UNIVERSITY OF
PLYMOUTH

A Historic Evaluation of Island Ecosystem Health:

The Influence of Environmental Parameters on Phytoplankton Abundance and Community Structure in Manx Waters

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A dissertation submitted for the degree of

Master of science in Marine Conservation

EXECUTIVE SUMMARY

This comprehensive analysis delves into the intricate interrelationships between environmental parameters and phytoplankton abundance within the Isle of Man region, representing a pioneering study in this geographical context. Key findings underscore the paramount role of temperature as a fundamental driver of diatom and dinoflagellate occurrence. Temperature emerges as a pivotal factor significantly influencing diatom ecology, while salinity, while acknowledged for its potential influence on diatom species composition, does not exhibit a significant correlation with diatom abundance.

This study reveals robust positive correlations between diatom abundance and oxygen saturation (OS) as well as soluble reactive phosphate (SRP) concentrations, highlighting the pronounced importance of oxygen and nutrient availability. Diatoms, integral components of the phytoplankton community, demonstrate a profound reliance on dissolved oxygen for respiratory processes and phosphate as an indispensable growth nutrient. These findings resonate with prior research, reinforcing the pivotal role of nutrient availability in fostering diatom proliferation.

In stark contrast, dinoflagellate abundance responds differentially to environmental factors. Elevated temperatures, in conjunction with projected increases in nutrient levels, instigate conspicuous spring and summer upswings in dinoflagellate abundance. This phenomenon hints at dynamic shifts in competition dynamics between diatoms and dinoflagellates, thereby imparting potential repercussions for the ecological equilibrium of the Irish Sea ecosystem.

In light of the empirical insights derived from this study, several prescient recommendations emerge for the purview of conservation management. These encompass diligent nutrient management strategies, informed by an ardent commitment to ameliorate nutrient pollution sources, specifically soluble reactive phosphate (SRP). Moreover, recognizing the ecological primacy of phytoplankton as a primary nutritional source for marine life, and is advocated for the integration of this awareness into comprehensive fisheries management strategies. This entails a discerning evaluation of the cascading effects of phytoplankton fluctuations on higher trophic levels, including economically valuable fish species.

Lastly, the construction of a Wastewater Treatment Plant (WwTP) at the Laxey (east) and Peel (west) sites is proposed. A WwTP, serving as a conduit for the removal and elimination of contaminants from wastewater, facilitates the conversion of wastewater into effluent suitable for reintroduction into the water cycle. Furthermore, consideration is given to augmenting the capacity of the WwTP to accommodate the needs of local populations as warranted.

In summary, this study affords invaluable insights into the intricate interplay between environmental parameters and phytoplankton communities within the Isle of Man region. These revelations carry profound implications for the ecological well-being and stability of the marine ecosystem, thereby accentuating the exigency of perpetual vigilance through ongoing monitoring and judicious management initiatives to safeguard its integrity. The ever-fluctuating nature of phytoplankton responses to evolving environmental conditions underscores the ineluctable necessity of sustained research to fortify the sanctity of Manx waters.

IMPACT SUMMARY

The marine environment confronts a diverse array of pressures, primarily driven by anthropogenic activities and the escalating impacts of climate change. Human activities have wrought considerable influence on phytoplankton communities, notably through the perturbation of nutrient balance and biodiversity loss. Overfishing and excessive exploitation of specific species disrupt the equilibrium of nutrients and the dynamics of the marine food web. As an illustrative example, the removal of large predatory fish sets the stage for an upsurge in smaller fish that feed on zooplankton, subsequently intensifying grazing pressure on phytoplankton and leading to their diminished abundance. Interactions with climate change serve to exacerbate these impacts on phytoplankton communities. The proliferation of warmer waters, ocean acidification, and shifts in ocean currents can further modify factors such as nutrient availability and light penetration, all of which are critical determinants of phytoplankton growth. Hence, it is imperative to underscore the significance of continuous monitoring of the marine environment in the Isle of man to comprehend and address the multifaceted influence of climate change within the Irish Sea. The Department of Environment, Food, and Agriculture (DEFA) steadfastly strives to safeguard and enrich the islands natural assets while upholding the core principles of environmental, economic, and social sustainability. This endeavour also aims to optimize quality of life, bolster international reputation, sustain food production, ensure energy security, and preserve outdoor amenity. DEFA is committed to routine monitoring, reporting, and maintenance of datasets encompassing a comprehensive array of environmental parameters. Among these, marine variables exhibit inherent natural fluctuations that are integral to the biological vitality of the sea. This formalised time-series initiative traces its origin back to 1904, revealing a discernible trend of escalating sea surface temperatures, with the most pronounced rate of increase discernible within the last three decades, mirroring the global pattern of rising ocean temperatures.

Long-term time-series such as the Isle of Man's database are one of the longest and most respected of various marine parameters in Europe, often used as a benchmark by which other data is compared, representing reference conditions for the Isle of Man and the wider Irish Sea. Such extensive and detailed datasets can also provide global insight into the importance of climate change, additionally providing a record of the changing state of the Irish Sea around the coastline and assisting in the differentiation between change induced by human actions and/or natural fluctuations.

The Isle of Man's marine monitoring program is in conjunction with the phytoplankton monitoring program, which started in 1995 and is of particular importance from a fisheries perspective. It fulfils a responsibility to monitor phytoplankton abundance and diversity, possibly associated with toxin production, as well as providing a statement of water quality status and offering insight into environmental change. Although the Isle of Man's database is widely respected in the science community due to its longevity and detail, this data is yet to be analysed and has not been integrated into the appropriate data platforms, such as the Plankton Lifeform Extraction Tool. Thus, creating the rationale for this dissertation investigation written in conjunction with DEFA. This dissertation will provide a comprehensive analysis of phytoplankton abundance and community assemblages in Manx waters in relation to climate change and allow Manx data to be incorporated into central databases for further examination in the greater context of phytoplankton trends in the Irish Sea.

Historic and extensive phytoplankton datasets are becoming increasingly important in informing the new generation of policy mechanisms that seek to manage the marine environment holistically. Thus, upon completion of this piece of work, DEFA can use these project findings as a historic ecosystem health assessment, using past phytoplankton data as a baseline to compare with current and ongoing data collection and analysis. Additionally, phytoplankton life forms that will be present in this project can be used as ecosystem indicators and provide insight for conservation strategies and management to achieve clean, healthy, safe, productive, and biologically diverse oceans and seas.

1) INTRODUCTION

The Isle of Man, situated in the Northern Irish Sea, covers an area of approximately 572 square kilometres (Figure 1), with is waters constituting approximately 87%, of its territory. These marine areas provide crucial ecosystems, falling within the categories of support, regulating, provisioning, and cultural, all of which benefit the Manx population (Pereira *et al*., 2005). The islands natural areas attract around 12 million visitors annually, with coastal regions being particularly popular. The Isle of Man Visitor Survey conducted in 2010 revealed that coastal areas enticed 77% of tourists, while 55% expressed a preference for inland nature locales (Canavan, 2013). Peel and Port Erin on the western side are renowned for their resort like qualities and contribute significantly to the island’s atmosphere and economy (Canavan, 2012). Tourists have articulated a strong desire to explore less-visited areas of the island, particularly its wildlife, remote landscapes ad natural beauty (Canavan, 2012). These locations hold significant meaning for residents and align with the importance of environmental conservation (Snepenger *et al*., 2007) in shaping the appeal of the region for both tourists and international visitors (Sedmak and Mihalic, 2008).

