Evaluating light and nutrient limitation in the Tagus estuary using a process-oriented ecological model

M Mateus PhD and R Neves PhD,
Instituto Superior Técnico, Universidade Técnica de Lisboa, Portugal

Over the past decades, the Tagus estuary (Lisbon, Portugal) has been the focus of several experimental and numerical studies. Field observations suggest that light plays the major role in the control of phytoplankton production in the system, with nutrient limitation only in some confined areas. Light limitation has also been inferred by some modelling studies, but it has been an assumption in most model applications to the estuary. In this study, a process-oriented ecological model for the water column, coupled with a 2-D hydrodynamic model, has been applied to the Tagus estuary to assess the influence of light and nutrients on phytoplankton production. The preliminary results obtained using the model suggests that the system is mostly controlled by light. Nevertheless, nutrients may also control production to some extent but only in lower estuarine areas and in summer. This numerical study seems to agree with the general information on the system, supporting the idea that light control has a major role in the Tagus estuary

AUTHORS' BIOGRAPHIES

Marcos Mateus holds a BSc degree in Marine Biology and a PhD in Environmental Engineering. He is an environmental scientist with Instituto Superior Técnico. Since 2001, Marcos has been involved in research projects relating to coastal resources management and marine ecosystems modelling studies. He is also a lecturer in Marine Biology and Marine Pollution.

Ramiro Neves is an environmental scientist and associated professor with Instituto Superior Técnico. He holds a BSc degree in Mechanical Engineering and a PhD in Environmental Engineering and has over 20 years of experience in environmental consulting. He is a specialist in environmental impact assessment in the marine and coastal environment and has been involved in the environmental assessment of a range of major projects, including estuarine eutrophication and other water resources management.

INTRODUCTION

Over the past decades, the industrial and urban expansion in most developed countries has pushed the natural state of estuarine systems to a state in which there is an artificial, often problematic, acceleration of eutrophication processes. Estuarine ecosystems usually have a high content of allochtonous material and high concentration of nutrients (comprising mesotrophic and eutrophic conditions), supporting high rates of phytoplankton and bacterial production. Of particular relevance in the study of impacted ecosystems is the interaction effects of the usual limiting factors such as light and nutrients on phytoplankton growth.[1] These studies may provide crucial information on long-term changes and may help highlight potential threats for the environment and humans.

The increase of both organic material and nutrients in the system above background levels, as a result of eutrophication, poses serious threats. Oxygen depletion and the increase in harmful algal blooms (HAB) are among the most serious threats that coastal systems such as estuaries can face.[2] The negative impact that cultural eutrophication has on natural aquatic systems has made it one of the main concerns of the most recent framework for environmental legislation on aquatic environments' protection, namely, the European Directive 2000/60/EC.[3] Of particular relevance are processes like the increase of anthropogenic nutrient loads resulting from wastewater discharges and agriculture intensification in the river basin leading to eutrophication. In this context, the question of whether an estuarine system is nutrient-limited like the San Francisco Bay[4] or light limited like many sub-tropical estuaries,[5] is of paramount importance in predictive studies.

Physical characteristics of the estuary, such as the residence time and turbidity, control the availability of nutrients and light in the system.[6] Ultimately, if a particular system is light limited, then nutrient enrichment will not have a significant impact on production. Nonetheless, if the enrichment occurs via the addition of organic material, then an increase in bacterial activity is expected, leading to potential oxygen depletion, both in the water column and in the sediment.

This study involves a model application to the Tagus estuary, Portugal. The main objective is to evaluate the model response when forced with several known variables, such as atmospheric parameters, river discharges and tide. The analyses of the results focus on the identification of the light and nutrient control on phytoplankton dynamics in the system.

Over the past few decades numerical models have become standard tools in the study of estuarine processes and are increasingly becoming indispensable in environmental studies and management decisions in coastal areas.[7] Until now, the Tagus estuary has been the focus of some modelling studies.[8,9] The model used in the study has been developed recently and reflects the state-of-the-art in marine ecological modelling. Therefore, this application represents the first numerical study of the Tagus estuary using a model with this kind of complexity. As such, results must be seen as preliminary.

Characterisation of the Tagus estuary

The Tagus estuary (38°44′N, 9°08′W) is a mesotidal system with semi-diurnal tides and tidal amplitudes ranging from 1 to 4m (mean tidal amplitude is 2.2m). With a surface area of some 320km^2 and a mean volume of 1900×10^6 m^3, it is the largest estuarine system on the Portuguese coast (Fig 1). Intertidal areas, composed mainly of mudflats, cover an area between 20 and 40% of the total estuarine area.

Inflow of saline water from the Atlantic and the considerable riverine input of freshwater largely determine the hydrographic conditions of the estuary. The mean river flow is 400m^3/s, but the Tagus river has significant seasonal and interannual variation. River discharge shows a clear seasonal pattern. From March to December, it has a rather constant monthly average flow of $\sim$330m^3/s. Higher values (peaking 900m^3/s) are recorded from January to March. Rivers Sorraia and Trancão are two smaller fresh water inputs to the system. The estuary also receives effluent discharges, mainly from urban (over 10 WWTP), industrial, and agricultural sources.

The wind regime in the area exhibits a marked seasonal pattern, with predominant winds from south and southwest during winter, rotating progressively to winds from northwest and north during spring, and maintaining these directions throughout the summer months. Seasonal variability of meteorological conditions together with that of river discharges induce a strong seasonal variability of both hydrodynamic and biogeochemical conditions.

A strong horizontal pattern is observed inside the estuary, controlled by the hydrodynamic conditions as a result of the tidal regime. Middle estuarine areas (and upper areas to a lesser extent) have more stable and homogenous conditions, with a high residence time, whereas lower estuarine areas are characterised by high variability. Except for some confined areas, thermal stratification inside the estuary during spring and summer is prevented by the relatively high flow and the shallow depth. The system is vertically well mixed all year around and has a mean tidal prism of 600×10^6 m^3, about one-third of the mean volume.

Several groups of primary producers can be found inside the estuary and in the surrounding coastal waters. The estuary has diverse phytoplankton population (especially Bacillariophyceae, Chlorophyceae, and Dinophyceae), with diatoms being the predominant.[10] Typically, limiting nutrients are never depleted and bloom control is ascribed to several biotic and abiotic factors (zooplankton grazing, residence time, light availability, etc). Other relevant primary producers in the system include microphytobenthos like benthic diatoms[11,12] and saltmarsh vegetation dominated by *Spartina maritima*, *Halimione portulacoides* and *Sarcocornia fruticosa*.[13]

MODELLING THE SYSTEM

Hydrodynamic model setup

The model domain encompasses the adjacent coastal area outside the estuary and a section of the upstream area of Tagus River. The MOHID hydrodynamic model (www.mohid.com) was used to characterise the flow regime for the whole study area. Its governing hydrodynamic equations have been described elsewhere,[14-16] and only a brief overview is presented here. The model uses a full 3-D hydrodynamic formulation with hydrostatic and Boussinesq approximations[17] and the general ocean turbulence model (GOTM) for the turbulent closure.[18] Tides, wind, and river outflow are the main forcing mechanisms for the circulation.

