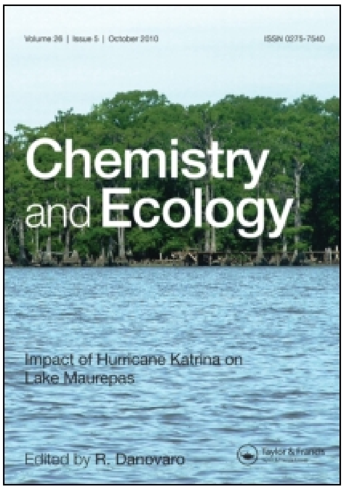

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SPATIAL AND TEMPORAL CHANGES OF SUSPENDED MATTER IN RELATION TO WIND AND VEGETATION COVER IN A MEDITERRANEAN SHALLOW COASTAL ENVIRONMENT

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Seasonal and spatial changes in seston, (POC), particulate organic carbon, (PON) particulate organic nitrogen and chlorophyll-a concentrations were studied on a monthly basis in a Mediterranean shallow coastal area (Stagnone di Marsala, Western Sicily) in order to gather information on factors controlling particulate organic matter distribution and composition. Seston concentration and composition were connected to the main physicochemical and biological driving factors, such as temperature, salinity, dissolved oxygen, wind-speed and biomass of submerged vegetation. The Stagnone di Marsala is characterized by high temperatures with strong seasonality (range: 11–28°C), while values ranged from 33 to 45 salinity. Total suspended organic matter concentrations (by ignition loss) ranged from 2 $mg\,l^{-1}$ (in summer) to 12 $mg\,l^{-1}$ (in winter) and chlorophyll-a concentrations from 0.02 to 2 $\mu g\,l^{-1}$. Despite a low POC/PON ratios (ranging from 5 to 11), the ratio of POC to chlorophyll (CHL-a) displayed very high values (annual average of 647). The data reported in this study, highlighting the oligotrophy of the Stagnone di Marsala area, indicate that the trophic state of the basin was controlled by different degrees of wind exposure (mean monthly wind velocity at exposed sites ranged between 4.2 and 6.7 $m\,s^{-1}$) and by gradients in vegetation cover. These two factors induced clear changes in the concentration and composition of the suspended particles, but played a different role in exposed and sheltered areas. Exposed areas with limited vegetation were characterized by large resuspension processes and wide temperature and salinity fluctuations caused by wind induced turbulence. In these areas, autotrophic biomass (as chlorophyll-a), due to phytoplankton and/or re-suspended microphytobenthos, appeared to play an important

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role in enhancing the quality of the organic particles. By contrast, in sheltered areas which were characterized by large amounts of plant detritus, the autotrophic biomass (mostly phytoplankton) was almost negligible and the availability of the suspended organic particles to consumers appeared to be dependent largely upon the bacterial ageing of vascular organic detritus.

Keywords: Shallow areas; trophic descriptors; wind; seagrass; suspended organic matter

INTRODUCTION

Shallow coastal areas are physically controlled environments characterized by two main processes: tides and river in flow (estuarine lagoons) and wind and wave energy ("typical" lagoons). Estuarine lagoons (mid-high latitude lagoons; *e.g.*, North America and North Europe) are often characterized by wide spatial and temporal temperature and salinity fluctuations related to the seasonally varying allochthonous (*i.e.*, river) inputs (Trousselier *et al.*, 1993; Painchaud *et al.*, 1995). In these environments, the direct role of auxiliary energy inputs such as wind stress or rain precipitation may be negligible. In contrast, tidal mixing in estuarine lagoons has often been considered one of the main factors (Sinclair *et al.*, 1981), while wind stress has only been considered important in water mixing.

Lagoons in semi-arid regions, such as in the south Mediterranean Sea, are characterized by small tidal effect and a low or negligible continental inflow. Here, the main energy source is represented by wind-induced waves and water dynamics, which can affect sediment resuspension (Wainright, 1987, 1990). These highly mixed conditions make it difficult to distinguish between phytoplankton and microphytobenthos resuspended into the water column because of the continuous exchanges between sediments and the overlying water column (MacIntyre *et al.*, 1996).

Studies dealing with shallow areas (lagoons, coral reef lagoons or estuaries) have shown great variability in their trophic state due to the unpredictable fluctuations of the principal driving forces (Painchaud *et al.*, 1990; Navarro *et al.*, 1993; Hamilton, 1994; Chassany de Casabianca *et al.*, 1995; Clavier *et al.*, 1995; Savenkoff *et al.*, 1995). These studies have also demonstrated that changes in the concentration of suspended organic matter and associated detritus, their residence time and lateral transport (rather than changes in temperature and salinity) may affect functional and structural characteristics of the inhabiting benthic communities (Sogard *et al.*, 1987; Scilipoti *et al.*, 1997) and the pelagic food web organization (Arfi and Buovy, 1995). However, such information in south Mediterranean lagoons and shallow water environments are extremely scarce (Giani *et al.*, 1995; Sarà *et al.*, 1995; Mazzola and Sarà, 1995; Pusceddu *et al.*, 1997) and although seagrass meadows appeared to play an important trophic role (Orth *et al.*, 1984; Mazzella *et al.*, 1989), the ecological features that affect biological processes in these shallow water ecosystems have still to be assessed.

The aim of this study is to investigate spatial and temporal fluctuations of suspended matter concentration and composition in relation to the main biotic/abiotic factors influencing a typical Mediterranean shallow water ecosystem. These parameters are used to identify chemical descriptor of the trophic state of these environments and new insights regarding the main factors controlling composition and distribution of the suspended particles will be proposed.