However, environmental change negatively impacts visitor numbers and recreational activities, affecting the islands economy. Climate factors are key in tourists’ destination choices, affecting travel timing and duration (Fang and Yin, 2015). Climate change impacts tourism across environmental, socio-cultural, and economic dimensions, especially in coastal and island areas (Wolf *et al*., 2021). This includes gradual changes like sea-level rise and ocean warming, as well as sudden events like flooding =, high waves, and extreme weather conditions which affect coastal areas and their associated marine attractions (Cetin, 2016).

This underscores the importance of considering public perceptions during decision-making and maintaining healthy ecosystems. Healthy ecosystems help purify water by retaining polluntants in vegetation, sediments, and soils (Lauf et al., 2014). For example, wetland habitats can reduce pollutants like phosphorus and nitrogen from agricultural runoff and sewage, lowering water processing costs (Bashar et al., 2018). Increased water quality reduces the risk of eutrophication, limits the impact on aquatic plants and organisms, and preserves the natural scenic beauty (Keeler *et al*., 2012). Conversely, poor water quality may discourage tourists from visiting the island.

Figure 1: Map of the Isle of Man showing smaller surrounding islands in relation to its location in the Irish sea (Quirk and Kimbell, 1997)

Climate change emerges as a profound influencer on marine ecosystems, particularly phytoplankton, impacting them both directly and indirectly. This is mainly exhibited through shifts in nutrient availability, temperature fluctuations, leading to associated changes in phytoplankton diversity, community structure, and temporal dynamics (Winder and Sommer, 2012). Given their pivotal role in global net primary production and climate regulation, comprehending the environmental factors underpinning shifts in species composition becomes a fundamental pursuit to forecast the repercussions of environmental changes on aquatic ecosystems across the island (Field et al., 1998).

Human activities exert both positive influences on social and economic scales on the Isle of Man, yet they also bear the potential to impede biodiversity and inflict damage on ecosystems (Chi et al., 2021). To mitigate such impacts, driven by the Manx population's reliance on their territorial waters, the notion of Island Ecosystem Health emerged, introduced by Rapport (1989). This framework posits that ecosystem health is a product of a complex interplay between natural and anthropogenic factors. The discernment between these factors affords precise identification of human-induced pressures (Harwell *et al*., 2019). Within this paradigm, the vigilant observation of the abundance and community structures of pivotal indicator species, such as phytoplankton lifeforms, becomes imperative (Peierls *et al*., 2003). Alterations in phytoplankton dynamics wield indirect repercussions on marine ecosystem services, cascading through marine food production, ecosystem health (Chassot *et al*., 2010), integrity (Jiang *et al*., 2018), and vulnerability (Jackson *et al*., 2017). Notably, anthropogenic pressures, including the network of shipping routes, bear an influence on these lifeforms (Roulet and Moore, 2006), a persistent influence established due to the reliance on ship routes for local and tourist access to the Isle of Man.

While anthropogenic pressures stand as prominent drivers of phytoplankton shifts, gaps remain within the literature concerning whether these pressures correlate and collectively precipitate concurrent impacts on phytoplankton response (Llort *et al*., 2015). This gives rise to the motivation for this dissertation investigation. The aims of this study are to (i) provide a comprehensive analysis of phytoplankton abundance in Manx waters in relation to environmental parameters, (ii) highlight human activities which had significant effects on phytoplankton abundance and (iii) strive to unravel the potential of lifeforms (diatom and dinoflagellate) as potent indicators of ecosystem health and offer conservation insight for phytoplankton lifeforms throughout the Isle of Man.

This investigation is in conjunction with The Department of Environment, Food and Agriculture (DEFA), with their trajectory marked by the development of the Marine Strategy for the Isle of Man. The Strategy's compass aligns with the realization of a comprehensive monitoring program that aspires to foster the emergence of pristine, productive, and biologically diverse waters surrounding the island.

2) METHODS

2.1 *Plankton Sampling and Analysis*

DEFA provided multiple datasets, including phytoplankton abundance by taxa, identified under light microscopy by trained technicians (from January 1995 to May 2012), biomass data (spanning January 1966 to December 2014), and environmental parameter data (ranging from February 1904 to December 2017).

Environmental data acquisition involved the use of a YSI Sonde and KOR software available at Kor Software (ysi.com). This software facilitated the seamless automatic upload of data acquired by the YSI Sonde during its deployment. The deployment process included sequential measurements taken at 37m and gradually elevated to the water's surface. Phytoplankton samples were extracted at each depth using ruttner bottles. These specialised bottles were deployed, and their closure was automated using a metal cap, effectively sealing the collected water. Subsequent to retrieval, the collected water samples underwent filtration and were transferred to testing tubes, a precautionary measure aimed at preventing potential sample entrapment during the analysis stage.

Samples were preserved with Lugol's Iodine, relying on colour changes rather than exact volumetric quantities. Two sets of phytoplankton samples were acquired for each depth, one for analysis by the APEM organisation and the other for analysis at the Isle of Man government laboratory. This approach ensured both independent validation and comprehensive data for subsequent assessment and comparison.

These datasets underwent thorough pre-processing before PLET submission (Ostle *et al*., 2021) ensuring their suitability for extracting monthly-aggregated lifeform data. The data handler was responsible for; (i) rectifying instances of "double counting," where a taxon is included in both higher and lower taxonomic groups within the same dataset, and (ii) excluding taxa that lacked records throughout the entire data collection period to prevent perceptible fluctuations in lifeform abundance due to methodological shifts.

Incorporating novel datasets into the PLET necessitates assigning AlphaID's to all taxa. Alpha diversity indices of phytoplankton are crucial for understanding trophic state variations throughout aquatic habitats (Meng et al., 2020). Following pre-processing, the data manager responsible for the PLET and the Plankton Lifeform Traits Master List manager meticulously scrutinise the submitted AlphaID's to detect any omissions or missing taxa. If missing taxa are found in the Master list, a thorough evaluation is conducted, involving expert consultations and discussions with data providers to ensure their compatibility with specific lifeforms.

A use-friendly data entry template on the PLET website simplifies accurate data input and is available for widespread use streamlining the process, enabling data handlers to format their data in matrix (wide) or list (long) format prior to submission. In this instance, matrix format was used for phytoplankton abundance, while list format was used for biomass data due to their univariate nature.

All plankton records, including those for this dissertation, were identified using light microscopy. Samples collected by DEFA undergo quality control by APEM Ltd, with results returned in two weeks. Phytoplankton abundance is calculated by multiplying sample abundance by the sampled water volume and are typically expressed as numerical values (cells) per litre.

2.2 *Plankton Lifeform Extraction Tool Functionality*

The PLET, accessible at https://www.dassh.ac.uk/lifeforms/ (Figure 2), allows users to select parameters such as time series dates, spatial area, and dataset name to generate monthly-averaged lifeform data in .csv format. This data includes sampling period, sample count, abundance classifications, and taxonomic groupings. Environmental data was then combined to create a consolidated dataset, excluding data points with significant gaps to maintain visualisation integrity and clarity.