Given the intense vertical mixing of the system, the model is set as a 2-D depth-integrated model. A single water layer was defined for the entire study area, with variable depth conditioned by topography at the bottom of the estuary. Model domain (Fig 1), with the geographical location of 38°30′–39°N and 8°51′–9°51′W, is characterised by a variable square grid with 73 × 94 computation points, with higher resolution inside the estuary with cells

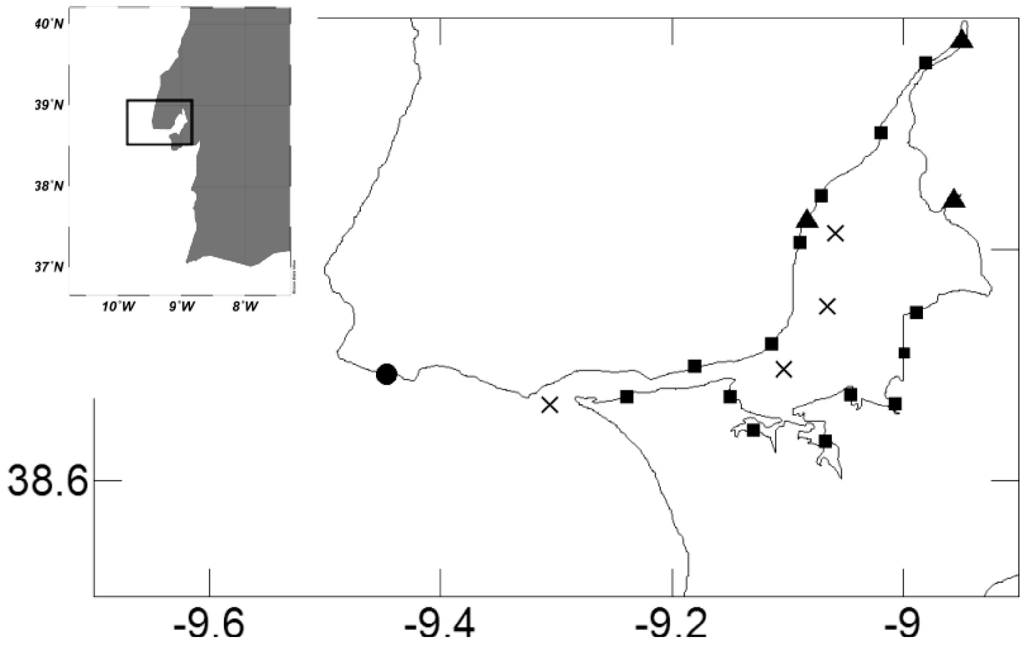

Fig 1: The modelled domain of the Tagus estuary with the inside window showing the geographical location. Three small islands located in the upper area of the estuary are not represented but have been considered in the model setup. Legend: monitoring sites (×); meteorological station (●); river discharge points (▲) - Tagus river on the top right corner, Sorraia and Trancão rivers on the left and right margin of the estuary, respectively; WWTP emission points (■)

covering ~3.72 km^2. Meteorological forcing, boundary conditions, and river discharges are explicitly imposed, all with temporal variability. The tide was imposed with tide-gauge elevations at the open boundary. Atmosphere–water interactions (eg, heat fluxes, wind stress, solar radiation) and the interaction between the bottom and water column (eg, cohesive sediments resuspension and deposition) are handled by the model.

The model runs with a time step of 60 seconds for a period of 20 months (April 2003 to January 2005). A spin-off period of two months of simulation period is used to achieve a proper bottom sediment pattern inside the estuary.

Ecological model setup

Mohid.Life.1.0 model[19] was coupled to the transport model as a zero dimensional water-quality/ecological model with an Eulerian formulation. The model has a decoupled carbon–nutrients dynamics with explicit parameterisation of carbon, nitrogen, phosphorus, silica, and oxygen cycles. It considers two major groups of producers in the system, diatoms and autotrophic flagellates, and also the dynamics of the microbial loop and several organic matter components. All living and organic matter compartments of the model have variable stoichiometry. Synthesis of chlorophyll *a* is simulated according to the scheme proposed by Geider *et al*,[20,21] allowing for a temporal and spatial variation of C:Chl*a* ratios in producer populations. Luxury uptake occurs in phytoplankton populations, with the carbon to nutrient ratio varying between twice and half the Redfield ratio. The Redfield ratio is assumed to be the threshold below which limitation occurs.

The food web is closed with a microzooplankton group, having a quadratic-density-dependent term (such that grazing rates decline at low prey biomass). This criteria was defined to compensate for the lack of top predators, according to evidences suggesting a threshold effect on grazing in natural microzooplankton assemblages.[22] The trophic structure was defined on the simple basis of a predatory action of consumers on producers, bacteria, and on themselves. Parameter values for phytoplankton, microzooplankton, and bacterioplankton were obtained from model applications with similar degree of complexity.[23-27] Model parameters for which precise estimates were unavailable (such as grazing rates and prey availability) were set by calibration of the model output against observed values of some state variables.

Light penetration in the water column is affected by chlorophyll and cohesive sediment concentrations and is computed within the model system. The ecological model iterates every 3600 seconds and runs for 18 months.

A simple sediment model was included to account for POM and biogenic silica digenesis (fixed mineralization rate of 0.1d^{-1}). PON and POP are converted to ammonium and phosphate, respectively, and biogenic silica to reactive silicate.

External conditions

Atmospheric forcing

High-frequency atmospheric forcing for radiation levels, wind (direction and intensity), air temperature, atmospheric relative humidity, and precipitation was achieved for the year 2004 using a comprehensive dataset with an hourly resolution. Values were measured at a meteorological station near Tagus estuary mouth, located at 9°26'48"O and 38°41'48"N (Fig 1).

River and WWTP discharges (inputs)

The model considers the input of three rivers: Tagus, Trancão, and Sorraia. Data for Tagus River was obtained from Instituto Nacional da Água (http://www.inag.pt). Tagus is the most significant contributor; Trancão and Sorraia have significantly lower flows, but act as nutrient and organic matter sources. River inputs are characterised by flow, temperature, salinity, concentration of cohesive sediments, nutrients, organic matter components, and biological constituents (see Fig 2 for an example for Tagus).

Considering the marked seasonal regime, a monthly value was used if available or if not, it is estimated. Nutrient loading (calculated from publicly accessible data) was derived mainly from fixed stations monitoring measurements. The discharges of WWTP inside the system were also considered in this study (Fig 1), with values for flow, nutrient, and organic matter loads obtained from field data and historical data provided by the Portuguese National Water authority – Instituto Nacional das Águas (INAG) – and from specific projects developed in the system.

