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REVIEW

Sensitivity of the Mediterranean Ecosystem to Nutrient Deposition: An Interdisciplinary Review

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ABSTRACT

Homogeneous methods for ecological applications to the nutrient cycle are analyzed, and the results are presented according to the marine ecology work discussed. To do justice to the explanations, the materials are summarized, and the methods are discussed and improved for both interested readers and experts in the field. Both the materials and the methods serve informative and popularizing as well as applicable and interpretive purposes and, in order to achieve the widest possible dissemination, are shared under the strict supervision of the earlier individual publications discussed here. The aeolian syntheses quantify the impact of atmospheric deposition of nutrients in the Western Mediterranean as one-twentieth of the baseline vertical fluxes of organic matter, while estimates for the Eastern Mediterranean reach one-eighth. Possible changes and additions in the global ocean are discussed as well as ecosystem updates and their relevance to the specific orography, hydrology and geochemistry associated with the lower trophodynamic degrees of freedom. Finally, the dynamics of the basins are analyzed, with increasing nutrient inputs leading to a top-down control of net plankton growth in the western basin and to an extremely nutrient-poor state in the eastern basin.

Keywords: Mediterranean Sea; Aerology; Biogeochemistry; Top-Down Control; Nutrient-Depleted Waters

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1. Introduction

The aeolian syntheses in the pelagic ecosystems were previously defined and the representations have been extended to include a developed and deepened dynamical significance of the contribution to the budget part. The changes and additions do not affect the previously obtained results [1], but have taken them up and improved their understanding by keeping them as references, namely to contribute with specific general approaches and to introduce explicit interpretations.

The methods can be used by geoscientists, whether they focus on the general geophysical and climatic topic or on interdisciplinary research. They are outlined here to ensure the widest possible dissemination and distribution among the partnerships listed in the acknowledgements and the general public, e.g., in the cited GLOBEC special issues and books [2], and the twenty-four authorships listed [3] for the BOUM experiment.

Given the scientific origin, the original presentation is maintained in the context of the Mediterranean projects, as well as the mathematical apparatus and the results. In this way, the methods presented are made valid for future research and applications and understandable for everyone.

In addition, the presentation is suitable for use in research programs in countries in Africa, the Middle East, the Mediterranean region, and the Mediterranean coasts, as well as in northern European regions, should projects be carried out to apply these methods.

The aim is to report on the impact of aeolian deposition using atmospheric data and methods selected to provide the best seasonal and annual estimates in the oligotrophic to mesotrophic regime. As our comments on the results confirm, it is not possible to introduce new data and methods for the reasons given above in the Materials and Methods section, but there is a link to other studies in the area covered by this review; indeed, working systems for seasonal biochemical cycles in different environments that are eutrophic and also subject to permanent features are cited to provide new potential methods and data analyzes. A eutrophic scenario is also shown in the mixed depletion of the Mediterranean Sea, nutrient-poor, oligotrophic in the eastern basin and relatively rich, mesotrophic in the western Mediterranean, but with still lower nutrient levels than observed in the Atlantic Ocean and Pacific Ocean.

The methods are presented in general terms and are therefore applicable in the ocean, in basin responses and in coastal seas. The logical thread linking these three approaches is their inherent accuracy, which leads to the reasonable assumption that they can be used in small-scale environments, in medium-scale and regional large-scale situations, and in coupled land-ocean-atmosphere applications. On the other hand, future projections of environmental parameters will necessarily require both accurate processes and the transition to stabilized dynamics to meaningfully couple the three systems and introduce semi-quantitative and discrete hierarchies between the different modules of the ecosystem.

In the Materials and Methods section, the correctness of the methods is derived from the given demonstrations, making them suitable for possible extensions of the scope and the introduction of new measurable parameters to complete the nutrient cycles.

This dynamic approach reflects the broad impact that quantitative ecology has found in recent years [4] to identify the channels of energy distribution in the overall system and to shed light on the natural behavior of individual species and selected communities, which is expressed in the Results section and summarized in the Discussion section.

2. Materials and Methods

2.1. Materials

For the discussion of the results and interpretations of the aeolian syntheses, the unabridged and revised version [5] is hereafter cited. This version includes new references representing the oligotrophic conditions of the Eastern Mediterranean and the mesotrophic situation of the Western Mediterranean, as well as further contributions on climatological applications and the description of data and methods.

The model configuration is improved and the description of the coupling is further developed: the explicit import of carbon release feeding into the carbonaceous compartment D_C links the carbon cycle to the nutrient cycles.The numerical experiment is described in detail, indicating the time integration and the turbulent diffusivity of the thermohaline field. The Chl:C transformation quota R_{SL} is included and the calibrated efficiencies for the ultraplankton S and the netplankton L are discussed [5]: the first compartment represents the autotrophs smaller than 10 μm and the second the autotrophs larger than 10 μm.

The validation of the 20-m chlorophyll concentrations at the surface using the synchronous satellite data from 1978 to 1985 and the seasonality are described in the discussion. The Chl:C ratios for the two phytoplankton compartments are presented analogously as annual mean values for the upper 20-m layer and the main Mediterranean regions are included in the station map [5]. The main advances have been made by also addressing the chemistry of nitrates and phosphates and the potential density profiles to compare the results with the data from the study of the zonal and meridional transects: adding syntheses of nutrient data and potential density to show the responses in different regions of the eastern basin and the western basin and their relationships to biomass.

The main points discuss the lines that need to be developed to show the ecosystem benefits and the three-dimensional perspective. The final presentation is part of this integration to discuss seasonal variability. Citations are added to provide experimental results of biochemistry in different regions of the Mediterranean. Additional information is included here to allow further investigation.

The values in **Table 1** show the variation of the carbon flux in the direction of the layers at 500 m depth for the two areas indicated. The values are consistent with estimates made during the first phase of the Mediterranean Targeted Project [6], and they are reasonably consistent with estimates of organic particles made later in the Western Mediterranean at 200 m depth [7, 8]. On the one hand, the earlier experimental estimates illustrated the differences between oligotrophic and eutrophic zones in the Mediterranean, partly on time scales consistent with the physical forcing; overall, they showed the orders of magnitude of quantities transferred from the upper layers to the intermediate layers. The increase due to the first atmospheric input is small in the western basin area, about 6%, and, for the second input, it is smaller, reaching an increase in mass transfer of only 2%. In the southern Adriatic, the increases are higher at 16% and 10%, respectively.