2.3 *The Plankton Index*

The Plankton Index (PI) originated in the UK to monitor shifts in plankton communities over time and space. It is employed in the European Union Marine Strategy Framework Directive (MSFD) to achieve Good Environmental Status (GES) in European seas by tracking plankton indicators, supporting biodiversity and food web goals. Additionally, the Convention for the Protection of the Marine Environment of the North-East Atlantic (OPSAR) uses the PI within the PH1/FW5 indicator framework to assess pelagic habitat biodiversity and contribute to MSFD evaluations. In this context, the PI, along with abundance trends of individual lifeforms, helps identify factors driving plankton communities' changes and assess their impact on pelagic habitat health.

Monthly lifeform abundances were obtained from the PLET, and the PI was calculated using the PH1 PLET tool from DASSH. An Rscript available on GitHub (https://github.com/hollam2/PH1_PLET_tool) was used to compute the lifeform pairs indicator and the Kendall statistic within a specified time range encompassing all lifeforms in the dataset.

The initial six years (1995-2000) were considered the “reference period”, setting the PI assessment framework. The subsequent six years (2001-2006) formed the “comparison period”, and the distribution of lifeform-lifeform states during this period was compared to the assessment framework to measure changes. This approach aimed to ensure data consistency and answer whether plankton communities in the most recent six years differ from those in the following six years in Manx waters.

The analysis focused on the period from 1996-2006, despite data availability from 1995-2012. This choice was driven by the temporal consistency and completeness of the data during this period, ensuring robustness and reliability from examining long-term trends in phytoplankton abundance. It also enabled comparisons with previous studies and established a baseline for understanding phytoplankton dynamics over an extended timeframe. This timeframe provided a solid foundation for meaningful conclusions and informed recommendations for conservation management, emphasising its suitability for a thorough assessment of ecological dynamics in this region.

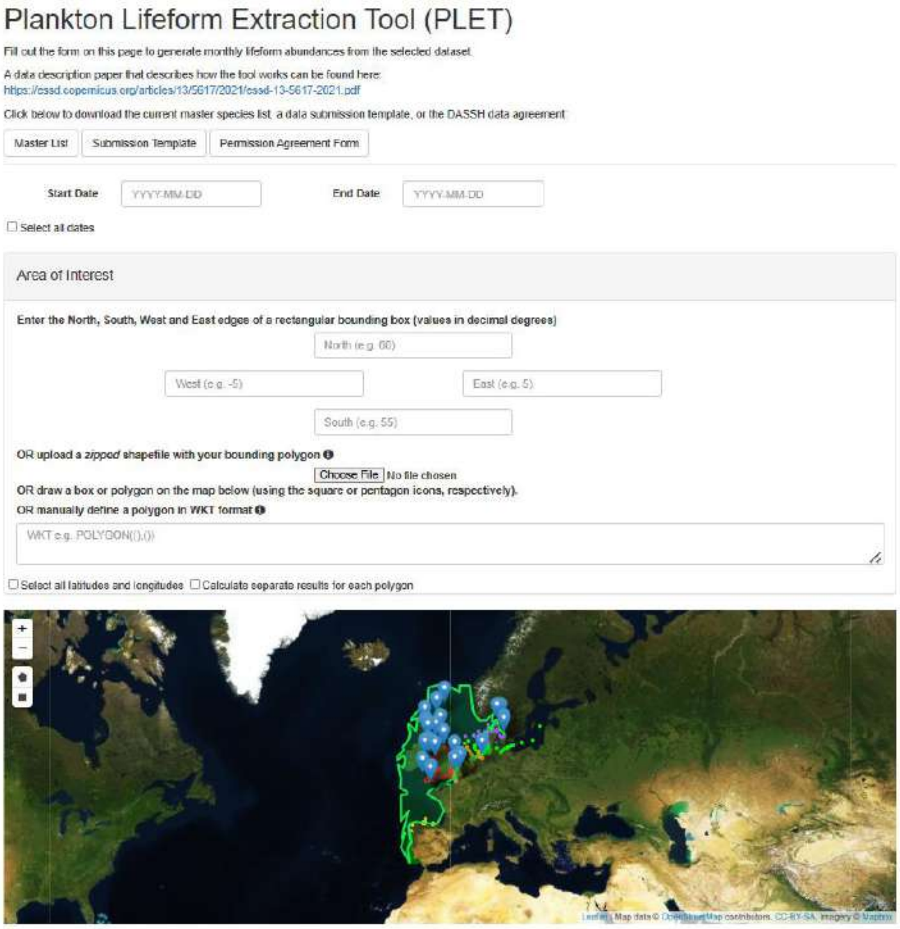
2.4 *Statistical Analysis*

All statistical analyses were conducted in Rstudio. Initial assessments of response variable normality, including diatom, dinoflagellate, and chlorophyll a, revealed significant positive skewness in the data. Anderson-Darling tests confirmed the data did not follow a normal distribution.

To address skewness, logarithmic transformations were applied to response variables. Correlation plots were generated for predictor variables such as temperature, salinity, oxygen saturation, soluble reactive phosphate, silicate, and nitrite, where a strong correlation between silicate and nitrite (correlation coefficient: 0.829) was identified. Nitrite was consequently excluded due to its low concentration and potential multicollinearity issues.

Once data preprocessing was complete, over-dispersion was observed in the data. To account for this, a negative binomial test within a generalized linear model framework was used. This approach introduced an additional parameter to model the over-dispersion.

Models were then fitted for each response variable, with log-transformation to manage data variability. The dredge function from the MuMIn package was used for stepwise variable selection using the Akaike Information Criterion (AIC) to ensure a robust and reliable analytical approach.



Plankton Lifeform Extraction Tool (PLET)

Fill out the form on this page to generate monthly lifeform abundances from the selected dataset.

A data description paper that describes how the tool works can be found here:
https://essd.copernicus.org/articles/13/5617/2021/essd-13-5617-2021.pdf

Click below to download the current master species list, a data submission template, or the DASSH data agreement

Enter the North, South, West and East edges of a rectangular bounding box (values in decimal degrees)

OR upload a *zipped* shapefile with your bounding polygon

OR draw a box or polygon on the map below (using the square or pentagon icons, respectively).

OR manually define a polygon in WKT format

Figure 2. The Plankton Lifeform Extraction Tool. A screenshot of the Plankton Lifeform Extraction Tool

3) Results

All results from lifeforms groups were analysed from samples of count per litre.

3.1 *Diatom Abundance*

The estimated coefficients provide insight into the effects of each predictor variable on the log-odds of diatom occurrence, while accounting for other variables in the model. The intercept term represents the estimated log-odds of diatom presence when all predictor variables are at mean levels. Notably, as Figure 3 shows temperature exhibited a significant negative association with diatom occurrence (Estimate: -0.36319, $p < 0.001$), indicating that a decrease in temperature was linked to an increased likelihood of diatom presence. Conversely, elevated concentrations of oxygen saturation (OS) were positively associated with diatom occurrence (Estimate: 0.08277, $p < 0.001$), as were higher levels of soluble reactive phosphorus (SRP) (Estimate: 0.74177, $p = 0.015$). Similarly, reduced concentrations of silicate were significantly associated with a decline in the likelihood of diatom presence (Estimate: -0.69259, $p < 0.001$). While salinity concentrations were included as a predictor variable, their effect on diatom abundance was not statistically significant ($p > 0.05$).