Boundary conditions

Boundary conditions imposed on the open oceanic boundaries were taken from values compiled by NODC for the area off Lisbon (http://www.nodc.noaa.gov/). Given the lack of data and the small contribution of these oceanic areas to estuarine dynamics, a constant value for each property was assumed as sufficient. The Dirichlet boundary condition was adopted.[28]

MODEL CALIBRATION

Given the decisive role of the physical control on the system, its proper characterisation is critical to achieve a correct simulation of the ecology. In this simulation, the hydrodynamic model was not calibrated for temperature, salinity, and sediment dynamics. These features have been exhaustively tested and the calibration and validation properly achieved in other studies using the MOHID hydrodynamic model.[29-31] This study relies on the assumption that the model correctly simulates these properties in the system based on successful applications in the past.

Four virtual sampling sites were established to monitor the evolution of model properties (Fig 1). The sites are disposed along a NE-SW transect, starting in the mid-estuary area and extending all the way down to the coastal estuarine zone at the river mouth (referred herein as MS1, MS2, MS3, MS4, numbered from the mid-estuary areas to the river mouth). The location of the virtual stations was set such that it matched with the location of some sampling sites monitored in the estuary during 2004 (S1 to S4 in Fig 1).

The calibration was performed in a step-by-step approach in a series of successive model runs, starting with a standard set of parameter values and sequentially changing some of them after checking the results at the end of each new run. Parameter values were constrained within limits that were considered to be biologically realistic. Considering the enormous range of different values that could lead to a reasonable fit between model results and in situ measurements, the 'optimal' solution was found when a satisfactory fit was achieved by changing the minimum set of parameters.[19]

DATA DESCRIPTION

Monitored data comprise ammonium, nitrate, chlorophyll *a*, and oxygen concentration values at each station. Only a monthly value is available for each property and there is limited data for winter months. Nevertheless, the temporal

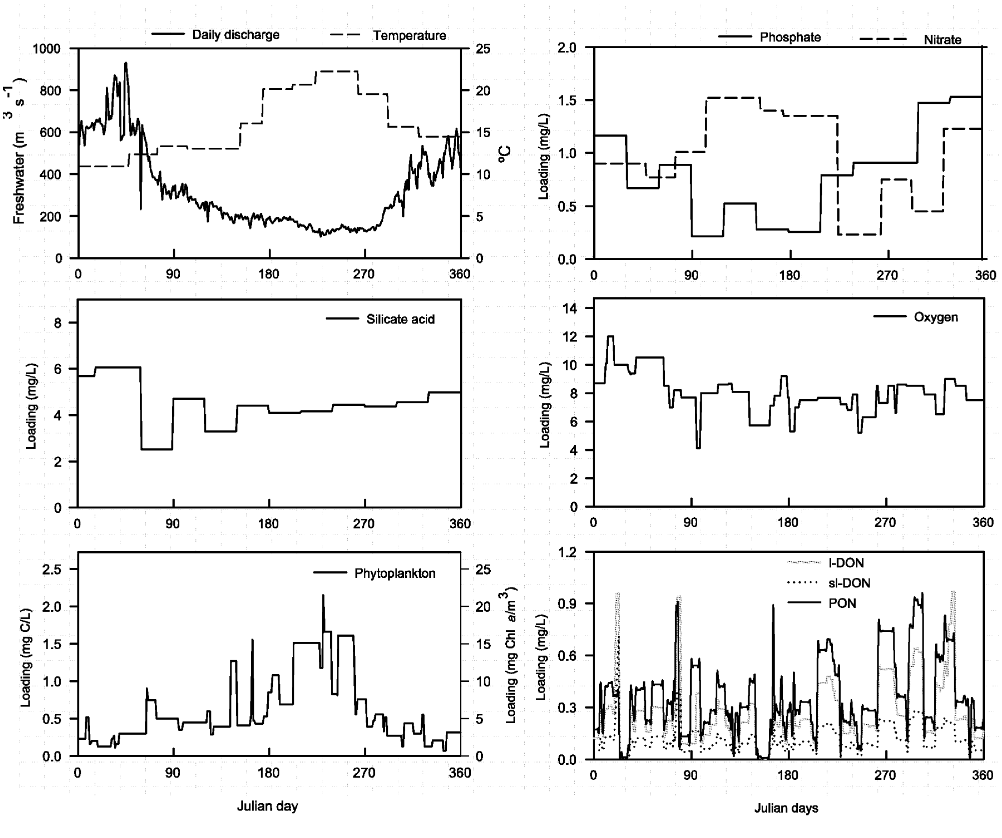

Fig 2: Data from the Tagus River used in the model forcing. Data on flow, temperature, chlorophyll *a*, and nutrients were obtained from measurements performed at a monitoring station located upstream during the timeframe of the study. Phytoplankton biomass was calculated from Chl*a* values assuming a fixed C:Chl*a* ratio of 60. Organic matter loads were estimated from nitrogen input data. Missing carbon and nutrient composition for phytoplankton and organic matter were derived from the field data on Chla based on the Redfield ratio

resolution of data can be considered satisfactory, considering that it is enough to reveal the seasonal patterns of the system. For simplicity, results are analysed on a seasonal scale and not a diurnal or tidal time scale (on the order of hours).

In-situ data (Fig 3) shows a seasonal trend in ammonium concentration, with lower values observed during summer months in all monitored sites. The same seasonal trend can be observed for nitrate concentrations, but only evident in data from MS2, MS3 and MS4. Nitrate concentrations reveal a clear longitudinal distribution pattern with decreasing concentrations from upper areas of the estuary (MS1) to the river mouth (MS4). MS1 shows consistently the highest measured values, reaching 0.25mgN l^{-1} for ammonium in late October and >0.8mgN l^{-1} for nitrate in winter, respectively. Concentrations are systematically higher at MS1 and decrease towards MS4. Generally, nutrient concentrations tend to be lower with increased distance from the upper estuary areas. These observations denote a clear influence from the river Tagus discharge. Also, nutrient concentrations decrease in summer is linked to the marked decrease in the discharges.

Of all measured parameters, Chl*a* has the most striking seasonal pattern, with spring/summer bloom (>10mgChl*a* m^{-3}) after low concentrations in winter (<2mgChl*a* m^{-3}). By the start of autumn (September 22), Chl*a* concentrations show a clear decreasing trend. The most obvious spatial and temporal pattern appears to be the higher Chl*a* concentrations inside the estuary (MS1 and MS2). Oxygen concentrations are very spatially homogenous, but having a seasonal variation with lower values in winter and higher in summer.

All monitored variables show a seasonal fluctuation but with different magnitudes, both temporal and spatial. The increase in Chl*a* is in phase with the increase of dissolved oxygen in water, as a result of the increase in production and consequent oxygen production. The same is true for ammonium and nitrate, only here the increase in Chl*a* overlaps the decrease in these nutrients as a result of uptake. The influence of river discharge cannot be ruled out of this explanation given the fluctuation in properties' loads throughout the year (Fig 2).

MODEL PERFORMANCE

Abiotic conditions

Model results for temperature (Fig 4) shows the typical seasonal pattern of mid-latitude estuarine system, with temperatures reaching 25°C during summer months. Temperature range is much greater inside the estuary, varying between 12-24°C at MS1 and only 14-18°C at MS4. Extremes in temperature values are observed at upper estuarine areas, denoting a clear spatial pattern.

