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# The role of inorganic nutrients and dissolved organic phosphorus in the phytoplankton dynamics of a Mediterranean bay A modeling study

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ABSTRACT

The effect of Dissolved Organic Phosphorus (DOP) availability and nutrient limitation of phytoplankton growth in an estuarine bay (Alfacs Bay, NW Mediterranean) have been studied by means of a zero-dimensional ecological model including nitrogen, phosphorus (organic and inorganic), two groups of phytoplankton (diatoms and flagellates), one group of zooplankton, and detritus. Simulations with and without DOP as an extra source of phosphorus for phytoplankton growth suggest that DOP plays an important role in the dynamics of the Alfacs Bay ecosystem. DOP is indeed necessary to simulate the observed draw-down of nitrate and build up of phytoplankton biomass. Two non-exclusive mechanisms allowing DOP availability for phytoplankton are possible: direct uptake, or remineralization to Dissolved Inorganic Phosphorus. Including both gives a better agreement with the observations. Inclusion of DOP in the model leads to predominance of phosphorus limitation of phytoplankton growth in fall and winter, and of nitrogen limitation in late spring and summer. Simulations with and without sediment resuspension suggest that this process does not significantly affect the nutrient budget in the bay.



## 1. Introduction

Coastal regions are highly dynamic and productive areas that have historically attracted human populations. In the confluence between a river mouth and the sea, estuaries hold a variety of habitats and have both a high ecological and economic value. Such areas process nutrients as they pass from the land to the sea, provide shelter and nursery grounds for many aquatic species, and support successful fisheries and aquaculture activities.

A major challenge in the study of marine coastal areas is understanding the interactions among physico-chemical variables and ecosystem behavior. Alfacs Bay represents a good case study for this challenge. Alfacs (NW Mediterranean, Fig. 1) is a shallow bay (3.13 m deep on average) characterized by human controlled freshwater discharge and subject to the typically small tides of the Mediterranean (less than 0.2 m). It is highly productive, and hosts successful aquaculture businesses (Camp and Delgado, 1987; DAAAR, 2008). However, algal blooms – some of them harmful – have been recurrent in Alfacs since 1989 (Delgado et al., 1990). Harmful algal blooms (HABs) consist of different species, such as the dinoflagellates *Alexandrium minutum* (Delgado et al., 1990), *Dinophysis sacculus* (Garcés et al., 1997) and *Karlodinium spp.* (formerly identified as *Gyrodinium corsicum*) (Garcés et al., 1999; Fernández-Tejedor et al., 2004), and diatoms of the genus *Pseudonitzschia* (Quijano-Sheggia et al., 2008). Their frequency has increased over the years, just as it has increased in other harbors of the neighboring Catalan coast (Vila et al., 2001). Some of these proliferations are associated with massive mortalities of cultured fish, and others cause mussel (*Mytillus galloprovincialis*) toxicity for humans (due to Diarrhetic or Paralytic Shellfish Poisoning). Because these blooms consist primarily of flagellates or diatoms, the dynamics of these groups and nutrient control of their populations will be one of the foci of this study.

The main sources of dissolved inorganic nutrients in Alfacs Bay are freshwater discharge from irrigation channels and treatment plants (Camp, 1994), ground water input, exchange with the open ocean through the mouth of the bay, flux from sediments (Delgado and Camp, 1987; Vidal, 1994), and recycling and remineralization from biological processes. Agricultural practice in the Ebre Delta, which is dominated by rice farming, delivers high inorganic nitrogen loads to the bay (of the order of 20–100 mmol N $m^{-3}$) through freshwater drainage channels. In general June and October are the months with

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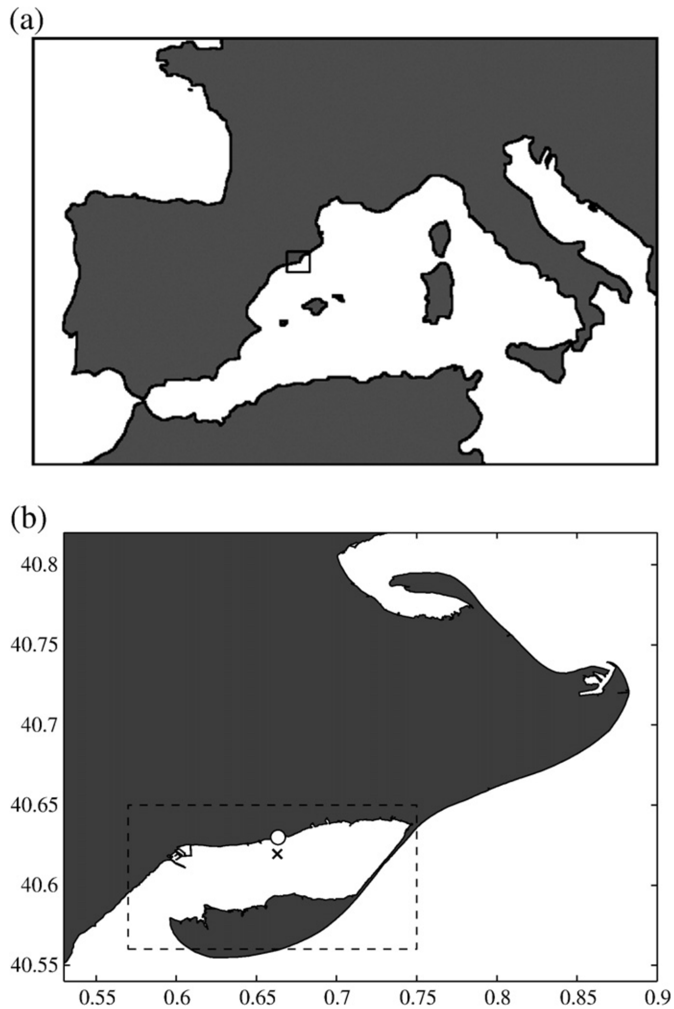


