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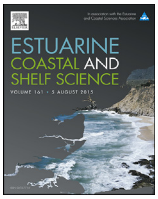

Structure of late summer phytoplankton community in the Firth of Lorn (Scotland) using microscopy and HPLC-CHEMTAX

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ABSTRACT

The Firth of Lorn is at the mouth of one of Scotland's largest fjordic sea lochs, Loch Linnhe. This sea loch, which is fed by a number of other inner lochs, supplies a significant flow of freshwater, which frequently causes the stratification of the water column. To investigate how environmental conditions influence the spatial distribution of phytoplankton in this region water samples were collected for phytoplankton (pigments and microscopy), and other environmental variables including nutrients. Chemotaxonomy was used to estimate the contribution of different taxonomic groups to total chlorophyll *a* (phytoplankton biomass index). Good agreement was obtained between chemotaxonomy and microscopy data. The highest levels of chlorophyll *a* (~2.6 mg m^{-3}) were found in the vicinity of Oban Bay, where cryptophytes, the most abundant group, dinoflagellates and other flagellates thrived in the stratified water column. Centric diatoms, mainly *Chaetoceros* sp. and *Skeletonema costatum*, were associated with NH_4 and SiO_2 concentrations and stratification, while pennate diatoms, mainly *Cylindrotheca* sp. and *Nitzchia* sp., were found to be associated with $NO_3 + NO_2$ and high surface mixed layer depths. Four diatom groups were identified in accordance to their surface to volume ratios, as well as their affinity to environmental parameters (nutrients) and turbulence. This study used a combination of physico-chemical data, classical microscopy methods (appropriate for large cells > 20 μm) and HPLC-CHEMTAX approaches (for large and small cells) to evaluate the distribution of phytoplankton functional groups in a fjordic coastal area.

1. Introduction

The Scottish west coast is characterised by the typical morphological, physical and hydrodynamic properties observed in other fjordic systems around the world. Sea lochs are narrow arms of sea with long, deep, steep-sided glacially carved basins that project into coastal land masses. They possess fjordic characteristics of a shallow sill that limits the horizontal exchange of water with the open ocean. Due to their large catchment areas, freshwater input to the coastal environment from fjords is commonly significant.

Fjords are typically characterised by a low salinity surface layer and dense deep water that may become isolated due to the presence of shallow sills. Deep water can be stagnant, mixing with surface water throught diffusive vertical mixing during episodic renewal events (Austin and Inall, 2002). When wind conditions are favourable and freshwater input into the loch is low, flooding tidal saline water flows over the sill(s) and sinks to the bottom due to its higher density (Gade and Edwards, 1980; Geyer and Cannon, 1982). The pre-existing freshwater is lifted up and flushed away. If renewal events are not frequent, deep water will accumulate for several months or sometimes years and will have oxygen depletion and enhanced nutrient levels (e.g. Gade and Edwards, 1980; Edwards and Grantham, 1986).

The existence of aquaculture farms may emphasize bottom oxygen reduction and nutrient increase, if flushing is not recurrent. Nutrients in surface waters vary seasonally, peaking in the winter months, and decreasing post spring bloom (Lønborg et al., 2009, Fehling et al., 2006) following seasonal salinity stratification. While eutrophication symptoms have been occasionally reported

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in the past in some lochs (e.g. Edwards and Grantham, 1986) and enhanced growth of macroalgae adjacent to aquaculture units can occur (Sanderson et al., 2012), there area is minimally anthropogenically impacted in terms of nutrient enrichment (Davidson et al., 2014).

Atlantic fjordic systems, such as the Scottish lochs are frequently subject to unstable weather conditions, given that wind strength and direction, precipitation and tides may vary substantially during short periods (Gaard et al., 2011). Such conditions may modify nutrient concentrations and have direct consequences in terms of phytoplankton biomass, leading to an increase or decrease in primary production due to rapid changes in oceanographic conditions (e.g. mixed layer depth, stratification). Changes in the stratification, light and turbulence conditions of the region may also have implications for community structure, favouring some phytoplankton groups over others (e.g. Margalef, 1978; Jones and Gowen, 1990), although these relationships are still poorly understood. Furthermore, tidal velocity and both wind intensity and direction may affect the structure and dynamics of the water column, which can determine the spatial pattern of phytoplankton distribution (Jones and Gowen, 1990).

Margalef's Mandala indicates that diatoms dominate in periods of high turbulance and nutrient concentrations (r-strategy) and dinoflagellates favouring more stratified and oligotrophic conditions (K-strategy; Margalef, 1978). This theory improved our understanding of phytoplankton dynamics. However, as discussed by Smayda and Reynolds (2001), the degree of vertical, micro-habitat structural differentiation that the turbulance axis allows, is also thought to be significant. There are several implications of this model compared to what has been previously proposed by Margalef (for details see Reynolds, 1988, 1996; 1997).

