

Nutrient Bioaccumulation in *Phragmites australis*: Management Tool for Reduction of Pollution in the Mar Menor

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Abstract We studied nutrient removal by *Phragmites australis* in the Albuñón rambla, the main drainage system that discharges into the Mar Menor, a Mediterranean coastal lagoon of high conservation interest, but highly threatened by point and nonpoint pollution derived from tourism and agricultural activities. We measured aerial biomass and N and P concentrations in both aboveground and belowground tissues of common reed during an annual cycle that included two cutting events and two periods of reed growth (one at the end of summer after cutting and another at the beginning of spring, following their natural cycle). The temporal variation of N and P concentrations was related to the phenology of the plant and cutting events. The maximum nutrient concentrations were recorded in young stems in the initial stages of the autumn growing season (35.86 mg N g⁻¹ and 2.38 mg P g⁻¹). The phosphorus dynamics showed evidence of translocation processes related with growth activity, although no evidence of N translocation was found. In November and in summer, when aerial growth ceases because of the hard conditions, the P concentration in rhizomes was higher than in stems, while in spring and in September, the period of maximal growth, the reverse relation was

found. The highest total amounts of the two elements in the aboveground biomass (0.54 Tm N ha⁻¹ and 0.25 Tm P ha⁻¹) were reached in July, coinciding with the highest biomass (3.72 kg DW m⁻²), which then decreased to approximately half in August. Nutrient content in the aboveground tissues was highly dependent on the ammonium and nitrate water concentrations. In addition, the N content was inversely related to the C_{org}/N of sediments, while the P content was influenced positively by the phosphorous concentration of the water. Common reed of the Albuñón rambla corresponds to the assimilation type, adapted to nutrient-rich habitats, which is characterized by a pronounced external N cycle and P internal reserves. Based on the results obtained, we propose a management plan for common reed to help control eutrophication of the Mar Menor lagoon. This would bring forward reed cutting to the beginning of summer, instead of August, coinciding with the time of maximum aerial biomass, greater nutrient retention, and lower risk of strong precipitation.

Keywords *Phragmites australis* · Nutrients · Bioaccumulation · Mar Menor · Water pollution

1 Introduction

Reed (*Phragmites australis* (Cav.) Trin. Former Steud) is a cosmopolitan emergent macrophyte species occurring in a wide range of aquatic habitats

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and has been widely investigated as bioabsorbent of macroelements and heavy metals. It functions well as a filter, reducing point and nonpoint pollution sources (Brix and Schierup 1989; Kiedrzyńska et al. 2008). Common reed is one of the emergent plants most commonly used in constructed wetlands for the enhancement of water quality in water treatment systems (Wathugala et al. 1987; Biddlestone et al. 1991; Brix 1994; Gómez Cerezo et al. 2000; Borin et al. 2001; Meuleman et al. 2002; Vyamazal 2002) due to its high growth rate and great capacity for nutrient accumulation in its stems, roots, and rhizomes (Ulrich and Burton 1985; Hocking 1989; Granéli et al. 1992; Kuehl and Khol 1993; Greenway and Woolley 1999; Romero et al. 1999; Wolfgang et al. 1999; Asaeda et al. 2002; Baldatoni et al. 2003; Kiedrzyńska et al. 2008). The capacity of natural wetlands to filter wastewater and nutrients from arable land also has been demonstrated (White et al. 2000; Newman and Pietro 2001; Cirujano et al. 2005; Álvarez-Rogel et al. 2006). Besides, reed beds have other important wetlands functions, including acting as a major breeding habitat for passerines (Poulin et al. 2002) and contributing to margin sediment stabilization and to habitat biodiversity, thus increasing its ecological and conservation value. However, reed tends to form monospecific and dominant stands and may alter ecological functions by the excessive expansion, adopting an invasive behavior (Lelong et al. 2007), especially in coastal marshes, where there are an increase of inputs of freshwater and nutrient loads and major presence of no vegetation areas (Minchinton and Bertness 2003).

