.48759	0.703	N/A	N/A	N/A
Phytoplankton abundance (Mv)	Fourth root	Month	2	2.7069	0.009*	1.7643	0.241	N/A
		Year	1	5.726	0.003*	3.1338	0.09	N/A
		Month \times year	2	4.8256	0.001*	N/A	N/A	2019: July - August 2020: June - August; July - August
Phytoplankton biomass (Mv)	Fourth root	Month	2	2.87	0.009*	8.71	0.007*	N/A
		Year	1	1.6946	0.163	3.5318	0.071	N/A
		Month \times year	2	4.0319	0.001*	N/A	N/A	2019: June - July; July - August 2020: May-June
Zooplankton abundance (Mv)	Fourth root	Month	2	2.0095	0.04*	1.6666	0.402	June-August
		Year	1	2.4906	0.022*	0.24917	0.709	2019-2020
		Month \times year	2	1.796	0.053	N/A	N/A	N/A

sampling stations over time, showing greatest variation around mean values. Ammonium represents a small dynamic nutrient pool affected by several biological processes, including: assimilation by phytoplankton;

nitrification and de-nitrification by bacteria; excretion by fish, invertebrates and other marine biota (Karl et al., 2008). Elsewhere, ammonium concentrations have been shown to be elevated locally

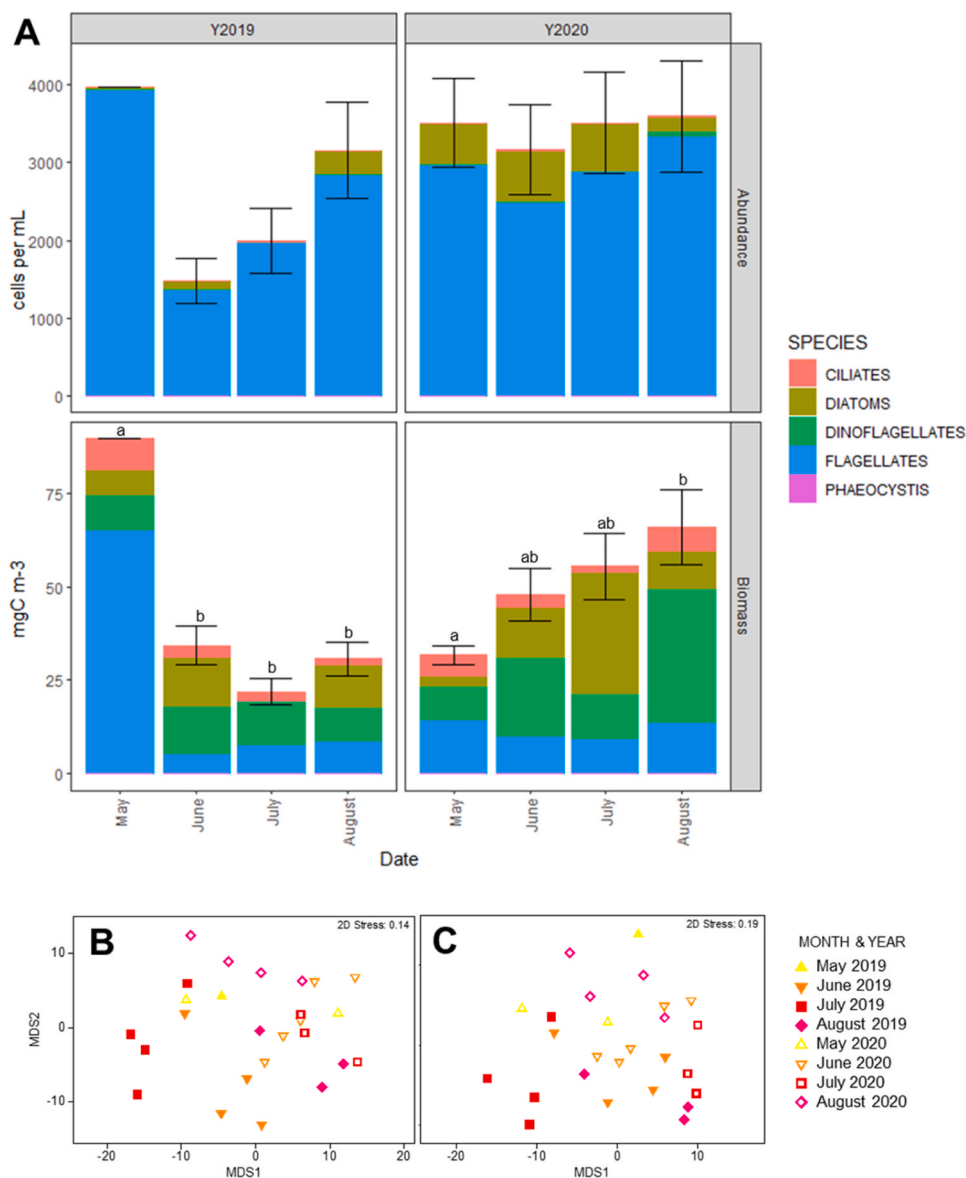


Fig. 5. A) Mean phytoplankton abundance (above) and biomass (below) at Station 1, at 2 m depth per month. Significant differences between months within years are denoted with letters, whereby months with the same letters indicate no difference between those months. Error bars represent SE of total mean phytoplankton abundance and biomass per month; B) mMDS plot of phytoplankton abundance between months and years; C) mMDS plot of phytoplankton biomass between months and years. Both mMDS plots are ordinated based on Bray–Curtis similarity matrices with fourth-root transformations.