Description of the Area

The study was carried out in the Stagnone di Marsala (37°52′ N; 12°28′ E) (Fig. 1) which is a shallow protected area with a 7 km N-S axis (15 km^2). A low calcarenitic platform (Isola Grande) separates the basin from the open sea. The northern mouth is 450 m wide and occasionally allows turbulent inputs of marine waters which characterize the northern non-vegetated area (sparse *Cymodocea nodosa*-250 ha) (Calvo *et al.*, 1996). The southern mouth is 1,450 m wide and is open to sea water inflow with internal tides. Two islands (Isola S. Maria and Isola S. Pantaleo) and the Strada Romana (Roman Road) act as mechanical obstacles to the water flow in the middle of the basin and they generate turbulence. The dominant seagrass, *Posidonia oceanica*, particularly luxuriant in the central-southern area (1180 ha; Calvo *et al.*, 1996), modifies the pattern of currents and the intensity of silting. No land inputs are present. Average current speeds ($5.39 \pm 0.82\,cm\,s^{-1}$) range from $4.92 \pm 1.54\,cm\,s^{-1}$ in the southern mouth to $2.34 \pm 0.87\,cm\,s^{-1}$ in the northern area.

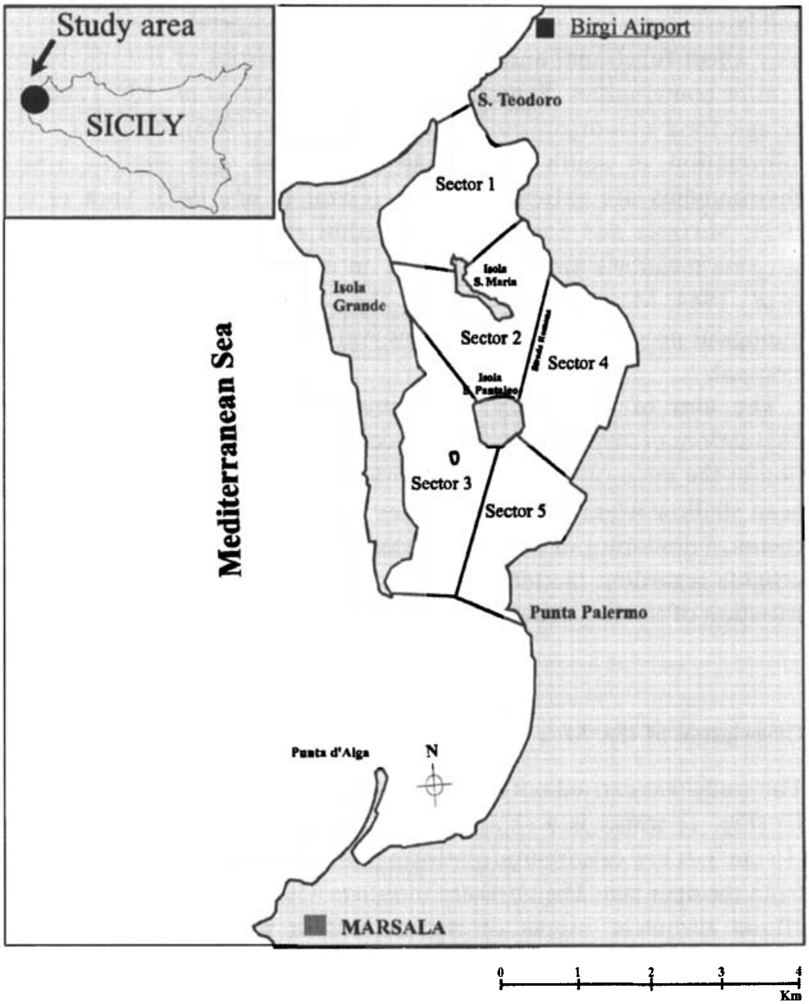


FIGURE 1 The study site, in Sicily.

MATERIALS AND METHODS

Surface water samples (0.5 m deep) were collected monthly from January to December 1994, using 10 l Niskin bottles at 10 sampling sites located along a north-south transect. The station location was selected according to differences in submerged vegetation cover (Tab. I). Water temperature (*T*), salinity (*S*), dissolved oxygen (DO) were measured *in situ* using a Hydrolab (Austin, USA) multiprobe. Water samples were screened through a 200 μm mesh net in order to remove large zooplankton and debris. Subsamples (500 to 2000 ml) were filtered on to pre-washed, precombusted (450°C, 4 h) and pre-weighed Whatman GF/F filters in order to determine total suspended matter (TSM), photosynthetic pigments and particulate organic carbon (POC) and nitrogen (PON). TSM determination was carried out gravimetrically after desiccation (60°C, 24 h) using a Sartorius balance (A200; accuracy ±1 μg). The organic fraction of seston (OSM) was determined by ignition loss (450°C, 4 h; the material remaining after combustion was the inorganic fraction (ISM) of TSM; Strickland and Parsons, 1972). Chloroplastic pigments (CPE) as the sum of chlorophyll-a (CHL-a) and phaeopigments (PHAEO) were determined according to Lorenzen and Jeffrey (1980). POC and PON were determined with a Perkin-Elmer CHN Elemental Analyser (Mod. 2400), using acetanilide at 925°C as a standard after the removal of inorganic carbon (Hickel, 1984; Iseki *et al.*, 1987). The meteorological station of Birgi Airport (Trapani) provided data on wind speed.

TABLE I Features of sampling sectors at the Stagnone di Marsala (*S* = Sampling sites per sector; *Sb* = substrate type; *D* = mean depth, m; *B* = Vegetation cover (Scilipoti, 1997; *cfr. M* and *M* section); *E* = exposure (Sarà, unpublished effective fetch data); *Vt* = vegetation type; *CN* = *Cymodocea nodosa*; *PO* = *Posidonia oceanica*; *CP* = *Caulerpa prolifera*; *MA* = *macroalgae*)

	S	*Sb*	*D*	*B*	*E*	*Vt*
Sector 1	3	muddy-sand	1.05	very low	exposed	CN sparse plus MA
Northern Basin						
Sector 2	2	sandy	1.10	average	partially	PO, average CN plus low MA density
Mid Basin					exposed	
Sector 3	1	sandy	1.20	high	sheltered	PO (covered area 21%), CN
West Channel						
Sector 4	2	muddy-sand	1.10	low	exposed	PO (covered area 5.9%), CN, CP
East Channel						
Sector 5	2	sandy	1.50	average	partially	PO (covered area 11.7%), average CN density
Southern Basin					exposed	

Four plant cover classes (as a sum of main vegetal taxa - *Posidonia oceanica*, *Cymodocea nodosa* and *Caulerpa prolifera*) were determined according to Scilipoti *et al.* (1997) and Scilipoti (1997): 0–25% (Class 1: very low); 25–50% (Class 2, low); 50–75% (Class 3; average) and 75–100% (Class 4; high). Vegetation cover data were compared with those obtained by remote sensing (Calvo *et al.*, 1996), thereby confirming our division of the area into 5 main different sectors (Fig. 1).