3.2 *Dinoflagellate Abundance*

The intercept term (-31.90433) represents the baseline log-odds of the phenomenon occurring when all predictors are at mean level suggesting a reduced likelihood under these circumstances. Figure 4 is showing that temperature emerges as a significant driver, displaying a positive association with the phenomenon's occurrence (Estimate: 0.39647, $p < 0.001$). A temperature increase corresponds to a notable 40% rise in the log-odds, emphasizing the sensitivity of the phenomenon to temperature fluctuations. Salinity's positive impact (Estimate: 0.81629, $p = 0.046501$) indicates a heightened likelihood with elevated salinity levels, although to a lesser extent than temperature. Oxygen saturation (OS) significantly contributes to dinoflagellate’s occurrence (Estimate: 0.06209, $p = 0.000304$), highlighting its influence in fostering favourable conditions. Soluble reactive phosphorus (SRP) concentration emerges as a pivotal factor (Estimate: 1.02273, $p = 0.000609$), underlining its substantial role in enhancing the likelihood of Dinoflagellate abundance. Conversely, silicate concentrations (Estimate: -0.04960, $p = 0.512269$) exhibit either minimal or limited influence.

3.3 *Chlorophyll a*

The intercept term (-0.06225) denotes the baseline log-odds of the phenomenon's occurrence when all predictor variables are held at mean level. With a p-value of 0.9961, the intercept does not attain statistical significance, implying a relatively neutral starting point. As shown in Figure 5, temperature exhibits a non-significant negative relationship (Estimate: -0.07689, $p = 0.1155$), suggesting that temperature variations may not substantially impact likelihood. Similarly, salinity shows a non-significant effect on the log-odds (Estimate: -0.01160, $p = 0.9753$), implying that salinity variations may not significantly sway occurrence. Oxygen saturation concentrations (OS) likewise displays a non-significant positive association (Estimate: 0.01636, $p = 0.2789$), implying that OS may not be a major driving factor of abundance. Soluble reactive phosphorus (SRP) concentration does not emerge as a significant influencer (Estimate: -0.26958, $p = 0.4557$), indicating that SRP may not strongly impact the log-odds of the abundance. Conversely, silicate concentrations emerge as a notable negative influencer (Estimate: -0.18769, $p = 0.0122$), suggesting that reduced silicate levels correspond to an increased likelihood of presence.

3.4 *Plankton Index*

In this analysis, Figure 7 is showing annual abundance patterns which revealed distinct peaks each year, with dinoflagellates consistently peaking in late summer. Kendall statistics and associated p-values were used to assess trends over time. For diatoms (p=0.35) and dinoflagellates (p=0.533), p-values exceeded 0.05, indicating no significant abundance changes over time. Diatom abundances increased from March to August visually, but no statistically significant change was detected when assessing average abundance over time.

Overall, the analysis suggests no significant annual abundance changes for both lifeforms, despite seasonal variations. The Plankton Index (PI) value of 0.54 indicates 54% of months in the comparison period had consistent abundance trends.

Figure 6 shows year-wise execution of the Rscript for specific year-to-year comparisons. Similarity percentages were observed: 67% for 1995 vs. 2001, 1995 vs. 2003, and 1995 vs. 2005; 50% for 2002 vs. 2004; and 25% for 2006 vs. other years. This tailored analysis approach provided insights into temporal dataset dynamics and similarity between different years.

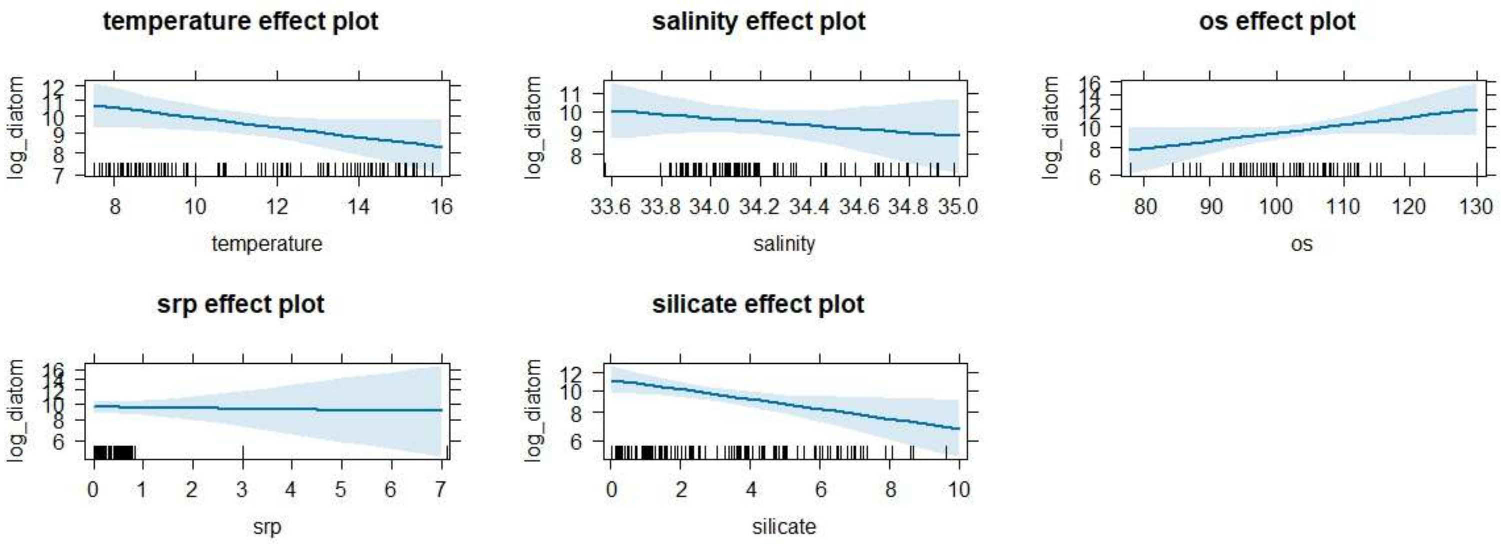


Figure 3. Log transformed Diatom abundance. Each environmental parameter analysed against diatom abundance over the time-series (1995-2012)