Salinity follows the same general pattern of temperature (Fig 4), with a wider range of values observed up inside the estuary (<5-25PSU at MS1) and small variations at the estuary mouth (27-35PSU at MS4). Like temperature, values reveal a strong seasonal fluctuation, especially in the inner areas of the estuary. Salinity shows a stronger signal of tidal influence with marked fortnightly fluctuations caused by the spring/neap cycle. Tidal effects and river discharge explain the higher values observed at the river mouth and lower salinity concentrations in the upper areas.

Cohesive sediments in the water column also show great spatial-temporal variation (Fig 4). At MS1, for example, concentrations range from 42 to 111mg l^{-1}. Higher values

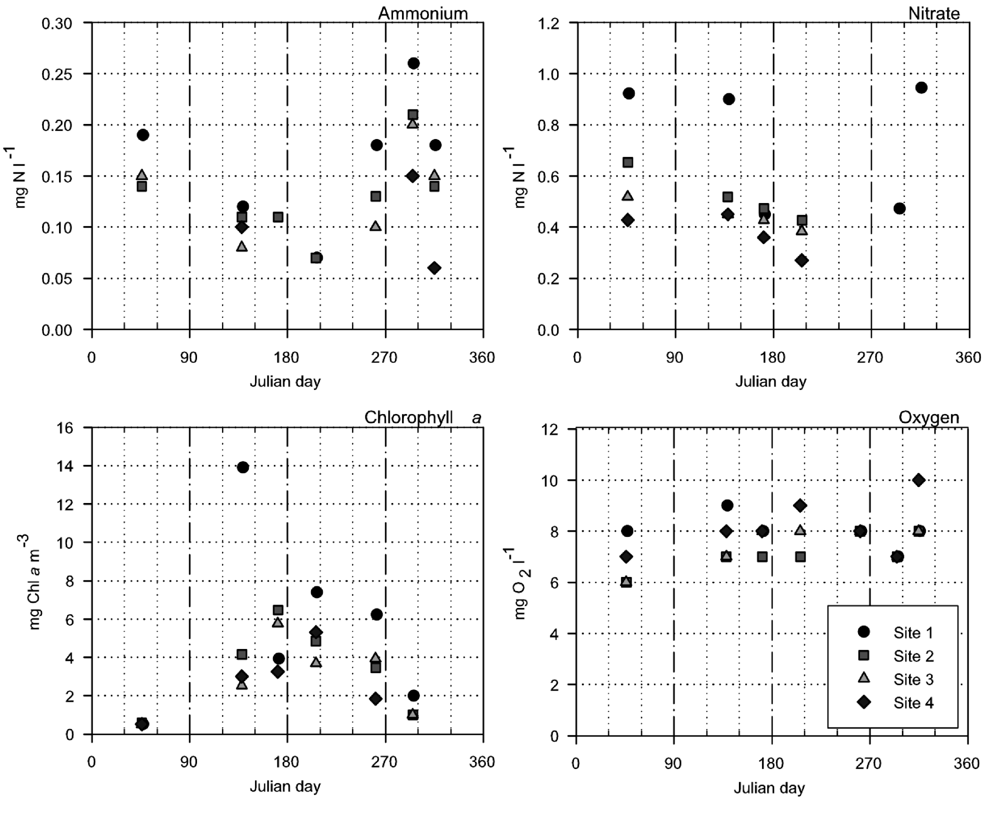

Fig 3: Comparison of measured variables between all the monitored sites

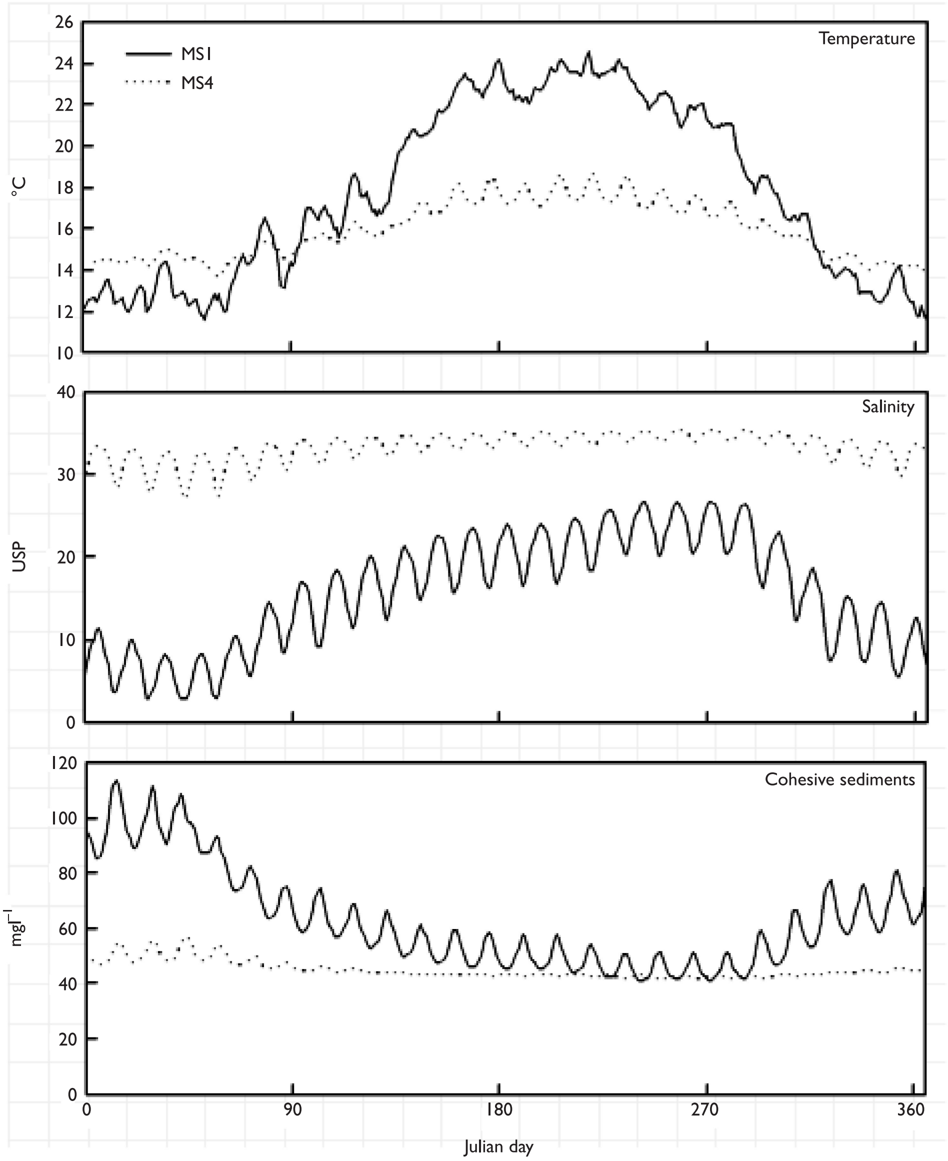

Fig 4: The results of the model for temperature, salinity, and cohesive sediments concentration at MS1 and MS4

are observed during winter months, while the lowest concentrations are observed in late summer months. Also, concentrations are higher in inner areas and lower estuarine areas show a much narrower range of variation (43 to 45mg l^{-1}). The spatial discrepancy in suspended sediment concentration is particularly evident in winter months, induced mostly by the Tagus river discharge.