The Mar Menor is the largest coastal lagoon in the Western Mediterranean and, together with its associate wetlands, forms an ecosystem of high ecological, fishing, and tourist value, recognized both nationally and internationally. It is included in the Ramsar List of Wetlands of International Importance, and it is also a Special Protected Area of Mediterranean Interest, Specially Protected Area under the EU Wild Birds Directive, and Site of Community Importance to be integrated in the Nature 2000 Network (EU Habitats Directive). Despite this protection status, it is increasingly threatened by intense agricultural and tourism activities. The high anthropogenic pressure in the surrounding watershed of the Mar Menor has led to an increase in nutrients and pollutants flowing through the watercourses into the lagoon, which causes

changes in the physical chemistry of water and sediments and in the biological communities of the lagoon (Terrados and Ros 1991; Pérez-Ruzafa et al. 2002; Lloret et al. 2005; Velasco et al. 2006).

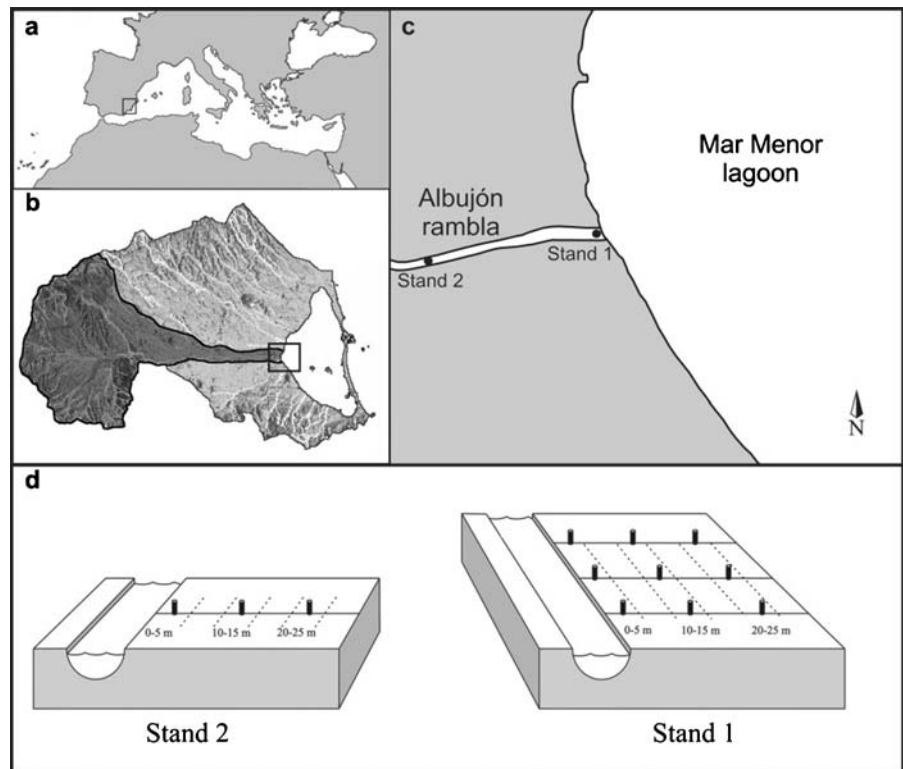
In this study, we measured nutrient removal by *P. australis* in the Albuñón rambla, the main drainage system that discharges into the Mar Menor, in which it forms a dense monospecific bed along the channel. Traditionally, in this area, the aerial biomass of the common reed is harvested each year in late summer as a cleaning measurement to prevent the catastrophic effect of flash floods on urban infrastructures. Our specific objectives were: (1) to analyze the seasonal variation of aerial biomass and nutrient concentrations (N and P) in common reed in the Albuñón rambla, both in the aboveground and belowground tissues; (2) to analyze the effect of cutting aerial biomass on nutrient bioaccumulation and water and sediment nutrient levels; (3) to determine environmental controlling factors of nutrient retention; and (4) to propose a management plan to increase the nutrient retention efficiency by plant and reduce the input of nutrients into the Mar Menor lagoon.