around mussel farms (Kaspar et al., 1985; Hylén et al., 2021). It is possible that any effects from farmed seaweeds (~2000 kg in 2020) on the local ammonium budget were compensated by inputs from farmed mussels (~100,000 kg) in Porthallow Bay. Nutrient concentrations (and variability) may not only be influenced by farmed seaweeds and mussels; variations in ammonium and other nutrients may also be influenced by terrestrial inputs via rivers (Bell et al., 2021) and benthic-pelagic coupling (Friedl et al., 1998). Overall nutrient requirements for cultivated seaweed biomass were met by surrounding waters, which are well-mixed and frequently exchanged in Porthallow Bay, an area previously shown not to be nutrient limited (Spatharis et al., 2007). Our results are consistent with other field data showing negligible effects on nutrients and plankton around similarly sized seaweed farms located elsewhere, including a 15 ha *S. latissima* farm in the Koster archipelago, Sweden (Visch et al., 2020) and a 21 ha giant kelp (*Macrocystis pyrifera*) farm in Chile (Buschmann et al., 2014). Furthermore, multi-scaled modelling indicates that seaweed (kelp) farms need to be much larger in area (>100 × larger) to significantly impact on local nutrient

concentrations and plankton biomass. For example, a 100 ha *S. latissima* farm in the Western Baltic was shown to remove only 0.07 % of available nitrogen and phosphorus (Kotta et al., 2022), while a 2500 ha *S. latissima* farm in Strangford Lough, Northern Ireland was simulated to reduce nutrient concentrations and plankton biomass by up to 25 % (Aldridge et al., 2021).

Phytoplankton abundance and biomass did not differ between summer 2019 and 2020, despite seaweed biomass being substantially (10x) greater at the Porthallow site in 2020 – further indicating that the farmed seaweed did not limit nutrient availability for local phytoplankton communities in these periods. Harmful algal blooms (including *Pseudo-nitzschia* spp. and *Dinophysis* spp.) were also more frequently recorded above advisory abundance thresholds in 2020 compared to 2019 (SI Table 4). Nevertheless, typical spring-summer successional changes in phytoplankton (and zooplankton) communities were observed at Porthallow in both 2019 and 2020. There was a typical transition from diatom to dinoflagellate blooms with increasing temperature, water column stratification/stabilization and inorganic