Nutrients

A fairly reasonable agreement is attained between model results and data for all stations (Fig 5), in respect to the seasonal patterns and concentration magnitude. Model results reveal a sharper seasonality in ammonium concentrations, especially in upper stations. Data shows some similarity between stations, with MS1 usually having higher values. Model results, however, show a clear decrease in ammonium from inner estuary to coastal zone (Fig 5, first row). The spring decrease in ammonium concentrations begins earlier in model results, but shows agreement with the observations. The lower summer values are produced correctly, usually with slightly higher values in model results at MS1-MS3 and lower at MS4 (<0.15mgN $l^{-}1$) when compared with sampled values. Nevertheless, the model is able to match measured values meaning that it captures ammonium dynamics.

Nitrate concentrations have a marked seasonal pattern in all studied sites (Fig 5, second row), with higher values in winter and a sharp decrease in summer. The model captures the yearly seasonal fluctuation in nitrate values, but a correct match between model and observations is seldom achieved (eg, MS1) and only a fairly approximation to the measured values is observed. Like ammonium, the seasonal pattern is not so evident in MS4 for nitrate, where concentrations tend to remain low the entire year (always below 0.5mgN l^{-1}). The model clearly fails to converge to the observed values at MS4. Despite the systematic overestimation of ammonium and underestimation of nitrate concentrations, model results are still in the same order of magnitude of measured values.

Silicate and phosphate show a seasonal pattern with higher concentrations in winter months and a marked de-

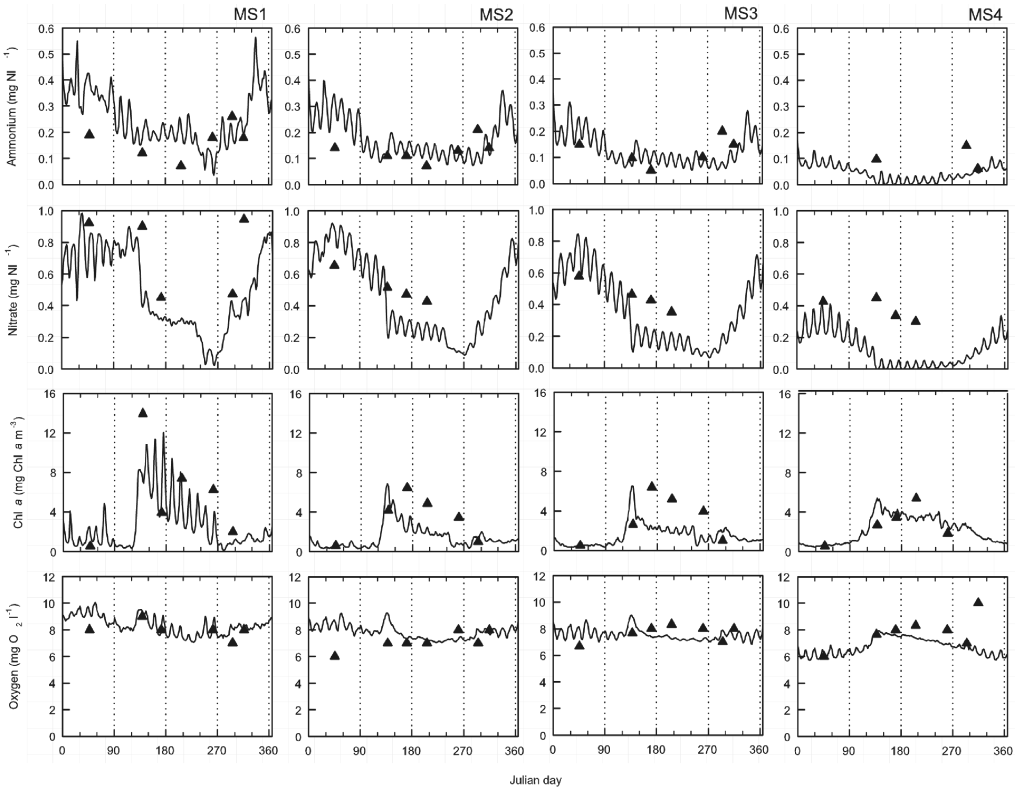

Fig 5: Ammonium, nitrate, total chlorophyll *a* (sum of the chlorophyll *a* content of both producer groups), and oxygen values from sampling sites (▲) and the results of the model (line)

pression during summer months (Fig 6). This depression is more pronounced in upper estuarine stations considering the annual range variation between winter and summer (0.1 to 1.35mgP l^{-1} for phosphate, and 0 to >6mgSi l^{-1} for silicate acid).

The model is able to describe the system's temporal and spatial variation. The rate and timing of the seasonal trend in nutrient variation is generally correct. Of particular relevance in model results is the fact that, while experiencing variable periods of low concentrations, none of the nutrient is entirely depleted in the system during summer.

By comparing the oxygen concentrations of model results and measured data (Fig 5, lower row) it is possible to see that the general tendency of this property is achieved. The different interval range of dissolved oxygen in data in the various check points is reproduced reasonably well for all sites. Nonetheless, the observed higher values in summer are not reproduced by the model for MS3 and MS4. Results denote a satisfactory oxygen balance by the model.

Phytoplankton

The simulated phytoplankton chlorophyll *a* distribution (Fig 5, third row) shows that the model reproduces the observed strong seasonal variation with a late spring/early summer peak in abundance, although with a lower magnitude in most cases. Measured values for the late-spring and summer months show consistently higher values for chlorophyll *a* than those obtained from the model. At MS1, while *in situ* data reaches 15.5mgChl*a* m^{-3}, model results only reach a total (sum of the chlorophyll *a* of both groups) maximum of 13.3mgChl*a* m^{-3} at the bloom peak. While missing the

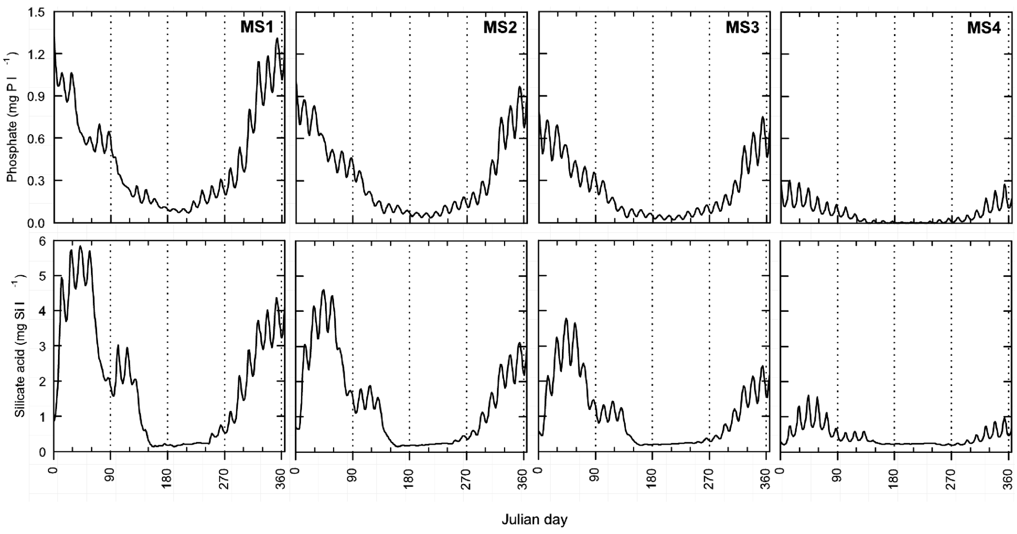

Fig 6: Predictions of the model for phosphate and silicate evolution at all model stations