2 Materials and Methods

2.1 Study Site

The Mar Menor is a hypersaline coastal lagoon in the SE of the Iberian Peninsula with an area of 135 km², a volume of 580 hm³ and a mean depth of 4 m. In its drainage basin, the main land uses are intensive agriculture and residential areas. The Campo de Cartagena, one of the main horticultural producers of Europe, is a lowland plain (1,440 km²), slightly inclined to the Mar Menor, of clayed soils dedicated to intensive agriculture with irrigated horticultural and citrus crops. A large part of the nutrients contained in agricultural soils of Campo de Cartagena enters to the lagoon through superficial or underground drainage. It is drained by several ephemeral watercourses or *ramblas*, which flow into the lagoon after episodic storm rainfall events, usually in autumn, causing washing and erosion processes with massive exports of water, sediments, and nutrients (Velasco et al. 2006). The Albuñón rambla is the principal watercourse (Fig. 1), draining a surface of 441 km², about one third of the total surface of the Campo de

Fig. 1 Location of the Mar Menor lagoon (a); the Campo de Cartagena and the Albuñón watershed (shaded; b); sampling sites in the Albuñón rambla (c); and graphic description of sampling points selected in the floodplain of stand 1 and 2 (d)



Cartagena. Since the 1980s, the last 7 km of the channel has flowed permanently due to the drainage from irrigation lands and sewage discharges. The principal urban point source of pollution is the effluent of Los Alcazares wastewater treatment plant, which insufficiently treats sewage from a population over 100,000 habitants in summer. Urban wastewater discharges into the Albuñón rambla 2 km upstream of its mouth in the Mar Menor, and it is in this reach of permanent water where the reed is well developed and occupies the floodplain.

The climate is semiarid Mediterranean, with a mean annual temperature of 17°C (Conesa 1990). The mean annual rainfall is 300 mm, with most precipitation concentrated into short episodic storm events in autumn and spring. At the end of the summer, traditionally, the Confederación Hidrográfica del Segura (the watershed hydrological management agency) cuts the aboveground biomass of common reed in the Albuñón rambla, using heavy machinery that causes a geomorphological alteration of the channel and the floodplain. Also, the stems are left in the floodplain, forming a thick layer of coarse detritus that are lixiviated and decomposed in the stream and/or exported to the Mar Menor in the case of flood events.

2.2 Sampling and Processing of Samples

The present study was carried out between September 2003 and September 2004, in the mouth of the Albuñón rambla. This period includes two cutting events and two periods of reed growth, one at the end of summer 2003 after its cut (rhizomes are not removed, and the good climatic conditions in autumn favor their growth) and another at the beginning of spring (following their natural cycle).

Nine sampling points were selected in the floodplain spatially distributed along three transects, as a function of the distance to the coastline: 50, 65, and 80 m. Inside each transect, sampling points in the floodplain were located at intervals according to distance to the channel: 0–5, 10–15, and 20–25 m (Fig. 1d). Seven samplings were carried out during the annual cycle, and in each sampling, samples were taken of the aerial (stems, leaves, and panicles) and subterranean parts (roots and rhizomes) of common reed. Also, at each date, aboveground biomass was estimated using the Thursby et al. method (2002), counting the stems included in a square plot (quadrat) of 25 cm side and the length of the five tallest stems. Nine plots per

date were sampled. Previously, we calculated the length–mass relationship from 50 individuals and the total biomass in five plots counting and measuring the total individuals. A regression equation was obtained between real biomass (B) and biomass calculated using the mean length of the five tallest stems (x), and this relationship was used to estimate aerial biomass on each date.

$$B = 0.43x + 113.33 \quad (R^2 = 0.97)$$

To determine the effect of cutting on nutrient concentrations in common reed, we compared the stand at the mouth (stand 1) with other stand situated 1 km up from the mouth (stand 2, which was not affected by the harvest), before cutting in August, and after cutting in September 2004. In stand 2, *Phragmites* samples were taken in three points in a unique transect.