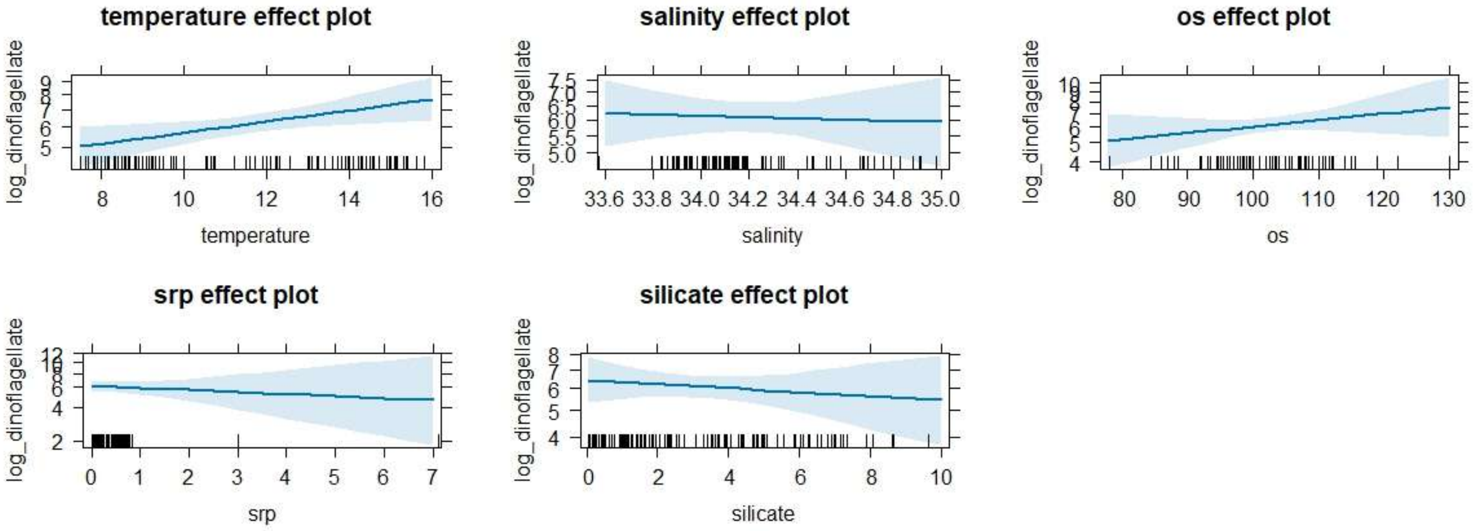


Figure 4. Log transformed Dinoflagellate abundance. Each environmental parameter analysed against dinoflagellate abundance over the time-series (1995-2012)

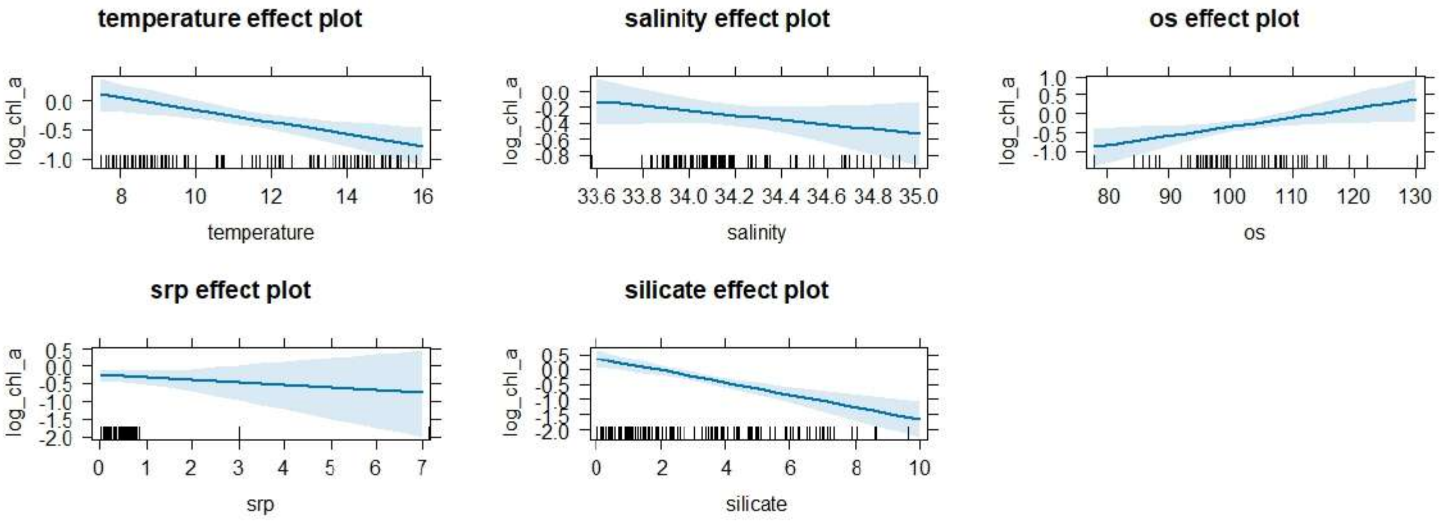


Figure 5. Log transformed Chlorophyll-a abundance. Each environmental parameter analysed against chlorophyll-a abundance over the time-series (1995-2012)

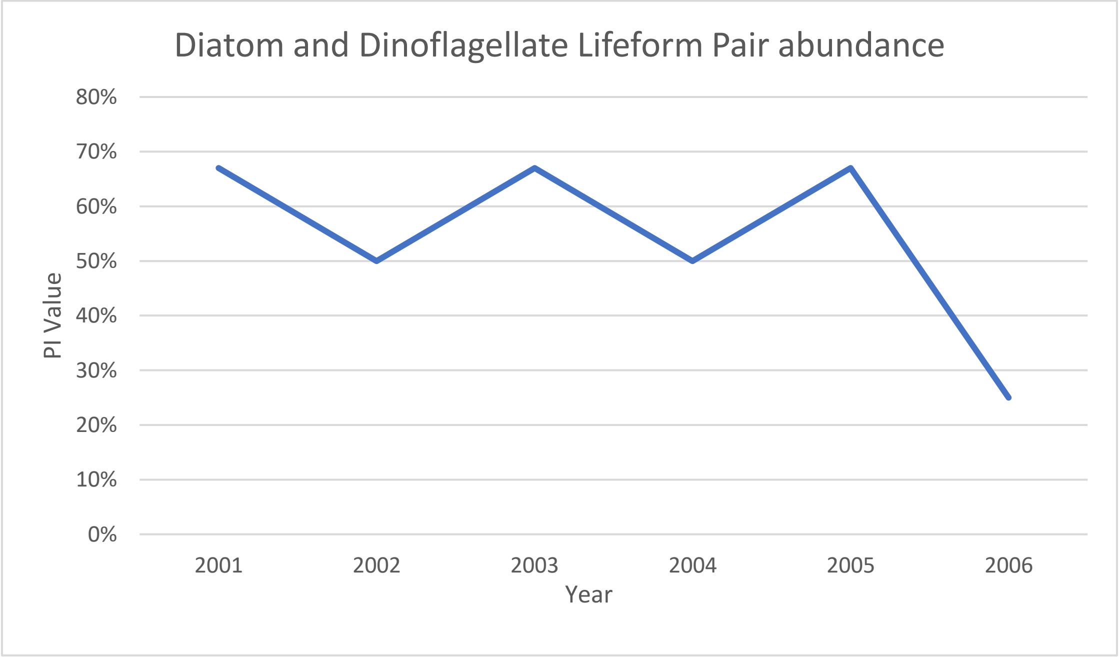


Figure 6. Diatom and Dinoflagellate lifeform pair abundance. Data for comparison periods have been compared and years have been analysed individually. The percentages show similarities of PI values when data was compared between the 1995 and 2000 reference conditions.