**Fig. 1.** Map of the study zone in Latitude/Longitude coordinates. - - Els Alfacs Bay; ○ : weather station; x: sampling site.

higher nutrient concentration in the channels, because the fields are fertilized in June and emptied in October after the crop (Muñoz, 1998). Phosphorus concentrations are generally low (0.5–1.5 mmol P $m^{-3}$). In addition to drainage channels, ground water seepage appears to be also an important source of nutrients, given the high nitrate concentrations in the Ebre Delta aquifers, where up to 1500 mmol N $m^{-3}$ have been reported (Ministerio de Obras Públicas, Transportes y Medio Ambiente; Ministerio de Industria y Energía, 1995; Torrecilla et al., 2005). The main nutrient sinks are exchanges with the sea and consumption by phytoplankton, which can also produce detrital matter sinking to the sediment. In addition to dissolved inorganic nutrients, dissolved organic compounds have been found in high concentration in the bay, in association with freshwater discharge. Recent studies (Loureiro et al., 2009) have documented much higher concentrations of dissolved organic phosphorus than of inorganic phosphorus concentrations during the summer.

In spite of previous work on the linkage between the phytoplankton community and the physics in Alfacs Bay (Artigas, 2008; Llebot et al., 2008), a good understanding of the main physico-chemical factors controlling the phytoplankton community is still lacking. One outstanding question concerning the ecology of Alfacs Bay is the role of nutrient fluxes on phytoplankton community succession and bloom development. Nutrient control of phytoplankton growth in Alfacs Bay has been addressed by several field studies, but with contrasting results. On one hand, Delgado and Camp (1987) reported a N:P ratio between 0.2 and 10.2, and by comparison with Redfield ratio concluded that nitrogen was the limiting nutrient of the system. On the other hand, Cruzado et al. (2002) found that phosphorus was the limiting nutrient in the Ebre Delta system and attributed this observation to the contribution of freshwater discharge, which is high in nitrogen and low in phosphorus. Freshwater input to Alfacs is indeed low in phosphorus due to its retention in the rice fields, as observed by Forès (1989). Finally, other studies point to a more complicated situation of alternating phosphorus and nitrogen limitation. Vidal (1994) considered that phosphorus was the main limiting nutrient for phytoplankton growth in Alfacs, but suggested that atmospheric and hydrodynamic forces could play key roles in alternating nitrogen and phosphorus limitation. Quijano-Sheggia et al. (2008) found that inorganic P limitation was frequent, especially during winter, while a few cases of inorganic N limitation were observed in summer. Thus, the question of the nutrient control in Alfacs remains still unanswered.

Our hypothesis is that phytoplankton production experiences a colimitation of nitrogen and phosphorus, and that the most limiting nutrient changes during the year, depending on the variability of the sources and sinks of both nutrients. Therefore, the general aim of this work is to ascertain, by means of an ecosystem model, which nutrient or nutrients potentially limit phytoplankton production in Alfacs and to describe the main sources and sinks of these nutrients and how they affect the phytoplankton community composition. In particular, we will test two main hypotheses. 1) nitrogen or phosphorus are most limiting for phytoplankton growth in different seasons affecting the plankton community composition. 2) this alternation can be explained by two processes that affect phosphorus availability, in addition to freshwater inputs: a) phosphorus release from the sediment after resuspension events due to wind stirring (Vidal, 1994); b) availability of dissolved organic phosphorus (DOP) as a source of P to phytoplankton through two non-exclusive mechanisms: remineralization to dissolved inorganic phosphorus (DIP) and direct uptake. Although the direct uptake of DOP has been shown by several experimental studies (Johannes, 1964; Currie and Kalff, 1984; Bentzen et al., 1992; Huang and Hong, 1999; Oh et al., 2002; Yamamoto et al., 2004) it is only rarely taken into account by ecological models. The input of detrital particulate phosphorus (PP) from freshwater could be another source of phosphorus (Aminot et al., 1993; Ruttenberg, 2001; Némery and Garnier, 2007). Although samples of particulate matter in the channels are very scarce, the few available data suggest that the concentration of particulate phosphorus (PP) ranges between 1 and 3 mmol P $m^{-3}$ (Muñoz, 1998). We did not present this third possibility in this manuscript because the fluxes of PP to the bay and the dissolution rates seem too small to add any substantial source of phosphorus to the bay.

In order to approximate the budgets and fluxes of nitrogen and phosphorus and to address the above hypotheses, we built a zero-dimensional ecological model of the estuarine mixed layer. The model includes nine state variables: zooplankton, flagellates, diatoms, dissolved inorganic nitrogen, dissolved inorganic phosphorus, dissolved organic nitrogen, dissolved organic phosphorus, detrital phosphorus, and detrital nitrogen. The forcing variables are water density, temperature, wind intensity, freshwater input, and velocities in and out of the bay, in addition to silicon that is introduced into the model based on a time series of measured concentrations.

In Section 2 we present the model equations and parameter values, and the choice of initial conditions and forcing used in the simulations. We also describe the field data. Section 3 reports the outcome of the various simulations using different sets of assumptions about the occurrence of sediment resuspension and the possibility of DOP utilization by phytoplankton, and presents the comparisons of these results with measured data. Section 4 presents a sensitivity analysis with respect to the fluxes and nutrient concentrations of the freshwater sources. The results are discussed in Section 5. Finally, we summarize our conclusions in Section 6.