On each date, water temperature, conductivity, salinity, and dissolved oxygen were measured in situ using a multiparametric recorder (WTW, Multiline P4). Discharge was estimated from measurements of depth and current velocity along a cross-section in the channel. Also, sediments and superficial water samples were taken both in the floodplain and in the channel. The samples were hermetically closed, kept at 4°C for transportation to the laboratory for later analyses of the nutrients. Water samples were filtered through pre-ashed and pre-weighed Whatman GF/F glass-fiber filters. Ammonium was converted to ammonia by adding 10 M NaOH solution and measured with an ammonia selective electrode connected to a pH/mV meter. The rest of the nutrients were determined according to standard methods (APHA 1992): nitrate by cadmium reduction method, nitrites by sulfanylic acid colorimetry, and phosphate by ascorbic acid colorimetry.

Sediments and common reed samples were dried previously in the oven at 60°C and next were ground with a mortar (sediments) and a mechanical grinder (*P. australis*) until a fine phase was obtained that facilitated nutrient analysis. The nitrogen and carbon concentrations of sediments and nitrogen concentration of reed samples were determined using an elementary analyzer (Carlo Erba CNHS-0 EA-1108). However, for phosphorus analysis, both types of samples (1 g of sediments and 0.25 g of reed) were subjected to sulfuric acid and potassium persulfate

digestion in an autoclave at 115°C for 1 h and then left to cool. The diluted digested solution was analyzed following the standard method for phosphate analysis by ascorbic acid colorimetry (APHA 1992).

2.3 Data Analyses

Analysis of the variance (ANOVA, one factor) was carried out to test differences in the concentrations of nutrients between the different treatments: in the distance gradients to the channel and the mouth, aboveground, and belowground tissues of the reed, water, and sediments in the floodplain and channel, and between reed stands. Previously, data were \log_{10} -transformed to meet normality assumptions. Pearson correlation coefficients were calculated between nutrient concentrations in common reed and environmental variables measured together with the mean monthly air temperature and C_{org}/N and N/P ratios. Multiple lineal regression models (Stepwise Forward) were carried out, the dependent variables being nutrient concentrations of the reed and the independent variables the environmental parameters analyzed. Statistical analyses were made with the Statistica 6 program.

3 Results

3.1 Physico-chemical Water Characteristics of the Albuji3n Rambla

The mean discharge of the Albuji3n rambla into the Mar Menor lagoon during the study period was 322.76 l s^{-1} , the highest value (949.20 l s^{-1}) being reached in April after strong spring rains. In general, superficial water in the mouth of the rambla was hyposaline (5.5 g l^{-1} mean salinity, 12.31 mS cm^{-1} mean conductivity), of basic pH (7.59 mean pH), poorly oxygenated (mean values of $5.44 \text{ mg O}_2 \text{ l}^{-1}$ and 61.41% O_2 saturation). The highest values for phosphates and ammonium in channel water were measured in August (0.74 and 9.20 mg l^{-1} , respectively) reflecting the high urban wastewater discharges. The highest concentrations of nitrites ($348.63 \text{ } \mu\text{g l}^{-1}$) and nitrates (29.44 mg l^{-1}) occurred in April, probably due to the washing of surrounding cultivated soils by the spring rains.

Table 1 Basic descriptive statistics of nutrient water concentrations from the channel and the floodplain and results of analysis of variance (ANOVA-one factor)

	Channel water				Floodplain water				F	p
	N	Mean ± SE	Min.	Max.	N	Mean ± SE	Min.	Max.		
N-NH ₄ ⁺ (mg l ⁻¹)	14	4.30±0.99	0.01(N-03)	9.20 (Au-04)	43	7.33±2.51	0.05 (F-04)	27.67 (S-03)	0.25	n.s.
N-NO ₂ ⁻ (μg l ⁻¹)	17	155.58±26.73	41.38 (N-03)	348.63 (A-04)	47	79.15±26.48	2.76 (N-03)	253.98 (A-04)	24.75	0.0000
N-NO ₃ ⁻ (mg l ⁻¹)	17	13.02±1.98	5.73 (J-04)	29.44 (A-04)	47	5.05±1.32	0.13 (J-04)	12.64 (A-04)	25.18	0.0000
P-PO ₄ ³⁻ (μg l ⁻¹)	17	410.95±88.10	3.59 (N-03)	740.72 (Au-04)	46	1399.59±457.30	144.81(A-04)	5470.91 (J-04)	0.28	n.s.