Temporal and spatial fluctuations of physical, chemical and trophic parameters were assessed by using a multi-factorial two-way analysis of variance (MANOVA) with space (sectors) and vegetation cover (cover class) as sources of variation (Helsel and Hirsch, 1992). When a significant difference ($p < 0.05$) for the main effect was observed, the mean values were analyzed by a Tukey multiple comparison test in order to determine the differences between sampling areas, months and percent vegetation cover. Data were transformed, only when necessary, to meet with the assumptions of parametric statistics and also was analyzed by principal component analysis (PCA) (Flury, 1988) using station by month environmental matrixes.

RESULTS

Hydrological Characteristics in the Sampling Sectors

Table II summarizes the measured hydrological parameters and wind speed. The temperature data showed a seasonal trend with warmest temperatures (Fig. 2) in August. Sectors 2 and 3 showed a mean annual temperature, which was significantly higher ($p < 0.05$) than in the other sectors. Seasonal changes in salinity were significantly correlated with temperature ($r = 0.80; p < 0.05; n = 120$) with the highest salinity ($p < 0.05$) values being recorded in sector 3. Dissolved oxygen was inversely proportional to temperature ($r = -0.89; p < 0.05; n = 120$).

Suspended chloroplastic pigments (CHL-a *vs.* PHAEO $r = 0.97$; $p < 0.05; n = 120$) showed a typical seasonal trend (Fig. 2) with high concentrations between January–March as well as in September. The highest concentrations of CPE ($p < 0.05$) occurred in the northern sector (1) and in the eastern channel (sector 4).

TABLE II Statistics and ANOVA results of the variables [F = Fisher value; P = p-level; (* = $P \leq 0.05$; ** = $P \leq 0.01$; *** = $P \leq 0.001$); ns = non-significant difference ($P \geq 0.05$)]

Variables	*Mean*	*±s.d.*	*Min*	*Max*	*Sector* $F_{4,60}$	*Sector* *P*
T(°C)	19.41	5.20	11.76	28.59	5.30	0.00(***)
S(psu)	39.55	2.44	33.12	45.52	8.43	0.00(***)
DO(mg l^{-1})	7.88	2.22	4.41	13.60	9.67	0.00(***)
OSM(mg l^{-1})	1.53	1.42	0.20	14.00	2.99	0.03(*)
ISM(mg l^{-1})	2.93	5.04	0.13	41.41	4.24	0.00(***)
CHL-a(μg l^{-1})	0.39	0.26	0.02	2.00	12.06	0.00(***)
PHAEO(μg l^{-1})	0.13	0.09	0.01	0.67	9.56	0.00(***)
POC(μg l^{-1})	193.52	187.23	32.60	1,288.29	7.23	0.00(***)
PON(μg l^{-1})	27.53	21.27	5.52	130.70	10.69	0.00(***)
POC/PON	6.82	1.28	4.88	10.85	7.55	0.00(***)
POC/CHL-a	647.37	832.11	95.97	6,902.17	2.39	0.06(ns)
Wind (m s^{-1})	5.39	0.82	4.17	6.74		

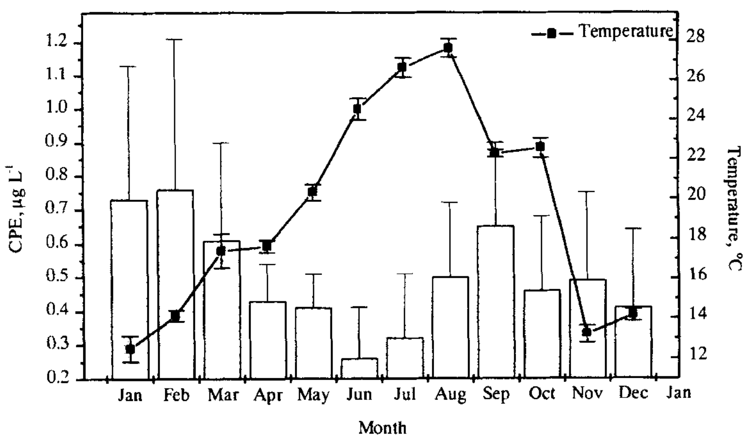


FIGURE 2 Monthly trend of Chloropigment Equivalent (CPE, μg l^{-1}; left axis-bars) and temperature (°C; right axis–solid square symbols) in the Stagnone. Standard deviations are reported.

Seasonal changes in ISM and OSM concentrations are reported in Figure 3. The inorganic fraction of seston (ISM) was significantly correlated to OSM ($r = 0.44; p < 0.05; n = 120$). On average, the highest annual values of TSM were found in sectors 1, 2 and 4 where concentrations were generally above 1 mg l^{-1}.