These estimates underline the importance of understanding the dynamics of the Aegean and the Adriatic: taking into account the different levels of physics and biogeochemistry [9] and including the thermohaline evolution north of 38° N in the Aegean with the dynamics of the straits and the analogous expansion north of 43° N in the Adriatic [10].

The zooplankton rate in **Figure 1** gives a total organic matter load of 0.0415 d^{-1}. This oceanic rate corresponds to five-thirds of the total amount of detritus produced by zooplankton compared to aeolian synthesis: in the Mediterranean, the netplankton compartment does not dominate in all regions and seasons where it is scarce, reducing the formation and removal of organic matter and the development of higher trophic cycles.

In addition, respiration of netplankton and ultraplankton contributes to nutrient availability. To summarize the total fluxes, all the consequences of grazing must be considered with ecosystem parameters: the gross primary production, the ingested part; the net primary production, the digested part that is assimilated; the egested part; the unassimilated, undigested part.

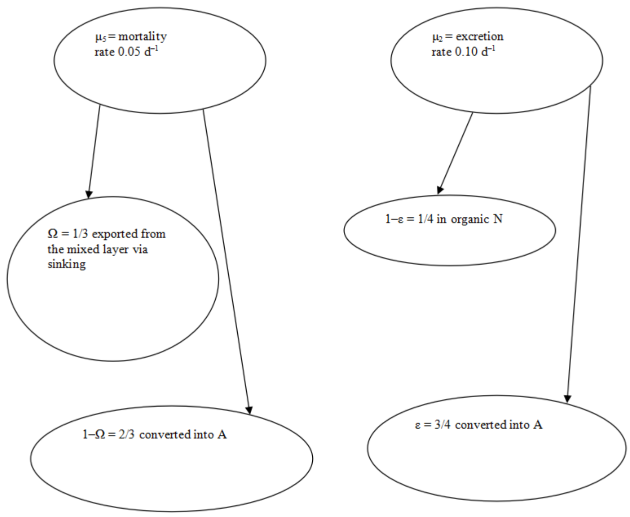
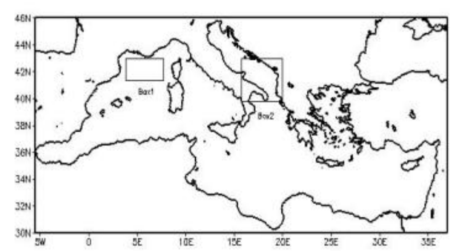


Figure 1. Focus on the mortality and excretion of zooplankton; pathways to inorganic and organic nutrients are also shown.

What has already been said about the excretion rate and the mortality rate also applies to the coupling between phytoplankton and zooplankton: the growth constant and the half-saturation agree with those of Fasham, Duklow and McKelvie [11] when the r_{NC} transformation is taken into account; the grazing efficiencies are calibrated in the light of this classical coupling parameterization [12].

Figure 2 shows the total nitrogen and phosphorus in the Mediterranean Sea during the two-year control test conducted under the bufferless zone conditions in the Strait of Gibraltar, the Adriatic Sea and the Aegean Sea to demonstrate the numerical equilibrium of the chemical tracers without atmospheric input. The standard deviations of total nitro-

Table 1. Downward carbon fluxes (mg C m^{-2} d^{-1}) from the western basin, *Box1* in the Gulf of Lions, and the eastern basin, *Box2* in the southern Adriatic Sea, the two areas of the Mediterranean shown, estimated at 500 m depth by the atmospheric input scenarios: without input baseline NIRUN, and geodynamic averages GARUN and atmospheric values AVRUN, with atmospheric nitrogen and phosphorus inputs added to the baseline.



	NIRUN	**GARUN**	**AVRUN**
Gulf of Lions *Box1*	59.7	63.3	61.1
Adriatic Sea *Box2*	24.4	28.5	26.8

gen and total phosphorus are 8.68 1012 µmol N and 5.83 1010 µmol P, respectively. The errors for the first year do not exceed 5.0 1012 µmol N and 5.0 1010 µmol P. Thus, the maximum errors for the total estimates are 70 tonnes of nitrogen and 1.6 tonnes of phosphorus per year after conversion from µmol to tonnes. These values correspond to losses of less than 0.000035% of total Mediterranean nitrogen and 0.0000016% of total Mediterranean phosphorus in the annual simulation. According to the biochemical budget discussed, the conservation of nitrogen and phosphorus in the different forms is obtained for the ecosystem, and the aeolian syntheses are obtained with the numerical accuracy indicated.

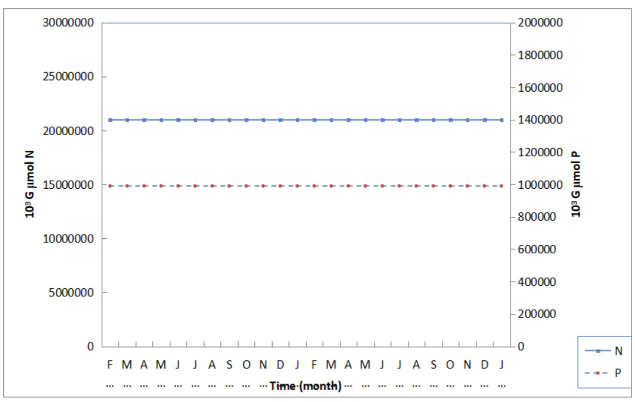


Figure 2. Two-year conservative evolution of the total nutrient content in the Mediterranean Sea in 103 G µmol; this evolution was carried out as a test without buffer zones in the Strait of Gibraltar, the Adriatic Sea and the Aegean Sea.

The processes are thus developed keeping the general parameters and, within this homogeneous description, the spatial differences associated with atmospheric deposition conditions are treated in detail. In addition, the mathematical approach is made more precise by rearranging the constitutive equations of the ecosystem and the individual steps can be repeated for the selected material by working with the released ECHYM material on the CD-ROM D40-M32 [13].