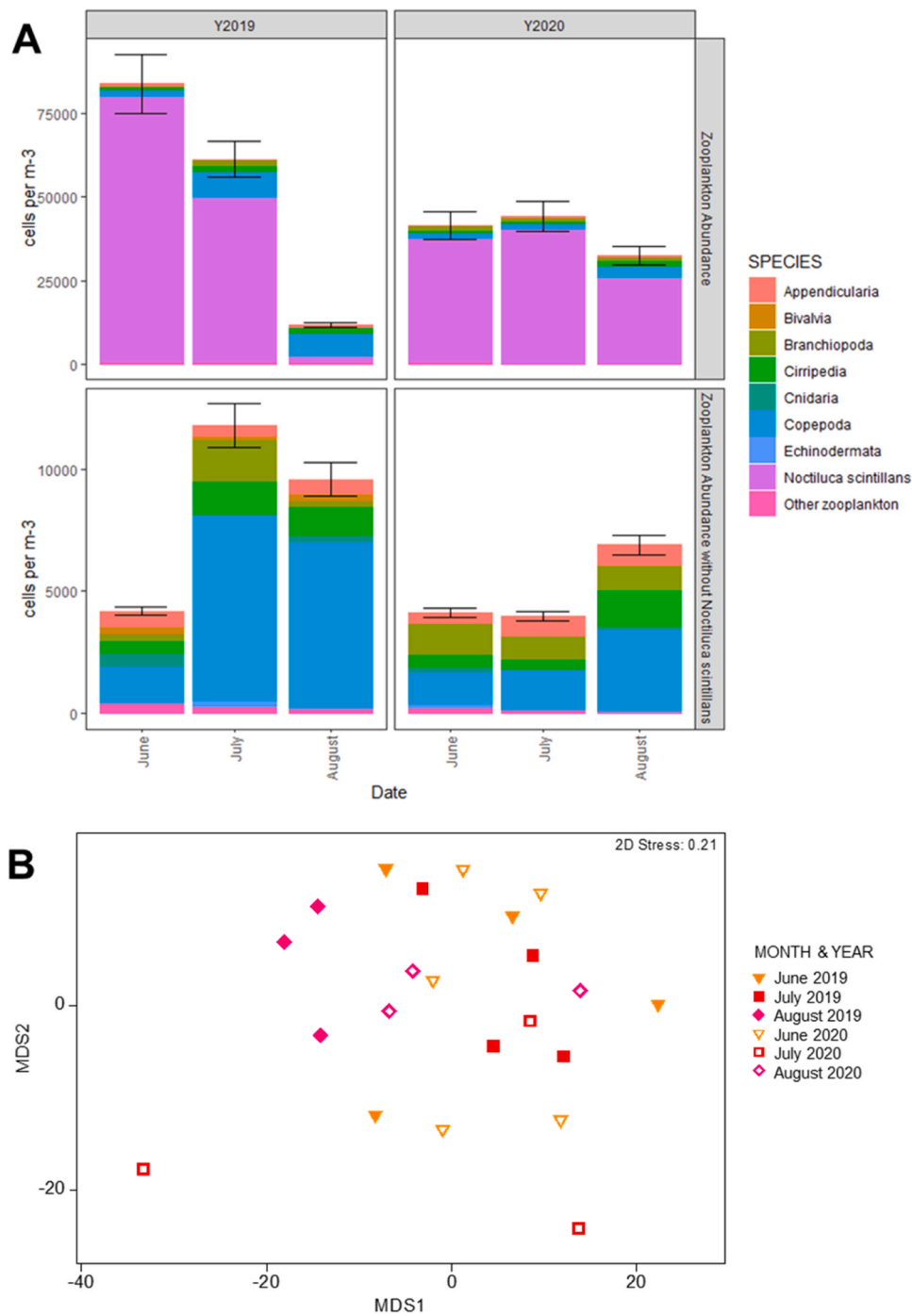


Fig. 6. A) Mean zooplankton abundance (above) and remaining zooplankton abundance with the dominant *Noctiluca scintillans* removed (below) at Station 1, at 2 m depth. Error bars represent SE of total mean zooplankton abundance per month; B) mMDS plot of zooplankton abundance between months and years ordinated based on Bray–Curtis similarity matrix with fourth-root transformations.

nutrient depletion during late spring to early summer (corresponding with maximal seaweed biomass) (Wasmund et al., 1998; Högländer et al., 2004). However, it is not known whether phytoplankton communities were affected by nutrient competition earlier in spring i.e. in April when kelp was growing and when nutrient concentrations fell. Nutrient ratios (silicate:dissolved inorganic nitrogen) in late spring and late summer were > 1, indicating that silicate (unaffected by seaweed farming) was not limiting diatom growth (Turner et al., 1998). Plankton communities tended to be dominated by dinoflagellates, including *Noctiluca scintillans*, which comprised a large proportion of plankton biomass, as previously shown in the summer for other coastal areas of

the western English Channel (Widdicombe et al., 2010; Brown et al., 2022).

Extending our monitoring time-series (beyond the summer) would not inform on the effects of farmed kelp (which are harvested in June) but would help to show if farmed mussels have a longer-term influence on local nutrient and phytoplankton dynamics (Koeve, 2001; Lazzari et al., 2012). It is worth noting that the design of the Porthallow Bay IMTA site is not optimal for the interception and regulation of water-borne nutrients, since the seaweed lines flank the west side of the site, while the tidal axis runs north-south (Fig. 1). In this situation, optimal site designs for regulation of nutrient concentrations would include

deploying seaweed lines on north and south facing edges of the IMTA site (i.e. upstream and downstream of the mussel lines).

5. Conclusions

The cultivation of seaweeds alongside shellfish in UK waters has the potential to provide significant socio-economic benefits by regulating nutrients associated with shellfish aquaculture, as well as agricultural runoff and municipal sewage discharges to estuarine and coastal areas. In Porthallow Bay, the small-scale farming of kelp (2 ha ~2000 kg of *S. latissima* and *S. polyschides*) alongside blue mussels (14 ha ~100,000 kg of *Mytilus edulis*) was shown to have no detectable effects on local nutrient concentrations and plankton dynamics. Whilst the lack of a perceptible environmental nutrient footprint is encouraging from a local (site) aquaculture licensing and management perspective, the lack of evidence of downregulation of nutrients (and coastal eutrophication) indicates that this ecosystem service is negligible for the small scale integrated multi-trophic aquaculture (IMTA) site in Porthallow Bay. Other monitoring and modelling studies in NW Europe and elsewhere indicate that nutrient regulation within aquaculture sites, including IMTAs, requires significantly higher (possibly >100 × higher) seaweed biomass than is currently present in Porthallow Bay. We assert that the Porthallow site is likely typical of other small-scale seaweed farms and IMTA sites currently being licensed in the UK.

Author statement

All work reported here has been undertaken by the authors. All data are provided in the manuscript and [Supplementary Information](#). All funding sources have been declared. There are no conflicts of interest.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.aqrep.2023.101789](https://doi.org/10.1016/j.aqrep.2023.101789).

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