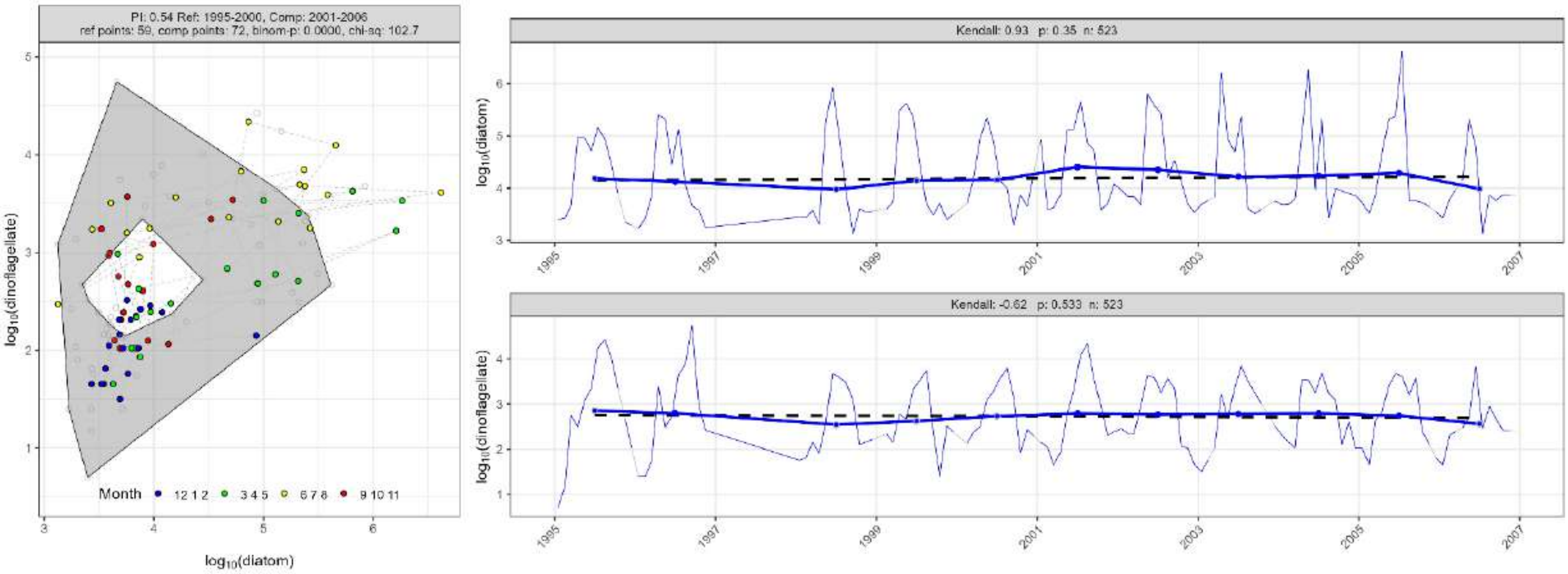


Figure 7. Time-series for Diatom and Dinoflagellate abundance.

Right- Showing annual peaks or declines in abundance through time showing Kenndall statistic and P value indicating if abundances have increased or decreased over time.

Left- X-axis shows dinoflagellate abundance and Y-axis shows diatom abundance with all coloured dots displaying a month.

4) Discussion

This study marks the first-ever comprehensive analysis of phytoplankton and environmental parameters in the Isle of Man region. These findings highlight the intricate relationships between environmental factors and phytoplankton abundance. Temperature significantly influences diatom and dinoflagellate abundance, revealing their sensitivity to temperature variations and the complexity of their responses to changing conditions. Additionally, oxygen saturation (OS) and soluble reactive phosphate (SRP) concentrations are associated with increased abundances of both diatoms and dinoflagellates, emphasizing the importance of oxygen and nutrient availability. Silicate strongly correlates with diatom abundance but does not impact dinoflagellates, highlighting their distinct requirements. Salinity notably affects dinoflagellate abundance, while its link with diatom abundance lacks statistical significance. Surprisingly, chlorophyll-a levels remain unaffected by the analysed environmental factors, suggesting other factors drive chlorophyll-a concentrations in this specific ecosystem.

4.1 Diatom Abundance

The intricate factors governing diatom abundance and distribution in natural ecosystems are multifaceted, often characterised by intercorrelations among major variables (Dalu *et al*., 2022). The observation of a negative correlation between temperature and diatom abundance aligns with existing literature, which magnifies the significance of temperature in diatom ecology (Adams *et al*., 2013). Diatoms' proclivity for cooler waters find supports in the combined influence of temperature and nutrient availability, as cooler waters typically harbour higher nutrient concentrations, facilitated by vertical nutrient mixing from deeper ocean layers. Furthermore, because of their elevated growth rates in cooler environments, this provides them with a competitive edge when compared to non-siliceous algae, which often thrive in warmer conditions (Mancuso *et al*., 2021). This supports the results of this study revealing the 40% increase of dinoflagellates when temperature increases. Seasonal dynamics further underscore diatom prevalence, with peaks typically occurring during cooler seasons like spring, as illustrated in figure 7. Thus, being commonly described as “coldwater flora” (Anderson, 2000). Although, nutrient was not a considered predictor variable, the assumption can be made that this observation may be associated with, though not exclusively caused by, sewage discharge. Marella *et al*., (2020) estimated that approximately 0.9 million litres of human waste are discharged into Peel Bay daily. However, the introduction of the innovative sewage approach represented by the IRIS scheme (2001), which surpasses European Commission guidelines on urban wastewater treatment, has limited the Isle of Man's impact on territorial waters. In contrast, densely populated neighbouring regions such as Liverpool Bay, have a more significant influence on nutrient inputs due to factors like industrial activities, stormwater run-off, port operations, urban growth, and shipping traffic (Howarth *et al*., 2007).

While it is observed that thriving diatoms may display temperature independence, it is crucial to acknowledge that changes in their abundance can yield valuable insights into a broader spectrum of climatic factors, extending beyond temperature (Wu *et al*., 2022). While the statistical analysis in this study did not find a significant association between salinity and diatom abundance, it is worth noting that existing literature suggests that salinity can strongly influence the composition of diatom species (Aida Campos *et al*., 2021). In a study conducted by Frost *et al*., 2023, it was demonstrated that salinity treatments had a pronounced impact on diatom communities, resulting in reduced diatom abundance and functional diversity.

Diatoms, as a group, exhibit specific salinity preferences, with their abundance typically peaking within the salinity range of 5-35 parts per thousand (ppt) (Bauch and Polyakova, 2003). In the present study, the observed salinity ranged from 33.57 to 34.97 ppt. Consequently, the magnitude of salinity variation may not have been substantial enough to drive a significant alteration in diatom abundance. Furthermore, it is important to consider that diatom species exhibit varying degrees of tolerance to salinity fluctuations (Stenger-Kovacs *et al*., 2023). For instance, euryhaline diatoms have evolved to thrive across a wide range of salinity levels, encompassing both lower and higher conditions, whereas stenohaline diatoms are more sensitive to salinity fluctuations and are typically found in more stable environments (Mukherjee *et al*., 2015). Thus, although the specific types of diatoms were not a focal point of this analysis, it can be inferred that stenohaline diatoms are likely more prevalent across the Isle of Man, owing to the relatively limited variation in salinity levels. However, it is essential to acknowledge that this conclusion is contingent upon numerous factors, including local environmental dynamics, seasonal variations, and resource availability, such as nutrients and light (Riotte-Lambert and Matthiopoulos, 2020).

To obtain a more precise assessment of the diatom community, a comprehensive analysis that includes species identification and quantification would be necessary. Additionally, variations in diatom tolerance observed across different studies may arise from complex interactions involving co-varying chemical stressors or biological factors inherent in aquatic ecosystems (Sagova-Mareckova *et al*., 2021). Recent studies have also proposed that diatom tolerances are predominantly shaped by adaptations to local water quality rather than adherence to niche conservatism (the retention of ancestral traits) (Virtanen *et al*., 2011), underscoring the potential for responses to vary across aquatic systems worldwide.