2.2. Methods

These aeolian syntheses indicate that the eastern basin, which is considered an oligotrophic environment, is in a state of increased nutrient depletion with contributions of new nitrogen and new phosphorus. The inverse estuarine circulation characteristic of the Mediterranean explains the scarcity of nitrogen and phosphorus nutrients in the deeper layers; this does not apply to the oligotrophic state in the euphotic zone. The zonal fluxes between the basins are also well represented and are important for the overall dynamics and oligotrophy [5]. The interpretation of the differences in the Strait of Sicily and the Ionian Sea may be related to an underestimation of the effects of evaporation in the Eastern Mediterranean. The physical system tries to restore the correct situation by restoring the surface salinity and therefore the fluxes of surface salinity; this point is potentially important for the dynamics of the eastern basin and suggests overcoming the assumption of a rigid lid.

In phytoplankton, the internal P:C ratio, R_{PC}, is higher than the ratio in the zooplankton compartment, r_{PC}, and therefore part of the biomass is allocated to zooplankton and the remaining part becomes carbonaceous detritus, D_C.

Figure 3 shows the growth functions for ultraplankton and netplankton under typical optimal nitrate concentrations, temperature and light. It can be seen that low nitrate concentrations favor the growth of the ultraplankton compartment, while high nitrate concentrations favor the growth of the netplankton. Mortality and exudation are not considered here as they affect the detrital compartment. However, in the left zone, which is subject to oligotrophic growth, these effects favor the ultraplankton compartment.

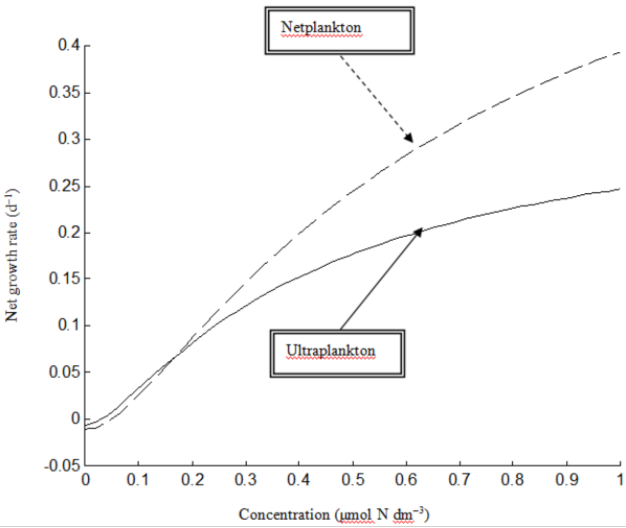


Figure 3. Net growth rates, gross primary production minus respiration, based on nitrate concentration only, of ultraplankton, full line, and netplankton, dashed line, both at 1 μmol C dm^{-3}, are integrated from the surface down to 100 m at 20 °C and half-day light limitation with a representative value of 0.27.

Another point relates to the general nitrogen limitation according to Fasham, Duklow and McKelvie [11]. There are proposals for different limitations of nitrate and ammonia; in general, the differences should be minimal due to the small amounts of the limiting factor ammonia. In any case, it is a matter of study to use different formulations, and we note that the nitrogen limitation chosen in the aeolian syntheses is also used by other three-dimensional modeling applications in the Pacific Ocean [14].

Furthermore, the formulation [15] of the ammonia inhibition may include some features that cannot be normalized in situations of eutrophication of the ecological system, but has no effect on the normalization of the growth factor in oligotrophic situations. In fact, the multiplication factor of the two limiting nutrients nitrogen and phosphorus does not exceed the unitary threshold because nutrient concentrations are low in the presence of primary producers.

The assumption of a minimum of nitrogen- and phosphorus-limiting functions is another possibility, which is also biologically correct. In both cases, the complexity of the system must include descriptions of the exchange within the nitrogen and phosphorus cycles. The minimum of independent phosphorus and nitrogen limitation requires the introduction of internal nutrients as independent variables [16], while, in the aeolian syntheses, the internal ratios are the N:P values in autotrophic organisms, the netplankton and the ultraplankton. The results of alternative approaches, such as the minimal formulation evaluated below, help to assess which of these options are both biologically realistic and accurate for representing nutrient uptake by the netplankton and ultraplankton, first at medium and then at large scales.

Several approaches have been proposed by Frost and Franzen [17]: the numerical experiment is modified by adding new limiting factors for phytoplankton uptake and used in one-dimensional applications. The limiting factors for phosphate, nitrate and ammonia are calculated according to the following minimum formulae, k_1 and k_2 are the half-saturation constants for nitrate N and ammonia A, respectively:

$$\text{If } \min\left[\frac{P}{k_P+P}, \frac{A}{k_2+A}+\frac{N}{k_1+N}\frac{k_2}{k_2+A}\right]=\frac{P}{k_P+P} \text{ then}$$

$$\lim(A)=\frac{\dfrac{A}{k_2+A}}{\dfrac{A}{k_2+A}+\dfrac{N}{k_1+N}\dfrac{k_2}{k_2+A}}\frac{P}{k_P+P} \tag{1}$$

$$\lim(N)=\frac{\dfrac{N}{k_1+N}\dfrac{k_2}{k_2+A}}{\dfrac{A}{k_2+A}+\dfrac{N}{k_1+N}\dfrac{k_2}{k_2+A}}\frac{P}{k_P+P} \tag{2}$$

$$\lim(P)=\frac{P}{k_P+P} \tag{3}$$

$$\text{If else } \min\left[\frac{P}{k_P+P}, \frac{A}{k_2+A}+\frac{N}{k_1+N}\frac{k_2}{k_2+A}\right]=\frac{A}{k_2+A}+\frac{N}{k_1+N}\frac{k_2}{k_2+A}$$

then

$$\lim(A)=\frac{A}{k_2+A} \tag{4}$$

$$\lim(N)=\frac{N}{k_1+N}\frac{k_2}{k_2+A} \tag{5}$$

$$\lim(P) = \frac{A}{k_2 + A} + \frac{N}{k_1 + N}\frac{k_2}{k_2 + A} \qquad (6)$$

The problem is not solved by taking a series of limiting factors, the first of which always inhibits the subsequent factors. In the Eastern Mediterranean, where one starts with phosphorus and then considers nitrogen, this method could perhaps lead to remarkable results in winter, but is less valid in temperate seasons where phytoplankton is co-limited by the availability of nitrogen and phosphorus [18].