timing and magnitude of the bloom peak, the model shows a good fit for June and July at this site. The strong oscillation seen in the results, induced mainly by the diel light regime and the tide, can account for this fit. Discrepancies between model predictions and data are more pronounced at MS2 and MS3 for the long term.

Despite being triggered at the same time, observations show that the timing of the maximum bloom peak is different among sites. Model results, on the other hand, show a slightly different scenario with the bloom peaking simultaneously in May at MS2, MS3 and MS4, and later at site MS1. In addition, the decay of the simulated bloom is faster than the observed distribution suggests. After an initial bloom, total chlorophyll *a* estimated by the model starts to decrease. Data reveal a decreasing tendency too, most clearly noticed at MS1 and MS3. The model predicts smaller subsequent peaks in phytoplankton in late summer. However, observations to support the existence of this feature were insufficient or not available.

The spatial distribution of chlorophyll *a* in the estuary for diatoms reveals some curious patterns. In winter, higher concentrations of chlorophyll *a* can be found in mid estuarine areas and in the south banks, while in summer there is a clear gradient from low concentrations in the lower estuarine area to high concentrations in the upper areas (Fig 7). Chlorophyll *a* concentrations in diatoms (Fig 7 and Fig 8) tends to decrease along the transect, with higher values at MS1 and lower values at MS4. In all stations, however, it is possible to identify the seasonal fluctuation. An inverse pattern is observed for autotrophic flagellates (Fig 7 and Fig 9), with higher values at MS4 and lower values at MS1. Hence, diatom dominance decreases and autotrophic flagellates dominance increases seaward.

A common feature to both groups in all model station is the seasonal fluctuation in C:Chl*a* ratio. There is a general pattern of lower values of C:Chl*a* during autumn/winter months and higher values in spring/summer. The values for C:Chl*a* vary around a minimum of 46 and 44, and a maximum of 114 and 102, in diatoms and autotrophic flagellates, respectively. Despite the constant fluctuation in the ratio, the increasing and decreasing tendency shows a clear adaptation to the changing conditions of the system. A spatial pattern in C:Chl*a* ratios is also observed, though not so obvious; they are systematically lower in inner areas when compared with the observed ratios at the river mouth (eg, C:Chl*a* ratio in diatoms increases from 78 in MS1 to 88 in MS4).

Underwater light climate control

Tidally driven resuspension and riverine source of sediments are important mechanisms influencing suspended matter concentration, determining the photic depth in the water column.[32] So, even when nutrient concentrations are relatively high, light availability is the key limitation. The results suggest light availability as the major controlling factor inside the estuary. This is a common feature to other estuaries.[33]

Similar to the high turbidity in most mesotidal estuaries

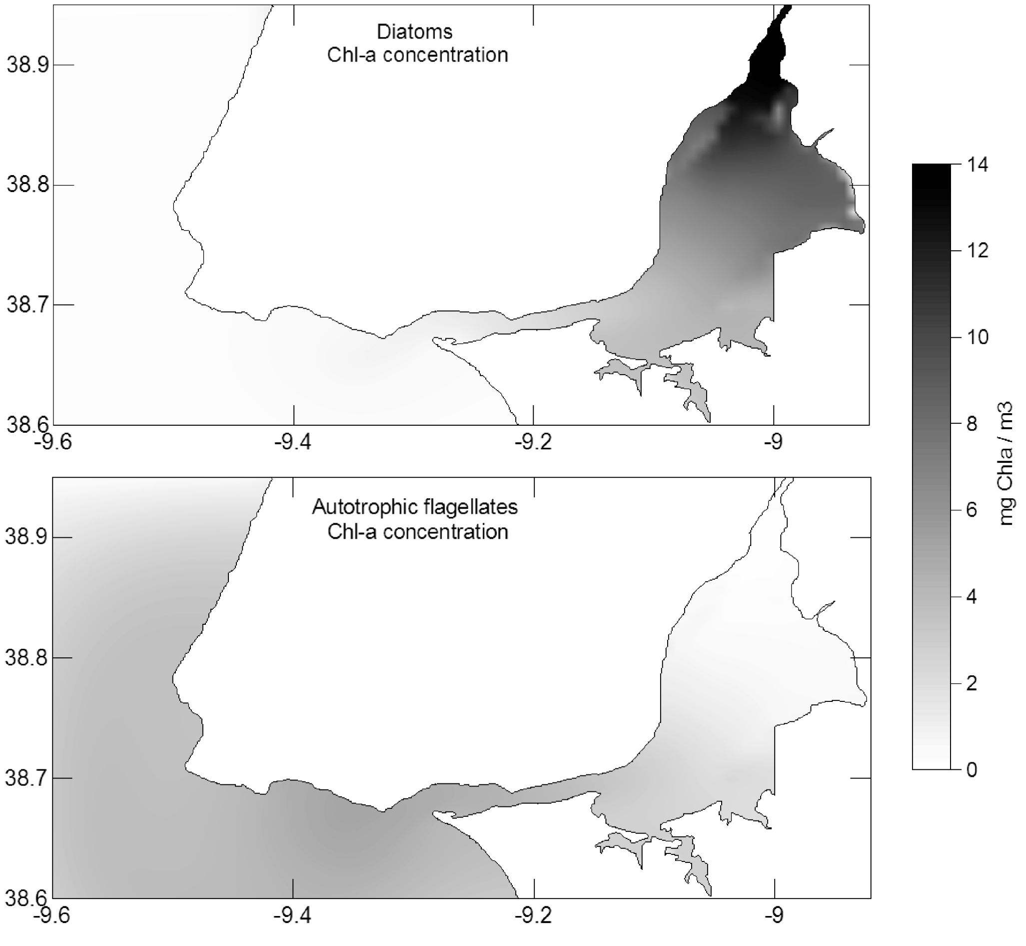

Fig 7: Modelled chlorophyll *a* concentration for diatoms and autotrophic flagellates at the Tagus estuary. Results for Julian day 139, 12.00pm, have been chosen because of the pronounced spatial difference between groups