In addition, this analysis reveals a consistent and significant correlation between higher levels of OS and SRP and increased diatom abundance. This observed link aligns with the physiological requirements of diatoms, which heavily rely on dissolved oxygen for respiration and their need for phosphate as a fundamental nutrient for their growth and photosynthetic processes (Prelle *et al*., 2019). The findings are consistent with previous studies that have emphasized the importance of nutrient availability, including SRP, in promoting diatom proliferation (Dong *et al*., 2011). Moreover, the correlation with OS highlights the relevance of oxygen supply in supporting the metabolic needs of diatoms (Benoiston *et al*., 2017). This suggests that the Irish Sea ecosystem may be sensitive to changes in nutrient input and oxygen levels, with potential implications for the entire marine food web and carbon cycling dynamics.

However, it's important to acknowledge potential limitations of this study. While our results show a strong statistical correlation, causation cannot be definitively established from this observational data. Further research, including experimental manipulations and modelling, is needed to elucidate the precise mechanisms driving diatom responses to changes in OS and SRP. Additionally, other factors such as light availability, water temperature, and predation pressures may also play a role in shaping diatom abundance in the Irish Sea, and their interactions warrant further investigation (Zhang *et al*., 2018). Nonetheless, the significance of nutrient and oxygen levels in regulating diatom populations underscores the need for continued monitoring and management efforts to ensure the health and stability of this vital marine ecosystem.

Silicate, an indispensable component for diatoms, plays a pivotal role in their growth and reproductive processes (Koester *et al*., 2016). Over this time-series, silicate concentrations exhibited irregular fluctuations, showing no consistent trend. These variations are likely attributed to the use of silicate from diatoms (Downing *et al*., 2016), which constituted the predominant phytoplankton group in this study. During periods of silicate deficiency, diatoms could have gone unnoticed, exhibiting disfigured and discoloured cells with impaired valve formation and metabolic processes (Yang *et al*., 2004). Conversely, increases in silicate levels were observed, potentially linked to rainfall events, as the Isle of Man doesn’t experience extreme seasonal transitions (Tian *et al*., 2012). Frequently, silicate concentrations fell below 2µm/L threshold, commonly considered as inhibitory for diatom growth (Eliasen *et al*., 2017). For instance, in August 2003, silicate concentrations plummeted to a mere 0.07µm/L. While this study does not delve into species-specific levels, this suggests a potential shift in the phytoplankton community, favouring smaller diatoms and other diminutive algal species (Fuchs and Franks, 2010). This variability in silicate thresholds highlights the diversity among diatom species in their sensitivity to silicate concentrations (Shi *et al*., 2015).

4.2 Dinoflagellate Abundance

The observed conflicting effect of temperature on dinoflagellate abundance compared to diatoms is consistent with findings from other studies in this field. Bi *et al*. (2021) investigated the response of diatom and dinoflagellate competition to various environmental factors. Similarly, they established that a shift back towards dinoflagellate competitive superiority occurred only at the highest temperatures and the highest nitrate concentrations, which aligns with prevalent findings in other studies (Malone, 1992; Xie *et al*., 2015). In line with our study, Bi *et al*. demonstrated that elevated temperatures, combined with increased nutrient levels, result in spring and summer increases in dinoflagellate abundances and, in some cases, blooms. Although this study did not confirm the occurrence of blooms throughout the time-series, Figure 7 illustrates that dinoflagellates consistently peak in abundance during the summer each year. This phenomenon can be attributed to the shift back towards dinoflagellate competitive superiority at higher temperatures (Hinder *et al*., 2012). While the annual mean temperatures of the Irish Sea do not exhibit significant fluctuations, we observed temperature increases, with the highest reaching 15.8°C. Although this is considered average for the region, it still demonstrates shifts in competition dynamics between these two lifeforms. Nitrate concentrations are also a crucial factor influencing dinoflagellate abundance and competitive dominance. Therefore, future studies in this area should consider nitrate concentrations as a contributing factor to explore further.

We are already aware that high temperatures and salinity are favourable for dinoflagellate growth, as well as diatoms (Roshith *et al*., 2018). Yoo (1991) reported that changes in salinity cause variations in the abundance and composition of dinoflagellates. When salinity levels are less than 15 psu, low euryhaline species are highly abundant, whereas highly euryhaline species are abundant when levels are between 156-30 psu, and stenohaline species are abundance when levels are >30 psu. In this study, salinity levels ranged from 33.5 to 34.9 psu; thus, we can assume this study area is highly abundant with stenohaline species. Initially, it was presumed that this region holds low diversity and does not have a thriving assemblage of dinoflagellates subject to salinity. However, because these salinity levels have a narrow range, it does not necessarily mean the region lacks diversity in terms of biology and ecology. Thus, future studies should delve deeper into specific species of stenohaline dinoflagellates, as they may hold genetic, species, or functional diversity (Murray *et al*., 2016).

This study has identified a significant influence of OS on the distribution and prevalence of dinoflagellate occurrence within the Irish Sea. This association can be attributed to several distinctive factors. Firstly, the Irish Sea exhibits dynamic water masses influenced by both Atlantic and Celtic Sea waters, resulting in spatial variations in oxygen content (Fernand *et al*., 2006). For example, coastal regions often register lower OS due to nutrient-rich terrestrial inputs, thereby fostering dinoflagellate proliferation (Signoret *et al*., 2006). Furthermore, seasonal stratification of water layers leads to the formation of oxygen-depletion zones in deeper layers, promoting the dominance of dinoflagellate species adapted to low-oxygen concentrations (Pitcher and Probyn, 2011). In February 2004, a significant decline in OS (78%) was observed, likely due to such seasonal stratification. It can be further inferred that *Gymnodinium catenatum*, a well-known dinoflagellate species in the Irish Sea, is present in this region particularly at this time and may also be responsible for the dinoflagellate abundance increase throughout summer months (Figure 7). Conversely, during most of the observed time-series, OS concentrations remained high, with the highest recorded at 115.5% in June 2005 and May 2008. Elevated OS concentrations in the Irish Sea can profoundly impact dinoflagellate species within this marine ecosystem (Okolodkov *et al*., 2007). While oxygen is vital for their metabolic processes, excessively high levels can disrupt dinoflagellate communities (Osma *et al*., 2016). These microorganisms, have evolved to specific environmental conditions, including optimal oxygen ranges (Hermoso *et al*., 2014). Excessive oxygen can potentially displace dinoflagellates adapted to lower oxygen environments, resulting in shifts in species composition (Persson and Smith, 2022). Moreover, elevated oxygen concentrations may arise from increased primary productivity, potentially stimulating the growth of competing phytoplankton species (Duffy and Stachowicz, 2006). Therefore, although OS is a critical factor, extreme elevations beyond the dinoflagellate' adapted range can introduce ecological complexities and impact the dynamics of these organisms within the Irish Sea (Dale, 2009).