Certainly, this method could lead to a profitable nutrient hierarchy by introducing silicates before phosphorus and nitrogen in eutrophic areas of the Western Mediterranean, which is detrimental to diatom growth and thus to the net-plankton compartment.

The aeolian influence is important when considering the average annual chlorophyll anomaly at 10 m depth, i.e., the response of the input chlorophyll minus the baseline chlorophyll. The Levantine Basin, the southern Ionian Sea and the central Tyrrhenian Sea show positive anomalies of 0.06 mg Chl m^{-3}. Negative anomalies, due only to atmospheric input, are found mainly in the Alboran Sea and the Gulf of Lions along the border, and to a lesser extent in the Algero-Provençal Basin. These effects are related to a stronger evolution of the total biomass in the baseline due in the first case to the anticyclonic circulation with the loss of organic matter towards the sediment, or in the other cases to the cyclonic eddy boundary influenced by topographic effects and boundary currents, with the loss of organic matter towards the shelf[5].

The analysis of monthly surface chlorophyll is indicative and provides maps of seasonality. They can also be used for comparisons with field data from a seasonal perspective. The monthly maps of surface chlorophyll show the highest signal in December and January in the western basin, while in the eastern basin the maxima occur one month later. In spring and summer, these signals occur only in the Alboran Sea and in some coastal areas of the Ligurian Sea. In the fall months, the conditions for the growth of new biomass are restored. The dynamic explanation for this seasonal development lies in the mixing and mesoscale processes that bring new nutrients to the surface layers at the end of the fall. These processes promote the growth of phytoplankton at the beginning of winter, which manifests itself in maximum chlorophyll levels at the surface and, as already mentioned, can be observed in mesoscale cyclonic eddies. This is followed by a maximum of chlorophyll signals due to initial stratification and the start of secondary production. Subsequently, exudation and lysis of biomass lead to a net flux of organic matter to the intermediate depths. Remineralization of organic matter into nutrients fertilizes these intermediate layers and creates the necessary conditions for the repeating cycle.

Measurements of carbon in phytoplankton of the Western Mediterranean and Eastern Mediterranean are vertically integrated [19, 20]. The annual Chl:C ratios and the monthly average values remain independent at this stage. Indirectly, these values are confirmed by the validation of the surface chlorophyll maps, whose results are mainly determined by the predominance of netplankton in the western basin and ultraplankton in the eastern basin [5].

The statistical analyzes over the last 36 months determine the mean values and 95% confidence intervals. The statistical ranges of the aeolian syntheses overlap in the western basin and are approximately the same in the eastern basin.

For the zonal transect 34° N in the Eastern Mediterranean, the general trends are in good agreement [5]. The values are very close to each other when integrated vertically along the transect. The higher chlorophyll content in the eastern part of this transect thus compensates for the lower biomass in its western part. The average values are therefore consistent in their confidence intervals with the interpolated MEDATLAS dataset [21] and may represent an unbiased response of the entire basin to aeolian nitrogen and phosphorus.

The general trend of lower chlorophyll content in the southern and central parts of the meridional transect 6° E in the Western Mediterranean compared to the interpolated MEDATLAS dataset, i.e., the eastern coast of Algeria and the Algero-Provençal Basin, is confirmed by the average values in these two areas of about 35 mg Chl m^{-2}. On the other hand, the value in the northern area, in the Gulf of Lions, is confirmed by the average of the raw data of 45 mg Chl m^{-2}. These results concerning the summer increase of the deep chlorophyll maximum compared to the values of the MEDATLAS dataset interpolated up to a sixth degree are consistent in different areas of the Western Mediterranean [7].

The lack of much data in the middle of this meridional transect allows a rough estimate of the average values. Apart from this lack of in situ data, most data are available in late spring and summer, leading to a clear dominance of well-defined deep chlorophyll maxima in spring and summer in the annual average with a flat overestimation from south to north in the upper layer of 0–200 m[21]. However, the opposite behavior is observed for the vertically integrated chlorophyll in the surface layer from the surface to 20 m, so that the interpolated MEDATLAS dataset underestimates both the synchronous CZCS data and the aeolian syntheses in the presence and absence of atmospheric inputs. As mentioned above, this is because the in situ data are mainly from late spring and summer, when the surface formation of the winter response to nutrient upwelling is not yet present. Therefore, the average values for the basin also appear to be an unbiased estimate of the response to fertilization in the western basin[5].

The aeolian concentrations of dissolved inorganic nitrogen and phosphorus are consistent with the respective nutriclines. The higher chlorophyll signals appear to be an upward response of phytoplankton to the new nutrient due to convective adjustments, and this intense dynamic occurs in the early winter months.

The dynamic explanation for this seasonal development lies in the mixing processes that bring new nutrients to the upper layers in late fall. This process favors the growth of phytoplankton in early winter, as can be seen from the chlorophyll maxima on the surface. Then, due to the initial stratification, there is a chlorophyll maximum at depth and the start of secondary production. Exudation and the death of autotrophic organisms lead to a net flow of organic matter into the intermediate layers. The remineralization of organic matter into nutrients fertilizes these intermediate layers and thus creates the necessary conditions for the annual cycle. The monthly variability in the zonal eastern transect and that in the meridional western transect include the seasonal variability of surface chlorophyll summarized above.

In the western basin, the winter bloom begins near the northern Gulf of Lions. When it reaches its peak, chlorophyll develops in the central part of the western transect, followed by its southern part. At the end of the year, new production conditions prevail as the conditions for an abundant supply of nutrients from several layers at depth are met. In the eastern basin, the Levantine Basin is characterized by an almost constant chlorophyll maximum at depth throughout the year with higher values in spring. This regenerated cycle is associated with a similar bloom in the western part of the eastern transect, which forms at a depth of about 75 m, then moves upwards and finally breaks off.

The production fluxes are compared with the average values of the field data and with the bio-optical estimates: there is general agreement with the bio-optical model results and with the estimates of primary production from the in situ data; secondary production also agrees well with the carbon data.