One of the innovations of Reynolds' approach is the identification of three primary adaptative strategies (C-S-R) rather than two (r-K). One of those strategies is characterised by small, r-selected, fast-growing, invasive, with high surface to volume ratio (S/V) colonist (C) species. These species are expected to dominate in stratified waters with high nutrient and light levels and would be susceptible to grazing (Alves-de-Souza et al., 2008). S species would be composed of large, with low S/V, slow-growing, K-selected, nutrient-stress tolerant organisms (Smayda and Reynolds, 2003). These species would dominate in high light, oligotrophic conditions and obtain their nutrients by mixotrophy or vertical migration (Alves-de-Souza et al., 2008). The R species would be the elongated but with high S/V ratio, light-harvesting, attuning, disturbance-tolerante ruderal species (Smayda and Reynolds, 2003). These species can harvest light under mixing conditions, with high nutrient concentrations (Alves-de-Souza et al., 2008).

Alves-de-Souza et al. (2008) presented one of the first applications of Reynolds' model to marine planktonic diatoms. They identified three diatom groups: D1, with S/V $> 1.5\ \mu m^{-1}$ and composed of taxa such as *Pseudo-nitzschia, Cylindrotheca* and *Leptocylindrus* that were mainly correlated with nitrate; D2, with S/V ~1 μm^{-1} and composed of several species of the genus *Chaetoceros*, also correlated with nitrate; and D3 with S/V between 0.5 and 0.8 μm^{-1} and composed of *Skeletonema, Talassionema* and *Rhizosolenia setigera* that were correlated with stratified conditions and high silicate concentrations.

In this study, we analysed phytoplankton data collected from the Firth of Lorn, in Western Scotland in order to: 1) evaluate the spatial distribution of the late summer phytoplankton community after a strong-wind event; 2) validate the chemotaxonomical approach to evaluate small phytoflagellates in this study region; 3) investigate the response of the phytoplankton community to physico-chemical parameters; and 4) provide insights regarding functional types in marine phytoplankton assemblages. Knowledge of how environmental conditions influence the spatial distribution of phytoplankton functional groups in sea-lochs is scarce. The phytoplankton community of the Firth of Lorn or adjacent sea lochs has been studied previously (Fehling et al., 2006 and references therein), however, these analyses typically concentrate on larger cells. Here, we combine the use of classical microscopy methods (appropriate for large cells) with novel HPLC-CHEMTAX approaches (for large and small cells) to evaluate the whole phytoplankton community. Environmental data were used to evaluate distribution of functional groups and to set the basis for future studies on phytoplankton temporal and spatial variability.

2. Methodology

2.1. Study site

The Firth of Lorn, in western Scotland, is at the mouth of one of Scotland's largest fjordic sea lochs, Loch Linnhe (Fig. 1). Loch Linnhe, which is fed by a number of other inner lochs, supplies a significant flow of freshwater to the coastal zone, which generally causes the stratification of the water column. The Firth of Lorn has a large variation in bathymetry and currents. Generally, net movement of seawater is northerly (Adams et al., 2014) and low salinity waters tend to run on the top of the water column due to their lower density. Tidal flows through the Sound of Luing and the Gulf of Corryvreckan, as well as its extension westwards named Great Race, are important currents that are well documented (e.g. Dale et al., 2011). These flows may have a turbulent nature and contribute to the high dispersion of particles.

2.2. Field campaign and environmental data

In-situ sampling was performed between the 10th and the 12th of September 2012, after a 1-week event of strong winds, onboard the Research Vessel ‘Seol Mara’. Samples were collected at 27 stations, mostly during flood and high tide, throughout the study site in the Firth of Lorn (Fig. 1). In each transect, stations were ~2 km apart from each other, with some exceptions due to the geomorphology of the system. The vertical profile of the water column was analysed for salinity and temperature using a Seabird CTD (conductivity–temperature–depth) profiler. Photosynthetic Active Radiation (PAR) was also measured. The instrument was also equipped with an *in vivo* chlorophyll fluorescence sensor, which was used to guide the sampling procedure at each station, and an additional oxygen sensor. The fluorescence probe was later calibrated with HPLC data, determined in the laboratory. Surface measurements taken with the fluorescence sensor were discarded for calibration purposes. Surface water samples (0–5 m depth) were collected at all stations, using a Niskin bottle, for nutrients, phytoplankton pigments and microscopy. At selected stations samples from the Deep Chlorophyll Maximum (DCM) were also collected.

2.3. Physical parameters

Seawater potential density ($kg\ m^{-3}$) was determined from temperature, salinity and pressure data collected by the CTD profiler in order to evaluate the water column physical structure (Brainerd and Gregg, 1995). The surface mixed layer (SML) depth was defined as the depth where density variations exceeded $0.05\ kg\ m^{-3}$ over a 1 m interval according to:

$$\Delta\sigma_\theta = \sigma_\theta(z) - \sigma_\theta(z_0);$$

where Z_0 is the surface depth (~2 m) and $\sigma_\theta(z) = \rho_\theta(z)\text{-}1000\ kg\ m^{-3}$

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