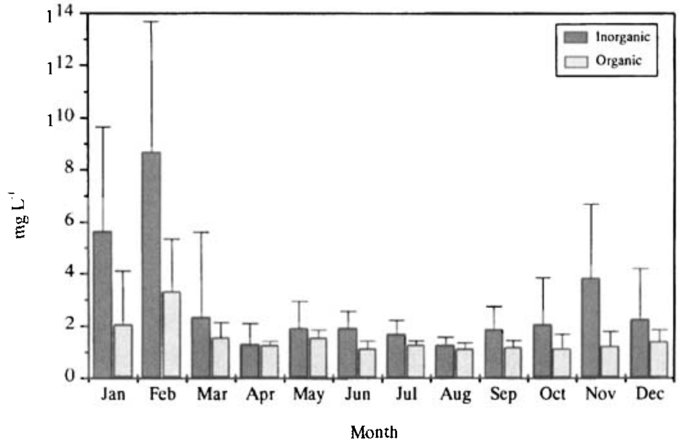


FIGURE 3 Monthly trend of inorganic (ISM, mg l^{-1}; left axis – gray bars) and organic component (OSM, mg l^{-1}; left axis – light gray bars) of total suspended matter in the Stagnone. Standard deviations are reported.

Seasonal changes in POC and PON concentrations (Fig. 4) were higher in three periods: January – March, May – June and October. This spatial pattern indicated a gradient from the northern to the southern sectors with sectors 1 and 2 presenting the highest concentrations. The POC and PON concentrations were significantly correlated ($r = 0.92$; $p < 0.05$; $n = 120$). Changes in the POC : PON ratio are presented in Figure 5. The POC : PON ratio was at its maximum level in winter and May – June. Sectors 1 and 4 presented POC : PON values, which were significantly ($p < 0.05$) lower than in other sectors. The POC/CHL-a ratio (Fig. 5) was significantly correlated to the POC/PON ratio ($r = 0.45$; $p < 0.05$; $n = 120$), and significantly higher values ($p < 0.05$) were found in sectors 1 and 2. POC and PON were also significantly correlated to TSM concentrations ($r = 0.56$; $p < 0.05$ and $r = 0.56$; $p < 0.05$ respectively).

Principal component analysis results (Tab. III) show the variability of the investigated parameters in the system. PC1 was mostly accounted for by organic matter descriptors (for 75% of the year) whereas physico-chemical parameters (basically salinity and temperature) correlated with the second principal component, which always explains less than 31 % of the variance.

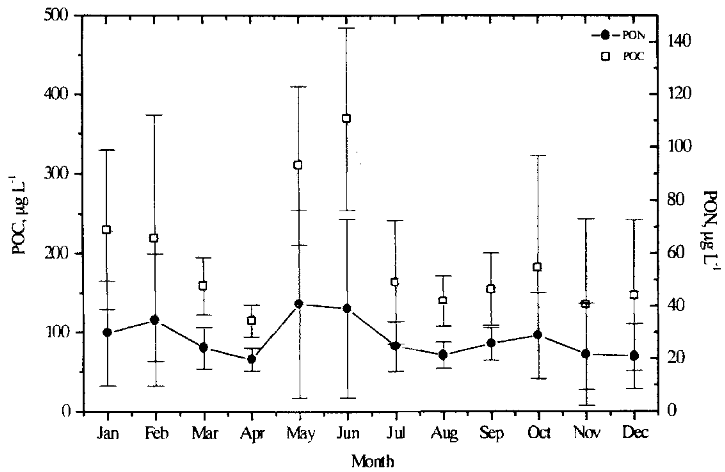


FIGURE 4 Monthly trend of POC ($\mu g\,l^{-1}$; left axis–solid circle symbols) and PON ($\mu g\ l^{-1}$; right axis–open square symbols) in the Stagnone. Standard deviations are reported.

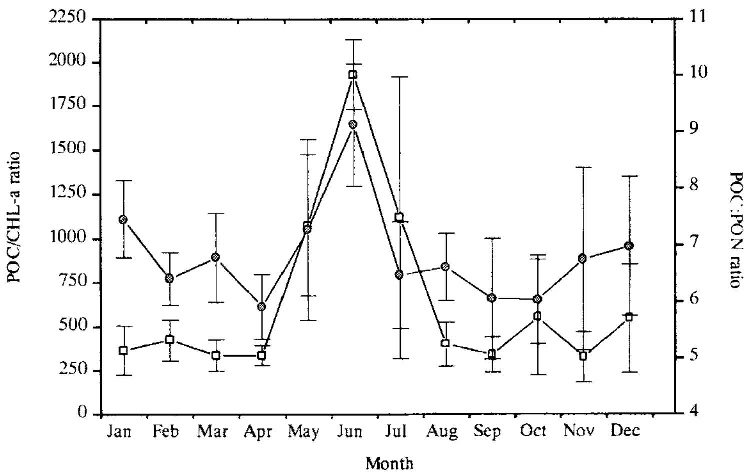


FIGURE 5 Monthly trend of POC/CHL-a ratio (left axis–open square symbols) and POC : PON ratio (right axis–solid circle symbols) in the Stagnone. Standard deviations are reported.

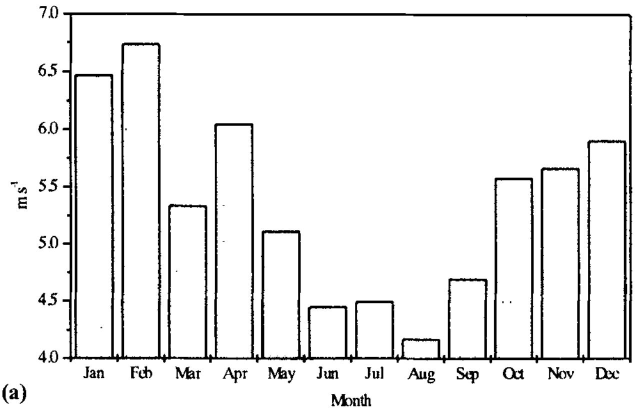
The Effects of Wind and Vegetation Cover on Water Column Features

Average wind velocity (Fig. 6a) shows two periods of high values: autumn-spring and summer (75% of the year). Winds came principally