3. Results

Analyzing the evolution of dissolved oxygen requires numerical experiments that are at least as long as the typical residence times in the Western Mediterranean, i.e., a few decades, and those of the Eastern Mediterranean, i.e., over a hundred years, longer than the years evaluated here with atmospheric inputs. Aeolian syntheses include not only the relaxation of dissolved oxygen, but also average surface currents of 20–30 cm s^{-1}, which have been detected in some areas.

The exchange in intermediate and deeper layers still needs to be verified to compare the given responses with future work. A specific sensitivity analysis for different oxygen fluxes between ocean and atmosphere – wind speed, sea state, and thermohaline field – is needed to maximize oxygen profiles.

The configuration maximizes the importance of the positive flux due to photosynthesis and the negative flux due to the biochemical demand for oxygen[22]. In addition, the formulation of light in the ecological system is consistent with the estimation of the heat budget. The photosynthetically available radiation depends on the total radiation reaching the sea surface under a clear sky, the length of the normalized day takes into account declination and latitude, and the values for light extinction introduce the realistic behaviors.

Five parameters can be estimated simultaneously in a 1D water column with daily measurements at 5, 50 and 100 m depth. The parameters that can be estimated are those that measure the following processes: light extinction coefficient for phytoplankton growth; grazing rate of zooplankton; maximum growth rate of netplankton; maximum growth rate of ultraplankton; Arrhenius basis of temperature coefficient for respiration, exudation, excretion and remineralization rates.

The variation in biomass is well described [22], with ultraplankton depending in relative sensitivity on the maximum growth rate of netplankton. When the parameter is varied by 10%, the biomass of the ultraplankton varies by about 20% and the bloom of the ultraplankton is delayed by one month in spring and two months in fall. However, even with this variation in the maximum growth rate of the netplankton parameter in relation to the nominal parameter, the coexistence between the two components of the autotrophs is maintained throughout the year. Moving to a 3D scenario, the two efficiency parameters for ultraplankton and netplankton are added due to the increase of two degrees of freedom.

Another formulation could try to reconstruct these differences between basins by simulating the self-shading of phytoplankton growth through the numerically simulated biomass and organic matter. In the aeolian syntheses, chlorophyll is introduced as a diagnostic variable via the Chl:C ratio. These regionally measured light limitation parameters are internally maintained by the variation of light extinction with depth and are constantly included in the Chl:C ratios for the ultraplankton and the netplankton. For this reason, these parameters cannot influence the results a priori. The validity of this formulation is confirmed by the surface chlorophyll maps produced with the synchronous Coastal Zone Color Scanner data from 1978 to 1985 [23], i.e., collected at the same time as the physical data were collected. The chlorophyll validations in the surface layer from the surface to 20 m are consistent with 10% improvements in correlations between CZCS and chlorophyll values compared to previous syntheses [24].

The forcing dates from the 1980s, as does its behavior in the buffer zones. The reason for choosing this time period is twofold. First, the estimates of currents in the western basin – about 0.95 Sv – and from the eastern basin – 1.5 Sv on average – are close to the measurements in the Strait of Gibraltar and the central Mediterranean [25] – with 1 Sv = 106 $m^3\ s^{-1}$. This is the main cause of zonal oligotrophy in the Mediterranean, and therefore the physical system is of great interest in agreement with the biochemical data. Secondly, the transient in the Eastern Mediterranean has increased the formation of deep water and uplifted the deeper and intermediate layers [26]. This has changed the situation when comparing the results with previous data. The aeolian syntheses are able to introduce these high-frequency convective processes [27], in this case with restorations of surface temperature and salinity, but also to assess the magnitude of the same effects in the Mediterranean.

Some general comparisons with the experimental data are considered from a seasonal perspective and the evolution towards stationarity is discussed. The fact that zooplankton levels remain low from the initial zooplankton biomass typical of the Eastern Mediterranean is consistent with experimental results in the Cretan Sea [28, 29]. The results remain at higher values because the aeolian syntheses in the zooplankton compartment include all the upper trophic levels that close the ecosystem. This is an important experimental basis for further calibration of the biological coupling constants.

It is true that the generic biochemical tracer here refers to the physical tracers and not to the dynamic equations. In fact, the transport terms are the same, but the biochemistry spreads as differently as θ and s due to different vertical diffusion constants. The fact that the viscosity is then larger than the diffusivity depends on the effects of vertical motions on this eddy-permitting general circulation model. In this direction, it might be useful to evaluate a finer spatial grid with an eighth of a degree or a tenth of a degree, i.e., 12.5 km or 10 km resolution. However, it does not seem reasonable to vertically multiply the number of levels in the intermediate and deeper layers, unless one needs to address ecological questions that require high resolution in reactive deep layers and seawater in contact with diagenetic sediments.

Another feature is the presence of surface fluxes in the physical tracers, in this case heat fluxes and the surface salinity restoration. The biochemical variables are instead subject to isolation conditions, with the exception of dissolved oxygen relaxation only at the surface, as this variable has no influence on the total nutrient content. In the aeolian syntheses, only locally balanced biochemical releases and uptakes are introduced, while the integral contents of nitrogen and phosphorus are maintained, except for the nutrient loads at the surface.

At the same time, the main applications of this aeolian framework are evaluated in their climatological implications and the validity of similar approaches for biogeochemical interactions on medium and longer time scales with nutrient deposition and ocean-atmosphere variability are tested.

From the laboratory basin perspective, the following general statement [30] can now be transferred and applied to the aerological framework: "It is a stereotype that the Mediterranean Sea can be somehow considered as a miniature ocean, especially for what concerns dense water formation processes. Mesoscale phenomena resulting from instability of the major Mediterranean currents have space and time scales that compare well with those encountered in the most energetic regions of the global ocean. Such Mediterranean studies will thus have a direct application in global oceanography."

In addition, some recent results on the N:P ratio in the Mediterranean are based on four facts: (1) the eastern part of the Mediterranean is on average higher than the corresponding oceanic Redfield ratio, which is 16:1, with a greater relative abundance of nitrogen over phosphorus in the rivers and in the atmosphere compared to the Redfield ratio; (2) organic phosphorus is recycled faster than organic nitrogen, the latter remaining in deeper layers due to the inverse estuarine circulation of the Mediterranean; (3) nitrogen fixation in the Mediterranean has only a limited impact [31]; (4) the impact of denitrification is negligible [32].