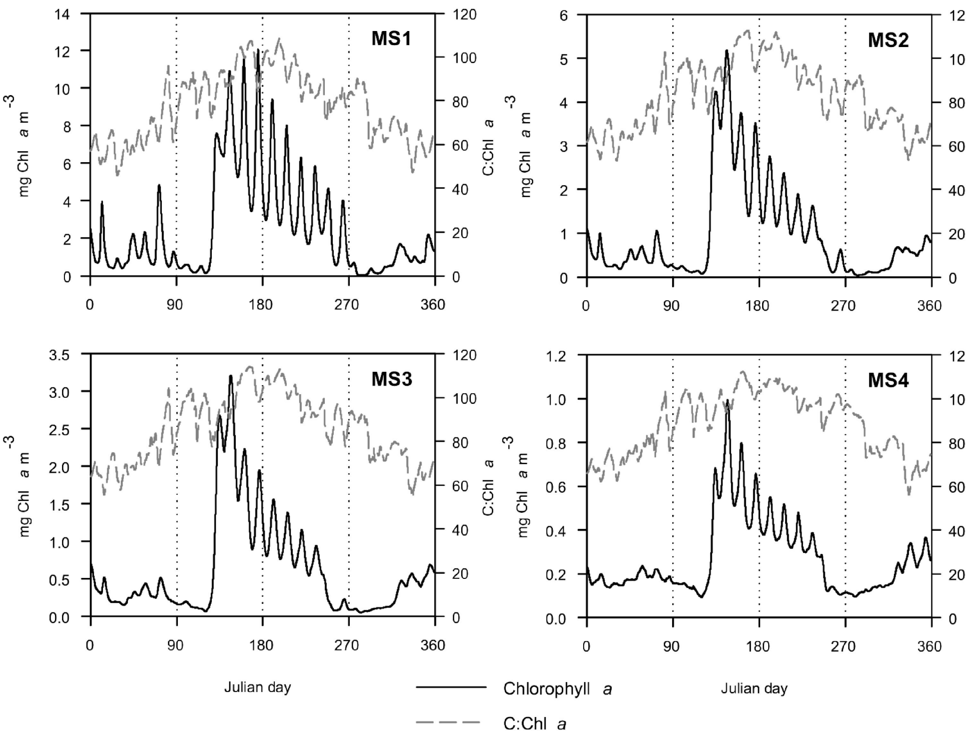

Fig 8: The results of the model for diatom: chlorophyll *a* concentration (grey line) and C:Chl*a* ratio (bold line)

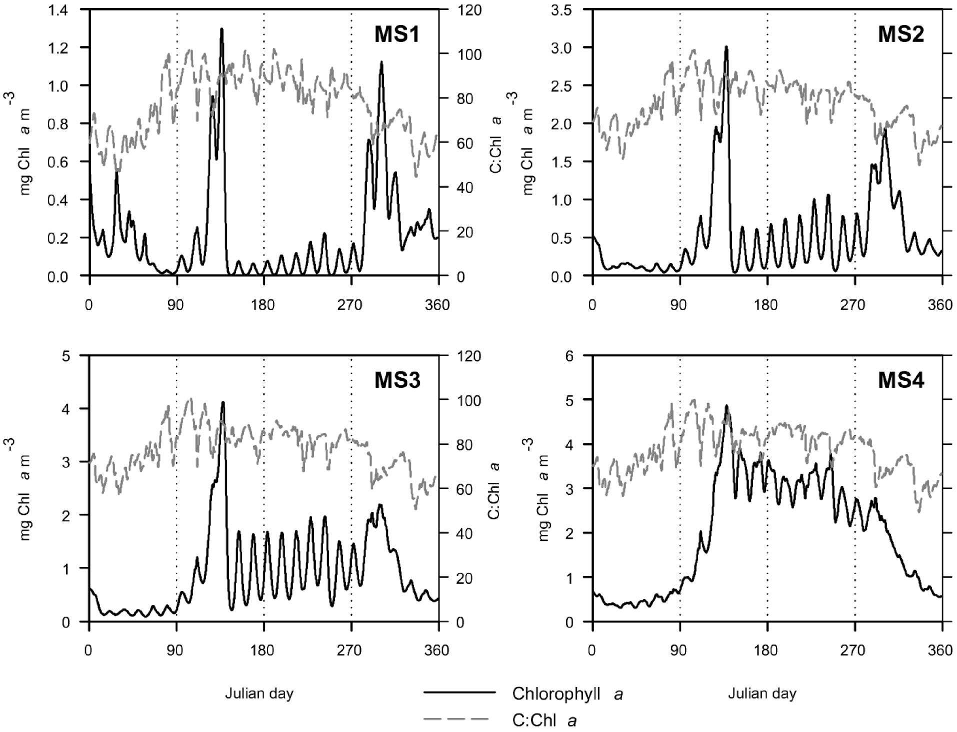

Fig 9: The results of the model for autotrophic flagellates: chlorophyll *a* concentration (grey line) and C:Chl*a* ratio (bold line)

along the European Atlantic seaboard, the high turbidity in Tagus resulting from strong tidal currents and resuspension of fine particles affects the underwater light climate. As such, light is a key limiting factor for primary production in these systems.[34] Because the estuary is well mixed, phytoplankton populations have to adapt to continuously changing irradiance conditions ranging from complete darkness to saturating light. Under such conditions, the estimation based on a photoadaptation mechanism such as the synthesis of chlorophyll *a* in response to environmental optical conditions is preferred to the estimation based on fixed C:Chl*a* ratios, because it helps to understand the influence of light.

The results indicate light as a controlling factor exhibits stronger effect in autumn/winter as a consequence of: (1) higher river discharges and sediments and organic matter in the water column and (2) the natural light regime characteristic of temperate zones. To compensate for lower light levels, the chlorophyll *a* content of the cells is increased in the model, which explains the observed patterns (Fig 8 and Fig 9). However, even if the C:Chl*a* ratio is appropriately characterised, the values are relatively higher than those that would be expected. Because the chlorophyll synthesis also depends on the nitrogen uptake, the observed fluctuation in the C:Chl*a* ratio obtained using the model is explained by the variable uptake of this nutrient. A quick look at the variation of both ammonium and nitrate makes this point clear. Higher biomass values were found in the upper estuary, reflecting the higher availability of nitrogen, both recycled in the system and added via river discharge; the higher values were also attributed to the higher residence time in this area of the estuary. The lower values were observed near the main channel (MS2 and MS3) as a consequence of the higher hydrodynamic circulation imposed mostly by tidal regime and magnitude. Even under the influence of wind-induced oceanic circulation in the outer estuarine zone, the conditions are still favourable to an accumulation, explaining the increase in chlorophyll *a* concentration from MS2 to MS4.

Nutrient control

The model assumes variable elemental composition (expressed as nutrient quotas), enabling to quantify the influence of nutrient deficiency at any given time (Fig 10). Only a mild nutrient limitation in autotrophic flagellates is observed during summer months for phosphorus. Higher decreases in nutrient quotas occur at MS4 for both producers, because the nutrient supply is limited when compared with MS1. Most of the nutrients introduced by the river are consumed in the upper areas, with only a fraction of it, along with regenerated nutrients inside the estuary, reaching the outer zone of the estuary. This is particularly relevant in summer months when the river flow is significantly reduced, decreasing its importance in the nutrient enrichment in the estuary. During this period, nutrient recycling inside the system becomes more important, as well as the enrichment via coastal water entering the estuary.

