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Seasonal and interannual variability in phytoplankton and nutrient dynamics along Line P in the NE subarctic Pacific

M. Angelica Peña [a,*], Diana E. Varela [b]

[a] *Institute of Ocean Sciences, Fisheries and Oceans Canada, P.O. Box 6000, Sydney, BC, Canada V8L 4B2*
[b] *Department of Biology and School of Earth and Ocean Sciences, University of Victoria, P.O. Box 3020, Station CSC, Victoria, BC, Canada V8W 3N5*

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Abstract

We analysed mixed-layer seasonal and interannual variability in phytoplankton biomass and macronutrient (NO_3 and $Si(OH)_4$) concentrations from three decades of observations, and nitrogen uptake rates from the 1990s along Line P in the NE subarctic Pacific. Chlorophyll *a* concentrations near 0.35 mg m^{-3} were observed year-round along Line P except at the nearshore station (P4) where chlorophyll *a* concentrations in spring were on average 2.4 times the winter values. In contrast, the temporal variability in carbon-to-chlorophyll ratios at the two main end members of Line P (P4 and OSP) was high. Large seasonal and interannual variability in NO_3 and $Si(OH)_4$ concentration were observed along Line P. Highest upper mixed-layer (top 15 m) nutrient concentrations occurred on the continental shelf in late summer and early fall due to seasonal coastal upwelling. Beyond the shelf, maximum nutrient concentrations increased gradually offshore, and were highest in late winter and early spring due to mixing by winter storms. Interannual variations in upper mixed-layer nutrient concentrations beyond the shelf (>128°W) were correlated with E–W winds and the PDO since 1988 but were not correlated with either climate index between 1973 and 1981. Despite differences in nutrient concentration, nutrient utilization (ΔNO_3 and $\Delta Si(OH)_4$) during the growing season were about 7.5 μM at all offshore stations. Variations in ΔNO_3 were correlated with those of $\Delta Si(OH)_4$. The annual cycle of absolute NO_3 uptake (ρNO_3) and NH_4 uptake (ρNH_4) rates by phytoplankton in the upper mixed-layer showed a weak increasing trend from winter to spring/summer for the period 1992–1997. Rates were more variable at the nearshore station (P4). Rates of ρNO_3 were low along the entire line despite abundant NO_3 and low iron (Fe), at the offshore portion of Line P and sufficient Fe at the nearshore station (P4). As a result, new production contributed on average to only $32 \pm 15\%$ of the total nitrogen (N) uptake along Line P. NO_3 utilization in the NE subarctic Pacific is probably controlled by a combination of environmental variables, including Fe, light and ambient NH_4 levels. Elevated ambient NH_4 concentrations seem to decrease the rates of new production (and *f*-ratios) in surface waters of the oceanic subarctic NE Pacific. Contrary to expectation, phytoplankton biomass, nutrient utilization (ΔNO_3 and $\Delta Si(OH)_4$), and nitrogen uptake ($\rho NO_3 + \rho NH_4$) varied relatively little along Line P, despite significant differences in the factors controlling phytoplankton composition assemblages and production. Future studies would benefit from including other variables, especially light limitation, to improve our understanding of the seasonal and interannual variability in phytoplankton biomass and nutrients in this region.

* Corresponding author. Tel.: +1 250 363 6576; fax: +1 250 363 6746.
E-mail address: penaa@pac.dfo-mpo.gc.ca (M.A. Peña).

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1. Introduction

More than four decades of observations have been carried out along Line P, which extends from the southwest corner of Vancouver Island to Ocean Station Papa (OSP, 50°N, 145°W) in the NE subarctic Pacific. Initially, hydrographic measurements were made at five oceanographic stations along Line P, but additional sampling sites and measurements were added in the following years until a transect of 13 stations was established in 1964. Since then, several programs including the SUbarctic Pacific Ecosystem Research (SUPER), VERtical Transport and EXchange (VERTEX) study, World Ocean Circulation Experiment (WOCE), the Joint Global Ocean Fluxes Study (JGOFS) and the GLOBal ECosystem project (GLOBEC) have carried out biogeochemical studies along this coastal-oceanic transect. This long time series of observations has provided valuable information on the spatial and temporal variability of biogeochemical variables and the planktonic ecosystem of the NE subarctic Pacific. It has also provided an invaluable background both for *in situ* experiments, such as the Subarctic Ecological Response to Iron Enrichment Study (SERIES), and for the development of ecosystem models (e.g. Evans and Parslow, 1985; Denman and Peña, 1999; Peña, 2003).

In the past decades, several interdisciplinary research programs conducted investigations on nutrient limitation, utilization and primary production at OSP, which lies in one of the major high-nitrate, low-chlorophyll (HNLC) regions of the world's oceans. As in other HNLC regions, the NE subarctic Pacific is characterized by low and quasi-constant chlorophyll *a* concentrations (without typical spring blooms), dominance of small phytoplankton cells, high macronutrient concentrations year-round, and Fe limitation of phytoplankton growth (Harrison et al., 2004). As a result of Fe limitation of primary productivity in surface waters of the NE subarctic Pacific, surface NO_3 and $Si(OH)_4$ concentrations are not regularly depleted in the summer, but decrease to only about half of their late winter values (Whitney and Freeland, 1999).

One of the main findings of the SUPER program in the 1980s was that microzooplankton are the main grazers at OSP, maintaining a tight control on the dominant small phytoplankton cells (Miller et al., 1991; Landry et al., 1993). They postulated that grazing by microzooplankton controls the phytoplankton stocks throughout the year due to the lack of deep vertical mixing in this region that would reduce phytoplankton and microzooplankton numbers to a minimum (as seen in the North Atlantic; see Parsons and Lalli, 1988). These microheterotrophs are also providing recycled nutrients for phytoplankton growth (Miller et al., 1991; Miller, 1993). Moreover, in agreement with earlier VERTEX studies (Martin and Fitzwater, 1988; Martin et al., 1989), the SUPER study concluded that Fe is limiting the growth of the large phytoplankton in the oceanic subarctic Pacific (Miller, 1993). Recently, results from the SERIES experiment have clearly shown that Fe ultimately limits macronutrient utilization and regulates new production during summer in the NE subarctic Pacific (Boyd et al., 2004; Marchetti et al., 2006).

Earlier studies identified Asian dust carried into the Gulf of Alaska by winds as the main (although small) source of Fe to this gyre (Boyd et al., 1998; Bishop et al., 2002), but recent studies have found that supplies of Fe through oceanic transport from the continental margin of the Gulf of Alaska are more important. During the winter of 1996, Lam et al. (2006) found that the OSP mixed-layer received a supply of bioavailable Fe from the continental margin, which stimulated the abundance of large chain-forming diatoms. Based on numerical models of ocean currents, they concluded that the Fe at OSP arrived from the Aleutian continental shelf via the Alaska Gyre. Similarly, based on the study of rare earth elements, Hongo et al. (2005) identified coastal waters as the primary metal source to the subarctic North Pacific. Another mechanism that supplies Fe-rich coastal waters to the open NE Pacific is the transport of Fe from the continental shelf/slope in subsurface waters by slow-moving mesoscale eddies (Johnson et al., 2005; Crawford et al., 2007a). Mesoscale eddies that are formed along the coast of the Queen Charlotte Islands and the Alexander Archipelago move westward carrying nutrient-rich coastal waters towards the HNLC region (Whitney and Robert, 2002). Episodic Fe inputs from these sources have the potential of significantly increase nutrient utilization and change the phytoplankton assemblage in the oceanic NE subarctic Pacific.