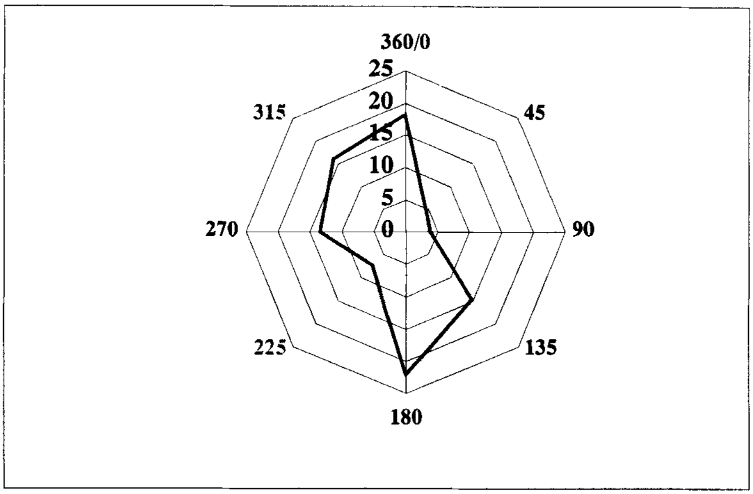
TABLE III Principal Component Analysis: monthly variance explained by the system. Only variables that loaded a significant contribution (> 0.70) to systemic variance are considered (V = most important variables; $T.V.$ = total variance)

Months	*PC*1 ($V > 0.70$)	*PC*1 (%*var*)	*PC*2 ($V > 0.70$)	*PC*2 (%*var*)	*PC*3 ($V > 0.70$)	*PC*3 (%*var*)	*T.V.*
Jan	POC, PON, CHL, PHAEO, ISM	51	T, pH	20	–	–	71
Feb	POC, PON, OSM, ISM, CHL, PHAEO	55	DO, pH	19	T	12	86
Mar	DO, T, pH, POC, PON	36	CHL, FEO	24	ISM	20	80
Apr	POC, PON, CHL, PHAEO, ISM	47	OSM	23	–	–	70
May	POC, PON, ISM	32	DO	28	T, pH	14	74
Jun	POC, PON, CHL, PHAEO, DO	44	OSM, ISM, pH	22	T, S	15	81
Jul	POC, PON	28	PHAEO	24	DO, OSM	18	70
Aug	POC, CHL, PHAEO, DO, pH	44	T, S, POC	26	OSM	15	85
Sept	CHL, PHAEO, POC, PON	41	OSM, DO	22	pH	15	78
Oct	POC, PON, CHL, PHAEO, OSM, pH, DO	50	T, S	20	ISM	14	84
Nov	T, POC, PON	48	PHAEO, DO, pH	30	–	–	78
Dec	CHL, PHAEO, OSM, ISM	41	T	22	S, POC	18	81
Annual	POC, PON	35	T, S, DO	33	–	–	68

from the second and fourth quadrant (Fig. 6b), whereas calm conditions were recorded during 20% of the time. Winds coming from third and fourth quadrant showed the highest intensity (Fig. 6c). Wind speed was negatively correlated with temperature and salinity and positively correlated with dissolved oxygen in almost all of the sectors (Tab. IV). Wind speed was significantly correlated to OSM, ISM and chlorophyll-a in sector 1, to OSM in sector 2 but negatively correlated to ISM in sector 3 ($p < 0.05$) and to POC and PON in sector 2. Total suspended matter and CPE concentrations (Tab. V, Fig. 7) showed highest values ($p < 0.05$) in sectors characterized by low vegetation cover. POC and PON showed similar patterns as their concentrations significantly



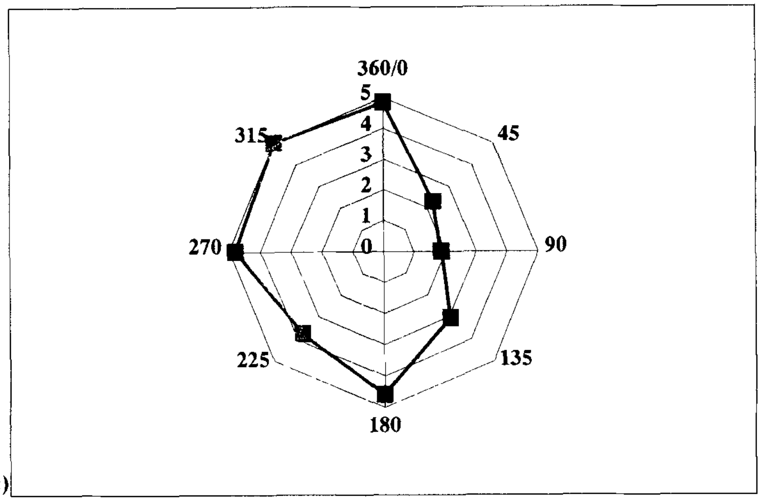
(a)



(b)

FIGURE 6 Monthly trend of wind velocity (a; m s^{-1}) in the Stagnone, wind frequency percentage (b; %) and mean wind velocity as function of coming direction (c; m s^{-1}).

($p < 0.05$) decreased from very low and low vegetation to high vegetation cover sectors. The lowest values of the POC/CHL-a ratio (Fig. 8) occurred in sectors with low vegetation cover ($p < 0.05$) whilst higher values were found in sectors with high and very low vegetation cover. Finally, the POC : PON ratio (Fig. 8) showed a significant difference ($p < 0.05$) between very low-low sectors and medium-high vegetation cover sectors.



(c)

FIGURE 6 (Continued).