Significant differences were found in nitrite and nitrate concentrations between channel and floodplain, being higher in the former. However, the floodplain presented higher ammonium and phosphate concentrations than the channel, although these differences were not significant. Temporal variations in the water nutrient concentrations were greater in the floodplain than in the channel, as observed from the larger standard errors, particularly for phosphates (Table 1).

When water nutrient levels between reaches were compared, a significant increase in concentration of phosphate (583.3 μg l⁻¹), nitrate (15.41 mg l⁻¹), and nitrite (112.6 μg l⁻¹) was observed in September 2003 after reed cutting in stand 1 in relation to stand 2, while in September 2004, only the nitrate level increased (9.51 mg l⁻¹), and the nitrite decreased (104 μg l⁻¹; Table 3).

3.2 Nutrient Sediment Content

The nitrogen, phosphorus, and organic carbon contents in sediment were significantly greater in the floodplain than in the channel (Table 2) through

the accumulation of dead shoots of common reed. The lowest nitrogen concentration in the floodplain occurred in September 2004 (0.60 mg N g⁻¹), while the maximum values were observed in November 2003 (2.43 mg N g⁻¹). Total phosphorus concentration peaked in August 2004 in the floodplain (0.59 mg P g⁻¹) and in July 2004 in the channel sediments (0.44 mg P g⁻¹). The C_{org} values were highest in summer, in July 2004 (230.43 mg C_{org} g⁻¹ in the floodplain and 39.87 mg C_{org} g⁻¹ in the channel sediments). No effect of cutting was observed on the nutrient content of sediment, when comparing reaches after the harvest of common reed, in both September 2003 and 2004 (Table 3).

3.3 Phenology and Aboveground Biomass of *P. australis*

P. australis is a perennial helophyte with strong winter dormancy requirements (Tylová et al. 2008). Its shoots are sensitive to frost, and senescence starts in autumn and is accompanied with the translocation of N- and P-rich compounds to the belowground organs (rhizomes) as reserves for over-wintering

Table 2 Basic descriptive statistics of nutrient sediment concentrations from the channel and the floodplain and results of analysis of variance (ANOVA-one factor)

	Channel sediments				Floodplain sediments				F	p
	N	Mean ± SE	Min.	Max.	N	Mean ± SE	Min.	Max.		
N (mg g ⁻¹)	21	0.63±0.12	0 (J-04, Au-04)	1.31 (A-04)	63	1.66±0.14	0.60 (S-04)	2.43 (N-03)	21.46	0.0000
P (mg g ⁻¹)	18	0.33±0.03	0.18 (F-04)	0.44 (J-04)	63	0.46±0.02	0.37 (S-03)	0.59 (Au-04)	19.48	0.0000
C _{org} (mg g ⁻¹)	20	20.31±2.86	4.80 (F-04)	39.87 (J-04)	63	107.27±15.04	11.96 (F-04)	230.46 (J-04)	13.73	0.0003

Table 3 Basic descriptive statistics of nutrient concentrations in water and sediments from the two studied reaches in September 2003 and September 2004 after reed common cutting and results of analysis of variance (ANOVA-one factor)