This important line of interpretation is also evident in the area of dissolved inorganic nutrients, which are dominated by remineralization of suspended and particulate organic matter and controlled by advection and diffusion with internal relationships that are very different from the Redfield ratios [33]. The study of the selected stations shows a significant variation of the N:P ratio in the upper layer from the surface to 200 m with an increase in the value in the spring and summer months, from April to September, and a relative dominance of the phosphate denominator P in the other months. This result points to a well-known situation [34]; there the main difference is that in ECHYM low ratios, about 10, are also present in summer and in subsurface areas in fall, while in the data they are found in fall and the first part of winter.

From the discussions on the areas, it appears that the aeolian syntheses are a valuable support in addressing the previous four points considered important for the Mediterranean region, with appropriate calibration in the different areas determined by the experimental data. A review paper emphasizes the importance of satellite data to complement the information from the in situ data and the spatial distribution factors of the data [34].

UNEP recommendations and planning work [35] emphasize the need for three plans to integrate knowledge of the Mediterranean Sea, which is divided into the Western, Central, Adriatic and an Eastern area corresponding to the Levantine Basin and the Aegean Sea for study purposes.

First, there are the basin areas and subbasin study regions that connect the coastal area to the open sea. Secondly, there are the sites of national interest, mostly on the coast, which are important from an artistic, historical, touristic and conservation point of view. Finally, there are the recognized sites, which are of international importance due to their connection with changes in the marine ecosystem for previous studies and research in the fields of ecology and climate change. The link between the different environments is established through eleven indicators whose gradation describes the environmental scenarios from the coast to the potential impact on the variability of the Mediterranean Sea and the subbasins [35].

The possibility of such integration, which is relevant to both the Mediterranean and the oceanic ecological environment, is not as immediate as in the timeline produced by this international working group.

However, there is an interesting synergy between national sites, which are certainly well maintained and adequately funded, and international sites, which depend on specific programs with uncertain operation and variable funding over the years, as well as large-scale sites working along data collection processes.

Perhaps because of the expansion of the field of research, these integrated syntheses at the basin scale are open to technical details, such as complex multiparameter boundary functions for growth or dynamic nutrient assimilation processes, and the models are becoming increasingly complex, both in terms of the large number of variables and the longer simulation periods, ranging from months to decades [36].

In this sense, the aeolian syntheses appear in a new light when used as a benchmark for the evolution of eddy-resolving dynamics from the consolidated eddy-permitting general circulation models.

Similarly, for a system model of intermediate complexity with a high fraction of deposition in areas interacting with the atmosphere, it is useful to have a biogeochemical model that provides reference results at different spatial scales and over long timescales, to make comparisons and assess progress in the subsequent complication of the description.

This control function is present in several recent works on coastal areas. Some coastal systems have an important component of aerological impacts comparable to those of rivers in the study area [37]. Another work [38] deals with the comparison of different ecosystems affected by important components such as the microphytoplankton and the benthic food web.

The use of satellite data has recently evolved to arrive at spatial estimates of chlorophyll area for water quality, to develop synthetic indicators and to compare these indirect data with model results, both in coastal and oligotrophic areas of the Mediterranean [39] and in bays and harbor areas [40].

In the western basin, a decrease in the biomass of the netplankton compartment is observed with nutrient loads. This result seems to contradict the higher primary productivity exhibited by this compartment in the presence of atmospheric inputs.

To interpret this point, we consider the secondary production SPZ, divided into the contributions of the ultraplankton and the netplankton, SPS and SPL, respectively the right arrows in **Figure 4.** The left arrows also represent the parts that are not taken up by the zooplankton, either by sloppy feeding or by release feeding.

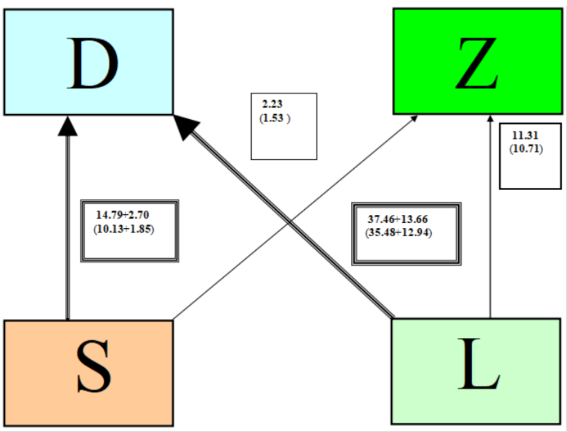


Figure 4. AVRUN western basin sloppy feedings and release feedings into organic carbon, respectively, first and second addends, and AVRUN western basin secondary production on ultraplankton S and netplankton L, and corresponding values for NIRUN western basin in parentheses; all values are in g C m^{-2} y^{-1}.

Zooplankton production therefore allows us to estimate a biomass indicator for the netplankton, where the preference coefficient is equal to one, as in the aeolian syntheses, using the following expressions

$$I_L = (k_H + S)\frac{SPZ - SPS}{\varepsilon_L g \underline{Z} R_{PC}/r_{PC} - SPZ + SPS} \tag{7}$$

with vertically integrated zooplankton $\underline{Z}$ in g C m^{-2} and the zooplankton grazing rate g on the annual time scale of SPZ and SPS.

The results can be generalized with the biomass indicator for compartment i

$$I_i = \left(k_H + \sum\nolimits_{j\neq i} S_j\right)\frac{SPZ - \sum\nolimits_{j\neq i} SPj}{\varepsilon_i g \underline{Z} R_{PC}/r_{PC} - SPZ + \sum\nolimits_{j\neq i} SPj} \tag{8}$$

and in the case of a single phytoplankton, e.g. in the case of the NPZD model – nutrient, phytoplankton, zooplankton, detritus – the expression is further simplified to

$$I_P = k_H \frac{SPZ}{\varepsilon_P g \underline{Z} R_{PC}/r_{PC} - SPZ} \tag{9}$$

Thus, if the indicator I_L decreases when nutrients increase, the ecosystem is no longer controlled by nutrient concentration but by zooplankton biomass and falls under top-down control, i.e., predation by higher trophic levels affects the increase in the abundance of autotrophs.