The model shows no signs of severe nutrient depletion in the summer, supporting the claim that the production in the system is not controlled by nutrients. The available data for ammonium and nitrate support this result. Limitation of phytoplankton growth by DIN has already been established in the upper areas of the estuary during summer.[35] Nonetheless, both the results obtained using this model and the *in situ* observations tend to disagree with this. So, it can be hypothesised that such limitation is not a common occurrence in the estuary (since *in situ* data used in this study does not support the above assumption) or that the model is failing to reproduce this limitation.

Because of the lack of *in situ* data for silica and phosphorus, conclusion has not been yet drawn regarding their roles in the control of production. Phosphorus limitation for phytoplankton growth has been observed in the Tagus coastal areas,[36] a fact that highlights the relevance of explicitly modelling its cycle in this particular system. The results of the model suggest that there is no apparent limitation by phosphorus (Fig 10), except for autotrophic flagellates in MS4, which is in agreement with the observations.

Nutrients do not limit production in the system but appear to exert some control on producer's group domi-

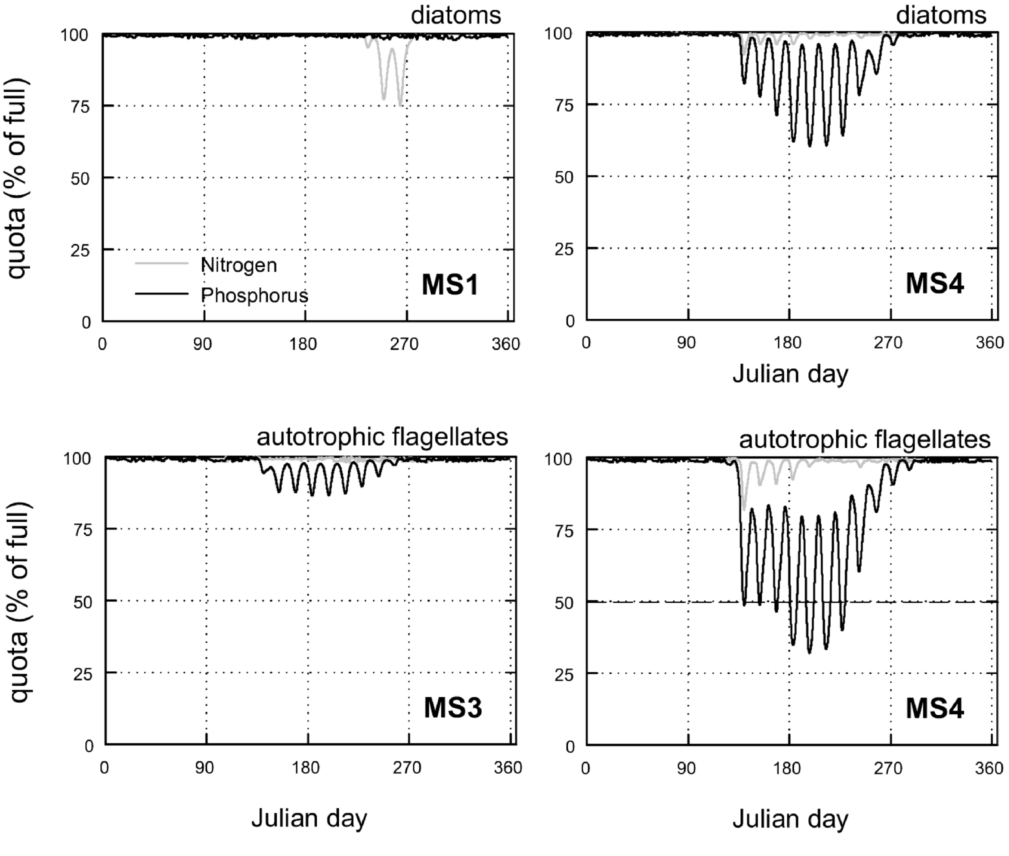

Fig 10: The results of the model results for nutrient limitation, expressed in cell quota of N and P, for diatoms (upper row) and autotrophic flagellates (lower row). Maximum cell quota (100% full) means that the internal C:Nut ratio is twice the Redfield ratio; minimum cell quota (0%) means that the internal C:Nut ratio is half the Redfield ratio. Limitation occurs when quota falls below 50% (Redfield ratio). Only the cases where significant decreases in nutrient quota occur are shown

nance. This can be particularly relevant for silica, because there is a clear decrease in the predominance of diatoms from inner estuarine areas toward the estuary mouth (Fig 7), showing a clear relationship between the availability of silica and the concentrations of diatoms. High values of silicate acid have been observed in the coastal areas outside the estuary in summer months.[36] Being out of the scope of the present study, no special attention was paid to the hydrodynamic regime along the coastal shelf outside the estuary. This area is characterised by upwelling events in late spring and summer,[37] with nutrient enrichment of surface waters and an associated high productivity. Because this seasonal phenomenon is not modelled, the influence of the nutrient-rich water is not considered, possibly conditioning the results of the model in lower estuarine areas during summer.

CONCLUSION

The results of the model suggest that light acts as a controlling factor inside the estuary, reinforcing the hypothesis of light limitation already proposed by other experimental and numerical studies.[10,36,9] This control has already been advanced by a detailed modelling effort using the MOHID hydrodynamic model with a coupled NPZ water quality model.[8] This study supports this premise using a more complex model that provides further insight into the ecological dynamics of the system.

The lack of a 'typical' nutrient control scenario is of particular relevance in the Tagus estuary case. The estuary receives the discharges from more than 10 WWTP, acting as point sources of nutrient supply. The estuary receives a nutrient input corresponding to about 3×10^6 population equivalents (PEQ), resulting from domestic and industrial discharges.[38] So far it has been suggested that a 50% decrease in the nutrient loads that reach the estuary via WWTP will not change the state of the system.[8] Additional WWTP are projected and, therefore, the nutrient load is expected to increase in the near future. Hypothetically, this increase in nutrients will not result in deleterious effects on the system. Nonetheless, the input of anthropogenic nutrients (N & P) may induce a change of Si:N in the system, possibly leading to conditions that allow for the dominance of flagellates over diatoms.[39-41] Climate changes will also have a marked effect in the system and will have to be considered in predictive studies on the future state of the estuary. Of particular importance in these studies is the effect that the expected reduction in the rainfall regime will have on the river flow and, consequently, on the ecologic dynamic of the estuary.

The variable parameterisation of carbon to nutrient ratios allows for the identification of conditions leading to values below the Redfield ratio, implying the limitation by nutrients. The results suggest that this is not a frequent pattern in Tagus estuary. On the basis of the above fact, the preliminary results of the model imply that the system is mostly controlled by light availability, given that the carbon to nutrient ratios only drop below the Redfield ratio on rare occasions. Nutrients may also control production to some extent, but only in lower estuarine areas and in summer. This numerical study seems to agree with the general information available on the system, supporting the idea of a strong control by light in the Tagus estuary.

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