Observed SRP fluctuations during this study, ranging from a low 0.005 µm(P) in June 2002 to a peak of 7.13 µm(P) in February 2012, offer insight into dinoflagellate population dynamics. This relationship reflects dinoflagellates' preference for phosphorus-rich environments, where SRP serves as a vital nutrient for growth (Dyhrman and Ruttenberg, 2006). Elevated SRP levels often accompany heightened primary productivity, fostering dinoflagellate thriving (Davi *et al*., 2019). Such high SRP levels may result from various human activities, including sewage and wastewater discharge containing high phosphorus compounds, contributing to nutrient enrichment and algal blooms (Jarvie *et al*., 2006). This may have been the cause behind the peak of SRP in June 2012, as also observed by La Jeunesse and Elliot (2004). Despite potential ecological consequences like harmful algal blooms, dinoflagellates demonstrate adaptability to shifting conditions and nutrient-rich habitats (Hallegraeff, 2010). Low SRP levels, which are largely found throughout this time-series, may occur naturally or due to factors like sedimentation and nutrient management, which the Isle of Man carries out through continuous data collection. Low SRP levels can impact primary production and marine food webs (Piroddi *et al*., 2021). In response to low SRP levels, dinoflagellates adapt growth rates, compete with other phytoplankton, employ nutrient storage, alter cell morphology, and may even produce toxins, demonstrating their adaptability in nutrient-limited environments (Li *et al*., 2015).

Contrary to findings suggesting that higher silicate concentrations correspond to increased diatom abundance, this study reveals that silicate had no discernible effect on dinoflagellates. This result can be attributed to the distinct reliance of diatoms on silicate, as it serves as a vital component in the formation of their cell walls composed of silica (Leblanc *et al.,* 2015). Consequently, diatoms exhibit an enhanced growth strategy and competitive advantage over other phytoplankton groups (Bothwell, 1988).

Although this investigation found no significant impact of silicate on dinoflagellates, it observed an increase in dinoflagellate abundance during the summer months (Figure 7). This trend persisted despite annual decreases in silicate concentrations from May to August. Comparable findings were reported by Kelly-Gerreyn *et al*., (2004) who modelled phytoplankton communities in the Irish Sea. Their models demonstrated that when silicate availability is reduced in summer months, diatom biomass decreases, allowing non-diatom species to outcompete diatoms for ammonium due to differences in growth rates between these groups (Dippner, 1998).

Furthermore, following the peak in dinoflagellate abundance during the summer, there was a subsequent decline in abundance. This decline may be attributed to increased grazing pressure on non-diatoms during the summer season, with non-diatoms experiencing extended growth at the expense of diatoms (Kelly-Gerreyn *et al*., 2004).

Additionally, the 2004 study found that reducing mesozooplankton grazing led to an increase in the biomass of microzooplankton. Consequently, the altered feeding habits of microzooplankton resulted in increased consumption of non-diatom lifeforms. This disrupted the competitive balance, allowing diatoms to maintain an advantage over non-diatoms despite their growth being controlled by silicate concentrations. This likely accounts for the observed lower decrease in dinoflagellate abundance in winter months compared to diatoms in this current study.

4.3 Chlorophyll-a Abundance

In this study, it was observed that among the five environmental parameters examined-temperature, salinity, OS, SRP, and silicate-only silicate appeared to have a significant effect. Salinity and temperature are key environmental qualities for the physical structure of aquatic structures, influencing phytoplankton communities, of which chlorophyll-a serves as a proxy (Shaha *et al.,* 2022). A study by Shaha *et al*., (2022) found a positive correlation between salinity and temperature with chlorophyll-a, which contradicts the findings of this current study. Several factors can explain this discrepancy. Firstly, these phytoplankton groups are sensitive to changes in nutrient availability, such as nitrate, phosphate, and silicate, which are vital for their growth (Julie *et al*, 2010). If nutrient availability is the primary limiting factor for diatoms and dinoflagellates, alterations in temperature and salinity can indirectly influence their abundance without directly affecting chlorophyll-a levels (Lane *et al*., 2007). Additionally, diatoms and dinoflagellates consist of diverse species, each with distinct responses to environmental variations (Peltomaa *et al*., 2019). Some species may be more responsive to temperature and salinity fluctuations, leading to shifts in their relative abundance, which, in turn, affect the overall phytoplankton community composition (von Scheibner *et al*., 2013). Trophic interactions, like zooplankton grazing preferences, can also play a role by selectively impacting one phytoplankton group over the other in response to environmental changes (Campbell *et al*., 2009). Phytoplankton communities possess adaptive and resilient traits, allowing them to maintain stable chlorophyll-a levels despite fluctuations in diatom and dinoflagellate populations (Chan *et al*., 2021).

5) Recommendations

Considering the findings from this study of phytoplankton in Manx waters, several key recommendations emerge for conservation management. Firstly, nutrient management should be prioritized, focusing on mitigating nutrient pollution sources like SRP and collaborating with neighbouring regions (Liverpool) to address these issues. Secondly, sustainable fisheries management is key to acknowledge the ecological significance of phytoplankton as a primary food source for marine life and incorporate this awareness into fisheries management strategies, considering the potential ripple effects of phytoplankton variations on higher trophic levels, including economically valuable fish species. Lastly, it is an important recommendation that a wastewater treatment plant (WwTP) is constructed for the Laxey (east) and Peel (west) sites. A WwTP is a process which removes and eliminates contaminants from wastewater and converts this into effluent that can be returned to the water cycle. WwTP'S can be further upgraded by providing a comprehensive secondary treatment scheme for these specific sites, while expanding its capacity to cater for town populations if necessary. Bedri *et al*., 2015 investigated the impacts on water quality from introducing a pipeline and holding tank to convey sewage across towns in Ireland. The results found E. coli distributions at the water's surface were extremely high across bathing waters prior to implementation. However, after implementation E. coli concentrations significantly depleted and water quality improved to “Excellent” under the Urban Wastewater Treatment Directive 91/271/EEC and the Bathing Water Directives 76/160/EEC and 2006/7/EC.

6) Conclusion

This analysis of phytoplankton and environmental parameters in the Isle of Man region has shed light on the intricate relationships between environmental factors and phytoplankton abundance. These findings emphasize the sensitivity of diatoms and dinoflagellates to temperature variations, with temperature emerging as a significant driver of their occurrence. While temperature plays a crucial role in diatom ecology, there was no significant associations between salinity and diatom abundance. However, it is essential to consider the potential influence of salinity on diatom species composition.

OS and SRP concentrations were found to be positively associated with diatom abundance, highlighting the importance of oxygen and nutrient availability. Diatoms rely heavily on dissolved oxygen for respiration and phosphate as a fundamental nutrient for growth and photosynthesis. These results are consistent with previous studies emphasizing the role of nutrient availability in promoting diatom proliferation.

In contrast, dinoflagellate abundance exhibited a different response to environmental factors. Elevated temperatures, in conjunction with predicted increased nutrient levels, were associated with spring and summer increases in abundance. These findings suggest a shift in competition dynamics between diatoms and dinoflagellates, with potential implications for the Irish Sea.

In conclusion, this study contributes valuable insights into the complex interactions between environmental parameters and phytoplankton communities in the Isle of Man region. These findings have implications for the ecological health and stability of this marine ecosystem, highlighting the need for continued monitoring and management efforts to ensure its security. The dynamic nature of phytoplankton responses to changing environmental conditions magnifies the importance of ongoing research to safeguard the integrity of Manx waters.

Word Count: 5,729

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