TABLE IV Spearman correlation between wind and variables at sampling sector ($n = 12$; * = $P \leq 0.05$; ** = $P \leq 0.01$; *** = $P \leq 0.001$); *ns* = non-significative difference ($P \geq 0.05$)]

Variables	*Sector* 1	*Sector* 2	*Sector* 3	*Sector* 4	*Sector* 5	*Area*
T(°C)	−0.86(***)	−0.86(***)	−0.86(***)	−0.87(***)	−0.86(***)	−0.86(***)
S(psu)	−0.79(***)	−0.85(***)	−0.93(***)	−0.87(***)	−0.93(***)	−0.83(***)
DO(mg l^{-1})	0.84(***)	0.82(***)	0.62(*)	0.83(***)	0.85(***)	0.83(***)
OSM(mg l^{-1})	0.69(**)	0.63(*)	−0.34(ns)	0.20(ns)	−0.25(ns)	0.66(**)
ISM(mg l^{-1})	0.78(***)	−0.06(ns)	−0.75(***)	0.07(ns)	−0.34(ns)	0.67(**)
CHL-a(μg l^{-1})	0.58(*)	0.18(ns)	0.24(ns)	−0.20(ns)	0.24(ns)	0.50(ns)
PHAEO(μg l^{-1})	0.56(ns)	0.25(ns)	0.21(ns)	−0.24(ns)	0.25(ns)	0.44(ns)
POC(μg l^{-1})	0.09(ns)	−0.70(**)	−0.46(ns)	−0.05(ns)	−0.57(ns)	0.01(ns)
PON(μg l^{-1})	0.25(ns)	−0.69(**)	−0.32(ns)	0.14(ns)	−0.65(*)	−0.04(ns)

DISCUSSION

The temperature and salinity values in the Marsala lagoon are similar to those reported in other typical Mediterranean lagoons and shallow coastal environments (Chassany de Casabianca, 1979a; Hamon *et al.*, 1979; Zaouali and Baeten, 1983; Friligos, 1989; Pusceddu and Fabiano,

TABLE V ANOVA results of the variables (* = $P \leq 0.05$; ** = $P \leq 0.01$; *** = $P \leq 0.001$); *ns* = non-significative difference ($P \geq 0.05$)]

Variables	*Cover*	*Cover*
	$F_{3,72}$	P
OSM ($mg\,l^{-1}$)	2.80	0.04(*)
ISM($mg\,l^{-1}$)	2.89	0.04(*)
CPE($\mu g\,l^{-1}$)	8.14	0.00(***)
POC($\mu g\,l^{-1}$)	5.81	0.001(***)
PON($\mu g\,l^{-1}$)	7.45	0.00(***)
POC/PON	2.82	0.04(*)
POC/CHL-a	6.67	0.00(***)

1994; Okuda, 1981). The system studied, appeared to be oligotrophic, displaying chlorophyll-a concentrations similar to those previously reported in the same area (Magazzù, 1982; Giani *et al.*, 1995) or in other highly oligotrophic environments of the southern Mediterranean Sea (Carrada *et al.*, 1996). Despite the presence of low chlorophyll-a concentrations and low phytoplankton biomass, the water column photosynthetic rate previously measured is high ($2\,mg\,C\,m^3\,h^{-1}$; Magazzù, 1977), indicating high specific phytoplankton growth rates ($\mu = 0.93 \pm 0.55$; Magazzù, 1982). These results may indicate the presence of rapid nutrient recycling and are supported by the high biomass and

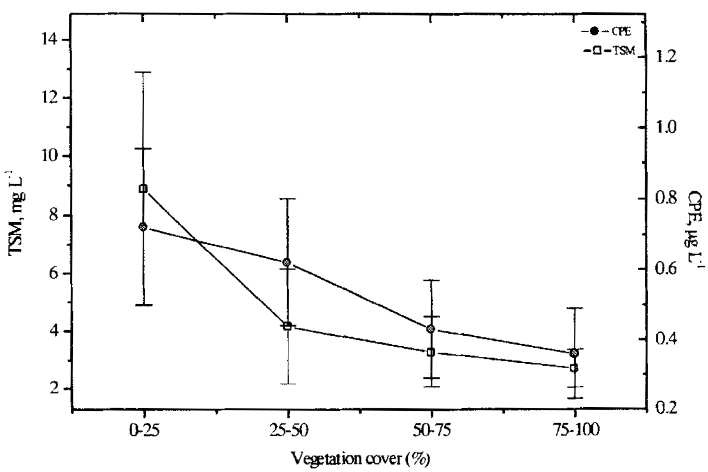


FIGURE 7 Total suspended matter (TSM, $mg\,l^{-1}$; left axis – open square symbols) and CPE, $\mu g\,l^{-1}$; right – solid circle symbols) pattern in relation to vegetation cover.

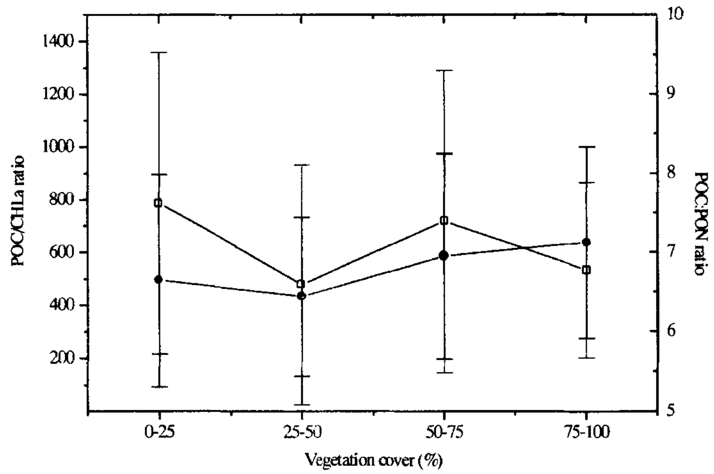
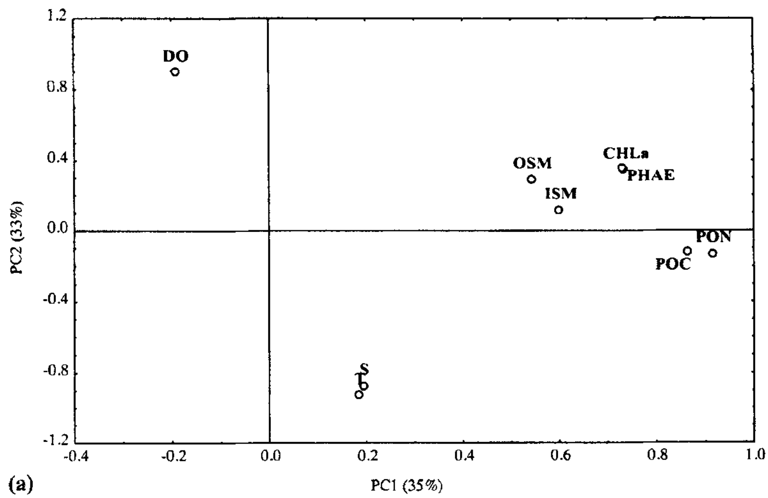