To interpret the fluxes in the western basin, the I_L indicator is calculated in the NIRUN and AVRUN cases: in the first case, without atmospheric inputs, the indicator is 1.06 from the fluxes of **Figure 4** and from the average S concentration in the euphotic zone; in the second case, with AVRUN nutrient inputs, I_L is 1.03. This decrease shows a situation of top-down control, where zooplankton biomass controls the growth of netplankton, even if there is greater nutrient abundance and an increase in all productions.

Thus, expressing everything in terms of total secondary production, SPZ, minus secondary production of ultraplankton, SPS, results in a larger contribution of zooplankton biomass to AVRUN than to the numerator, which represents only netplankton production: since the biomass indicator is the grazing equation, which is solved in terms of L, the concentration of netplankton consequently decreases with the atmospheric contribution.

The biomasses agree well with experimental data [41, 42], but the link to production may not yet be precise enough to evaluate the I_L indicator experimentally. The aeolian syntheses span a three-year period and provide an integrated spatial calibration of the four biological coupling constants: grazing rate, grazing half-saturation, ultraplankton efficiency, netplankton efficiency.

However, the indicator increases in the eastern basin: I_L is 0.53 for NIRUN and 0.54 for AVRUN. In fact, an increase in nutrients corresponds to an increase in biomass in both compartments of the autotrophs, with a higher increase for *S* and a lower increase for the netplankton compartment. It has been shown that the biomass of the eastern basin agrees well with both the phytoplankton data and the secondary production. It even represents an upper limit with respect to the data, as the zooplankton biomass completes the ecosystem and includes all higher trophic cycles.

This top-down control in the western basin for a given compartment allows the study of ecosystem functioning in the western basin, while a bottom-up control prevails in the oligotrophic eastern basin. A refined calibration of the model based on integrated experimental data forms the basis for a new research program in which solutions are explored by bringing the system just below this threshold, by moderately reducing the coupling constants or by misaligning the chosen constants in the western basin relative to those in the eastern basin. The classical coupling constants [43] can be replaced by estimates from the field as well as by parameters determined in the laboratory.

During the same period as the aeolian syntheses, data on ecosystem functioning in the Western Mediterranean, and in particular on copepod abundance and secondary productivity, have been analyzed and some work suggests a top-down control in this ecosystem sector [44]. It should be noted that the aeolian syntheses are different as they focus on primary production. However, an important ecological fact remains to be noted that could affect the mesotrophic western basin in more parts and more sectors of its ecosystem.

Attention then turned to the decadal periods of the Western Mediterranean [45], one of which covers the period of the current syntheses; their work led to a further interpretation of the bottom-up control on the abundances of secondary producers.

The topic is therefore of great interest and could potentially be studied at multiple spatial scales and in multiparametric systems. This biological information needs to be correlated with the interannual and decadal variations in the physics and chemistry of the Mediterranean Sea, which depend on both the variable conditions in the western basin due to Atlantic input and in the eastern basin due to evaporation, to obtain a dynamic insight [46].

To study the entire carbon cycle, one could simply incorporate the total alkalinity method to obtain the dynamics of limiting nutrients and their fluxes with the atmosphere and sediment. One could also divide the detritus into two compartments, one with dissolved organic matter and the other with particulate organic matter. In any case, the biochemical interactions and the constitutive equations depend on the environment chosen for the dynamic study and the specific problem being investigated.

The ultimate goal is to develop a model that can be used as a dynamic ecosystem not only for marine environments, including sedimentary areas, but also for inland waters. Evidence for this program is, first, the use of water classification methods [47] and, second, the fact that the linkage of coastal systems to the open ocean has been done both at the oceanological level and as an integration of constitutive equations derived from marine and coastal data of different origins.

4. Discussion

The results of the Mediterranean forced by nitrogen and phosphorus deposition are analyzed and the effects of aeolian variations on the ecosystem are interpreted. The processes are further developed while maintaining the general parameters and the spatial differences associated with atmospheric deposition conditions are discussed in detail in the context of a homogeneous description. Furthermore, the general approach is clarified by allowing a reformulation of the constitutive equations for the ecosystem and providing additional information. Overall, a comprehensive overview of the methods is provided, which will be useful for those who have already used the results and comments or wish to develop new applications based on these methods.

General circulation is discussed as a mechanism for the depletion of nitrogen and phosphorus in deeper layers. Both the nutrient-depleted upper layer and the higher nutrient concentration below the corresponding nutricline are addressed. These features of nutrient distribution due to the biological pump are illustrated, such as the limiting role of the two nutrients nitrogen and phosphorus driven by mesoscale processes, although other limiting nutrients, e.g., silicates, play a role in the more energetic Western Mediterranean.

The vertical integrations of zooplankton show differences of about 10% between the syntheses. The details of the possible changes in the ecosystem are of interest and contrast markedly with the differences in the presence and absence of the size classes discussed.

The most important contribution of the cited papers is to have established a dynamic, concrete definition of oligotrophic, mesotrophic and eutrophic ecosystems. The Eastern Mediterranean is oligotrophic and will remain so even if the total deposition is complete and limited to the limiting nutrients: secondary production increases naturally by 36% due to aeolian fertilization, but primary production increases much more, by 48%, favoring smaller ultraplankton in a bottom-up environment. The Western Mediterranean, on the other hand, starts under mesotrophic conditions with an even growth of primary and secondary components of the food chain, but can transition to slightly eutrophic conditions after fertilization with dissolved inorganic nutrients corresponding to total dry and wet deposition: primary production increases by 9%, but secondary production increases more, by 12%, so that the latter takes control of the food chain in the eutrophic top-down regime.

It is therefore not surprising that in certain areas of the Western Mediterranean, episodic fertilization by aeolian dust can change the ecosystem from a mixed to a top-down control, from a mesotrophic to a eutrophic regime. The two caveats for evaluating these fertilization events are a mesoscale resolution and a thorough control of evaporation in the basins.