FIGURE 8 POC/CHL-a (left axis – open square symbols) and POC : PON (right axis – solid circle symbols) ratios pattern in relation to vegetation cover.

elevated activity of the heterotrophic bacterial assemblages (Genovese, 1969). Under these conditions, the ability of phytoplankton to use inorganic nutrients very rapidly may, in fact, allow for a high rate of growth, independently of the total biomass (Goldman, 1979).

In this study, total suspended matter concentrations were lower when compared to other Mediterranean lagoons (Pusceddu *et al.*, 1996) or shallow water environments which are both characterized by large water column mixing and sediment resuspension (such as in the northern Adriatic, Sorokin *et al.*, 1996). However, few differences were observed in comparison to seston loads reported in other south Mediterranean areas (Tucci *et al.*, 1996). By contrast, POC and PON values were similar or lower than those reported in other Mediterranean lagoons (Pusceddu *et al.*, 1996) but much higher than those reported in the open sea (Fabiano *et al.*, 1996). Principal component analysis highlighted the presence of two key descriptors (chemical/trophic as organic matter descriptors and chemical/physical factors-Tab. III) which characterized the trophic state of the system and inter-sector variability.

The results of the PCA, dealing with the spatial and temporal analysis of the investigated parameters (Figs. 9a and b), indicated that salinity and temperature played only a secondary role as forcing



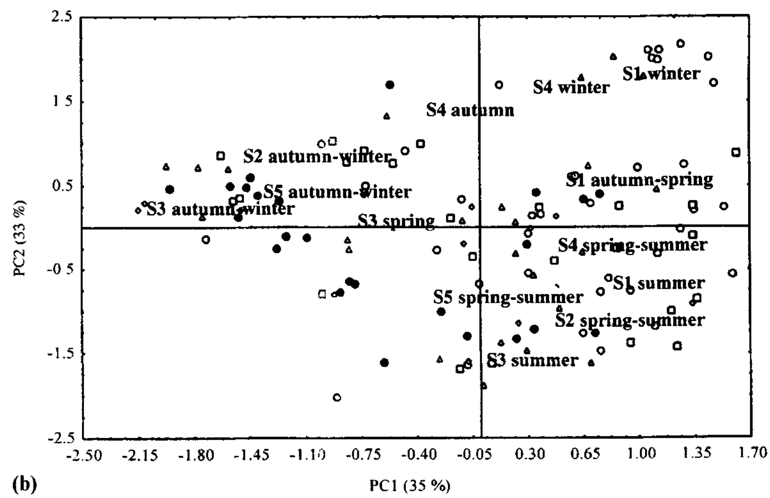


FIGURE 9 (a) and (b) Principal Component Analysis: Spatial and temporal model. (open circle symbols – Sector 1; open square symbols – Sector 2; open diamond symbols – Sector 3; open up triangle symbols – Sector 4; solid circle symbols – Sector 5).

functions in the system and, in no sector did they appear to be the driving factors for the other trophic descriptors. The absence of depth or distance-from-sea gradients of temperature and salinity, such as those found in estuaries or lagoons characterized this basin as a marine semi-enclosed environment. Factors which show a pattern typical and similar to the adjacent sea (Pusceddu *et al.*, 1997), can be considered irrelevant in the structuring of communities, whilst the quality and quantity of trophic resources (depending on producers and distribution factors, *i.e.*, wind-driven hydrodynamical processes) could have a predominant role. Indeed, the importance of trophic parameters has also been highlighted in other geographical areas (Costa-Moreira and Carmouze, 1991; Aliaume *et al.*, 1993; Vincente *et al.*, 1995; Zine and Menioui, 1995).

The Three Ecological Sub-systems of the Stagnone Ecosystem

Clear differences were observed between sectors for which it is possible to distinguish at least three sub-systems (*i.e.*, areas of the Stagnone ecosystem constrained to different ecological conditions) (Fig. 10).

The first sub-system is represented by sector 1 and partially by sector 4, which could be as an index of areas highly exposed to wind stress and partially non-vegetated. The vegetal community is composed mainly of sparse *Cymodocea nodosa*, *Caulerpa prolifera* and benthic diatoms and could, therefore, represent a retrogressive status of the *Posidonia* ecosystem succession. This could be the relevant case when the retrogression is due to natural physical forcing (wind stress) and not due to anthropogenic eutrophication. This sub-system is characterized by large amounts of suspended matter (with a high inorganic fraction) and is affected by sediment resuspension throughout the year (without evident seasonality but with pulse/pulse behaviour). This observation has been confirmed by Pusceddu *et al.* (1997) who have shown a different pattern between factors controlling the water dynamics (resuspension in the northern area and sedimentation in the southern area). Recently Arfi *et al.* (1993) have reported similar wind-controlled characteristics for other shallow areas. Large amounts of mineral seston, in this case, (although information about this may be often irrelevant and reductive), could be a major signal of resuspension and lateral transport due to wind-waves. Due to the reduced plant biomass, these sectors appeared to be affected by wind-induced coastal erosion with a consequent increase in the allochthonous input, as described for other areas (MacIntyre *et al.*, 1996). POM appeared to be largely diluted and of low nutritional