The distribution of nutrients in the studied biochemical compartments emphasizes the role of ultraplankton in the Mediterranean Sea, whose oligotrophy can be explained as a response to basin recirculation. The inverse estuarine circulation leads to a negative nutrient balance for the Strait of Gibraltar, as the surface water imported from the Atlantic is nutrient-poor and relatively nutrient-rich intermediate water is exported. The detailed hydrodynamics and biogeochemical dynamics, which are determined by river inputs and atmospheric influences, explain the variability of the ecosystem.

Finally, basin responses are analyzed, with netplankton growth in the western basin driven by the top of the food chain and increasing oligotrophy in the eastern basin driven by higher atmospheric nutrient inputs.

In this review, the processes are further developed while retaining the general parameters. Within this homogeneous description, the spatial differences associated with the three atmospheric deposition conditions are treated in detail. In addition, the mathematical approach is made more precise by allowing the reshaping of the constitutive equations for the ecosystem and allowing the individual steps to be repeated for the selected material by working with a defined numerical code, which is included in the cited final presentation. Furthermore, the details in the biogeochemical scenarios of the three cases of atmospheric deposition have been revised and we obtain additional information when analyzing the numerical responses in different regions of the Mediterranean Sea. These details and the completeness mentioned above are two of the reasons for this review. Another reason is the goal now achieved of collecting comments from the partnerships and making an appropriate contribution to the evolving understanding of ocean-atmosphere connections.

These aeolian syntheses suggest that the Mediterranean is a candidate for a classical homogeneous parameterization of the carbon cycle. The Western Mediterranean is subject to a top-down control of biological growth, whereas the Eastern Mediterranean is subject to a bottom-up control. If the ubiquitous parameterization is considered valid and only the effects of particulate matter shading are phenomenological, the Eastern Mediterranean favors the permanence of carbon followed by total nitrogen, as the remineralization processes of organic carbon take longer than the remineralization of organic nitrogen phases and phosphorus. There is a preferential release of dissolved phosphorus, which is tracked in the outflowing intermediate water and transported westward through the Sicily Channel to the Western Mediterranean, while large parts of the organic carbon and nitrogen phases are transported to deeper isolated layers and remain available in the Eastern Mediterranean.

5. Conclusions

In this review, two components of phytoplankton in Mediterranean basins exposed to aeolian inputs are analyzed.

This study of oligotrophism focuses mainly on understanding and describing the biological details of the structure and function of the pelagic food web, its species composition, its trophic groups and its trophic interaction. The built-in carbon cycle can be extended to oceanic environments and large-scale studies.

Similar applications of this work can be carried out in certain subtropical ocean eddies. The advantage of this model is that the food web structure and trophic interactions vary from west to east as the ratio of available nitrate to phosphate shifts longitudinally depending on the budgets of the Mediterranean Sea, which is mainly exposed to Atlantic input.

In the oceanic context, it is possible to investigate hypotheses such as those on the specific nutrient limitation of primary production and the shift between the dominance of bacterioplankton or microphytoplankton in the functioning of the photic food web, including the mechanisms behind the observed shifts in the size distribution of organisms, possibly with different internal nutrient ratios, and the deposition of organic matter, possibly with different remineralization rates.

In addition, this multinutrient model also provides a benchmark for investigating the mechanisms affecting the balance between autochthonous production and decomposition of dissolved organic matter, and could help in distinguishing between nitrogen fixation and atmospheric deposition hypotheses in some oligotrophic areas of the Atlantic Ocean, such as the oligotrophic Beta Triangle [48].

Research into the mechanisms underlying oceanic oligotrophism can be extended to the interactions of the C cycle with the N and P cycles. Indeed, there is a strong link between a better understanding of oligotrophism and various socio-economic interests, including freshwater discharges and fisheries. Production in these oligotrophic areas is driven by the rapid recycling of nutrients, each of which has remineralization rate ratios of 1:2:4 in this benchmark model, and by the proximity of the shelf to continental nutrient sources and ocean basins.

The high nutrient, low chlorophyll cases in the Pacific Ocean can be treated consistently with this benchmark model, but include very different latitudinal regions with very different forcing and acclimation factors, such as the Southern Ocean, Subarctic Pacific, and Equatorial Pacific. In these oligoelemental cases, the various hypotheses about the input of iron from intermediate layers or from aeolian depositions can be tested by examining iron at the same level as the silicates here in (1)–(6) [49].

In this review, the contrasting ecosystems are emphasized, from eutrophic responses in the Western Mediterranean to extremely oligotrophic environments in the Eastern Mediterranean. In the post-1980s periods examined here, various periods were studied with similar models in the Mediterranean. In particular, when considering the transient event of 1987–1995 [50], which immediately followed the period of these aeolian scenarios, the production and transfer of material from the surface levels to the intermediate layers was not subject to significant changes. Therefore, a model of this complexity also appears to provide reliable results for medium time scales, which are characteristic of global change scenarios and define the interactions between algal species, whether invasive or native, and seagrass meadows, climatic and permanent [51]. This benchmark model enables the development of decadal scenarios [10] to track global climate change due to its inherent stability and the conservative properties of the tracers. In addition, validation was done in the cited references and is performed here by Chlorophyll.

Author Contributions

Conceptualization, G.C. and M.P.; methodology, G.C.; software, M.P.; validation, G.C. and M.P.; formal analysis, G.C.; investigation, G.C. and M.P.; resources, M.P.; data curation, M.P.; writing—original draft preparation, G.C.; writing—review and editing, G.C.; visualization, G.C. and M.P.; supervision, G.C.; project administration, G.C and M.P.; funding acquisition, G.C. All authors have read and agreed to the published version of the manuscript.

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Not applicable.

Data Availability Statement

The datasets are public and are presented here with reference to the respective source. Supplementary information relevant to the discussion section of this review can be found in the handle at https://hdl.handle.net/20.500.14083/27684 and in the comments and notes at https://bg.copernicus.org/preprints/bgd-2007-0035.

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Conflicts of Interest

The authors declare no conflict of interest, do not use artificial intelligence tools, and adhere to the Creative Commons Attribution-Non Commercial 4.0 International license https://creativecommons.org/licenses/by-nc/4.0/deed.en. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results. Nevertheless, they eventually approved the public datasets in D40-M32, and the coordinator Centre National de la Recherche Scientifique, Perpignan and the partner Universitat Autònoma de Barcelona disseminated the results of the deliverable.

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