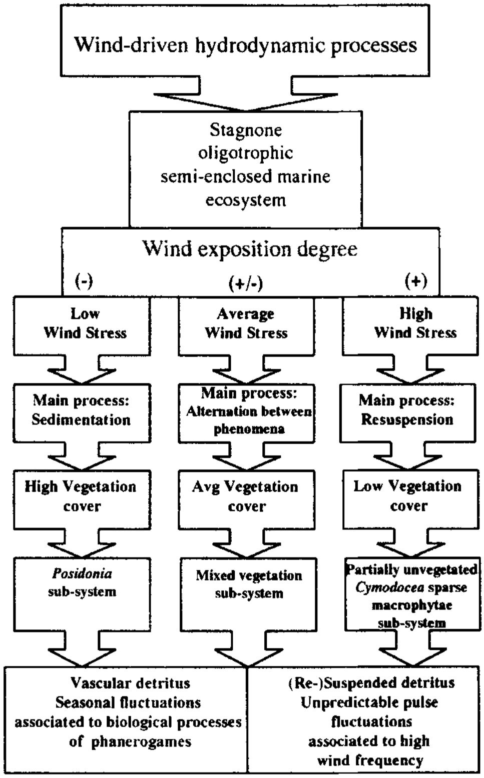


FIGURE 10 Schematic representation of the main processes, which control the Stagnone ecosystem.

quality (as indicated by the low CHL-a concentrations). Carper and Bachman (1984) have calculated, as in other sites, the theoretical critical wind speed required for inducting particle resuspension and other authors (Kullenberg, 1972; Kullenberg, 1976; Levasseur *et al.*, 1983; Millet and Cecchi, 1992) have established a threshold value of $4\,m\,s^{-1}$ after which significant resuspension effects may occur affecting the biological and physical properties of the water column. In the study area, wind speed often exceeded $4-5\,m\,s^{-1}$ in exposed sites. Demers *et al.* (1987) observed a strong increase in chlorophyll-a, phaeopigments, POC concentration and in the number of benthic diatoms in the water column each time the wind reached a velocity of $4\,m\,s^{-1}$ whilst MacIntyre *et al.* (1996) observed that the resuspension of sediments and associated microflora affected the rate of photosynthesis within the water column by reducing light penetration and increasing the amount of suspended chlorophyll.

Sectors 1 and 4, typified these wind-controlled conditions, although the autotrophic component did not account for more than 1% of particulate matter. In our case, the limited increase in CHL-a concentration may, however, be related to the extreme oligotrophy of the system, so that the benthic contribution to autotrophic biomass was probably reduced. Wainright (1987) demonstrated that planktonic microbial growth could be stimulated by resuspension of sedimentary material within a few hours. This data may partially support the high growth rates observed in our system for phytoplankton.

The second sub-system is represented by the most sheltered and vegetated sector 3 (predominance of *Posidonia oceanica*). This area was affected by typical seasonal fluctuations in suspended organic matter correlated to seagrass primary production which was characterized by a strong seasonality (high in late spring to summer and low in fall and winter) with a large release of leaves in autumn-winter (up to 90% of the plant biomass, Whittmann, 1984; Velimirov, 1987). Benner *et al.* (1988) observed that plant detritus is likely to represent an important source of nutrition in the food web of aquatic ecosystems, which are receiving large amounts of plant biomass. In the studied area, *Posidonia oceanica* meadows are characterized by high standing crops with values close to the highest reported values for the entire Mediterranean area (Buia *et al.*, 1992; Mazzella *et al.*, 1995). The low concentrations of POC and PON were probably due, (i) to high settling velocity of degraded *Posidonia* particles, making a small contribution to the suspended organic matter pool and remaining concentrated in the wrack beds on the sediments, unless occasionally resuspended by wind (Velimirov, 1987), or (ii) the effect of current attenuation in the seagrass bed (Ward *et al.*, 1984). The lowering of the variation coefficient of POC concentration (Demers *et al.*, 1987), which could demonstrate the homogenous distribution of suspended matter in the water column, could be due to a wind speed lower than 4 – 5 m s^{-1} (Millet and Cecchi, 1992; Trousselier *et al.*, 1993). By contrast, Danovaro and Fabiano (1995) reported a highest C:N ratio of *Posidonia* detritus (ranging from 6.8 to 26.7; mean being about 12 – 15) with marked seasonal fluctuations. Indeed, in accordance with these findings, areas containing *Posidonia* meadows displayed highest

POC/CHL-a and POC : PON ratios (about 10), whose seasonal patterns were clearly related to the biological cycle of the seagrass. Consequently, leaf detritus, which is highly refractory and has high C : N values (Velimirov, 1987), could exceed other types of production (macroalgae, benthic diatoms, phytoplankton and bacteria) (Mazzella *et al.*, 1995).

The third sub-system was represented by sector 2 which is surrounded by islands, the barrier of the Strada Romana and by sector 5 which is adjacent to the sea. It is characterized by higher bottom depths (compared to the other sectors) and high current speed. Both sectors are partially sheltered from the wind and showed a medium level of vegetation cover, which appear to be showing intermediate conditions between the first two sub-systems. In these sectors the balance between sedimentation and resuspension processes was typical of areas where the effects of the alteration of sedimentation rate were evident. This result could be the first degree of retrogression in the succession of the *Posidonia* ecosystem, which effectively produces vegetation composed of differing elements (*Posidonia*, *Cymodocea* and macroalgae). Under these conditions, the values of trophic variables were intermediate between the situation dominated by the resuspension processes and sedimentation, precisely because of the continuous alternation between those two phenomena. This situation could also represent a retrogressive stage in the *Posidonia* ecosystem as determined by natural physical forcing.

CONCLUSIONS

In an attempt to generalise these results, we may conclude that the Stagnone di Marsala is a xero-Mediterranean ecosystem-type controlled by wind-driven hydrodynamic processes (Fig. 10), which produce (as a function of the degree of wind exposure measured as fetch) different and contemporary stages of Mediterranean *Posidonia* ecosystem succession. Furthermore information about other factors, including bacterial dynamics and the levels of availability of particulate and dissolved organic matter, are necessary if we are to understand better the relationships between biotic and abiotic components in this Mediterranean area.

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All literature cited in this paper is available at the corresponding author's address.

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