	September 2003			<i>F</i>	<i>P</i>	September 2004			<i>F</i>	<i>P</i>
	<i>N</i>	Stand 1 Mean ± SE	Stand 2 Mean ± SE			<i>N</i>	Stand 1 Mean ± SE	Stand 2 Mean ± SE		
N-NH ₄ ⁺ water (mg l ⁻¹)	2	8.63±0.79	9.99±1.63	0.53	n.s.	3	4.77±0.57	5.48±0.14	1.65	n.s.
N-NO ₂ ⁻ water (μg l ⁻¹)	2	136.31±21.55	23.71±4.76	46.95	0.02	3	72.17±16.14	176.08±38.76	7.84	0.04
N-NO ₃ ⁻ water (mg l ⁻¹)	2	15.40±3.91	0	129.65	0.007	3	16.13±2.04	6.61±1.49	13.18	0.02
P-PO ₄ ³⁻ water (μg l ⁻¹)	2	583.29±50.79	23.80±1.06	1,056	0.009	3	538.09±380.79	1389.74±444.65	2.51	n.s.
P sed (mg g ⁻¹)	6	2.98±0.29	3.18±0.29	6.73	n.s.	6	4.12±0.80	6.89±0.84	2.32	n.s.
N sed (mg g ⁻¹)	3	1.26±0.25	1.08±0.25	0.42	n.s.	3	0	2.37±1.25	3.89	n.s.
C _{org} sed (mg g ⁻¹)	3	17.17±5.50	19.43±0.16	0.43	n.s.	3	98.03±64.75	550.36±215.09	7.12	n.s.

(Kohl et al. 1998). During this period, rhizomes grow horizontally before terminating in an upward apex and becoming dormant until spring. During the spring growing season, the aerial shoots arise from the rhizomes. Large buds formed the previous fall are the first to emerge, with smaller spring-formed buds emerging later. Following the emergence, stems grow rapidly, and floration occurs in summer (Gucker 2008).

Phenology of *P. australis* in the Albuñón rambla during the studied period follows the general pattern, although with some variations in relation to weather conditions and cutting events (Fig. 2). Stems in the mouth of the rambla were cut during the last week of August in both years (2003 and 2004). After cutting, a new fast growth period started, the new stems reaching a mean length of 46 and 57 cm after 10–15 days, respectively. At the beginning of November 2003, the stems reached 136 cm mean height. In December and January, the senescence of the above-ground biomass began, and by the middle of February,

practically all the old stems were dry, although new stems also began to emerge at this time. By the end of April, the new stems had reached a mean height of 145 cm. Stems attained their maximum height and biomass by the middle of July (Fig. 3), while the biomass decreased in August. Flowering started in August.

3.4 Nutrient Content of *P. australis*

Preliminary tests pointed to no differences in nutrient content tissues along transects in stand 1. Mean N concentration was higher in the aboveground tissues (stems and leaves) than in belowground parts (roots and rhizomes) of the plant, while no significant differences were found for P (Table 4).

The pattern of temporal variation of N and P concentrations was related to plant phenology (Fig. 4). The maximum concentrations for the two nutrients were observed in young stems in the initial stages of the autumn growing season (35.86 mg

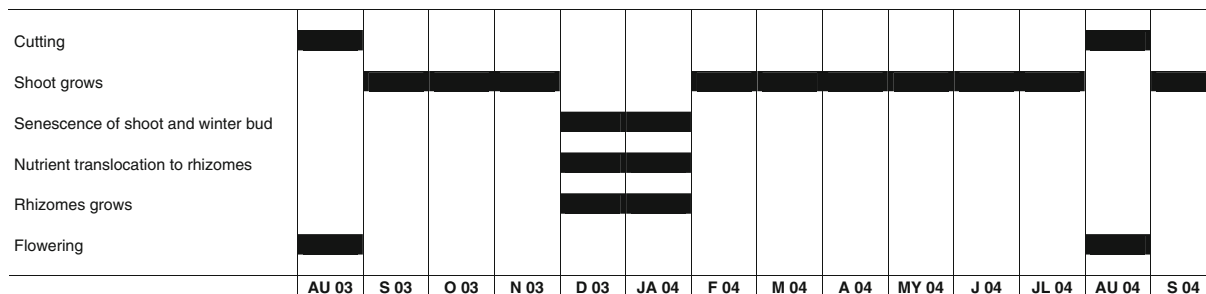
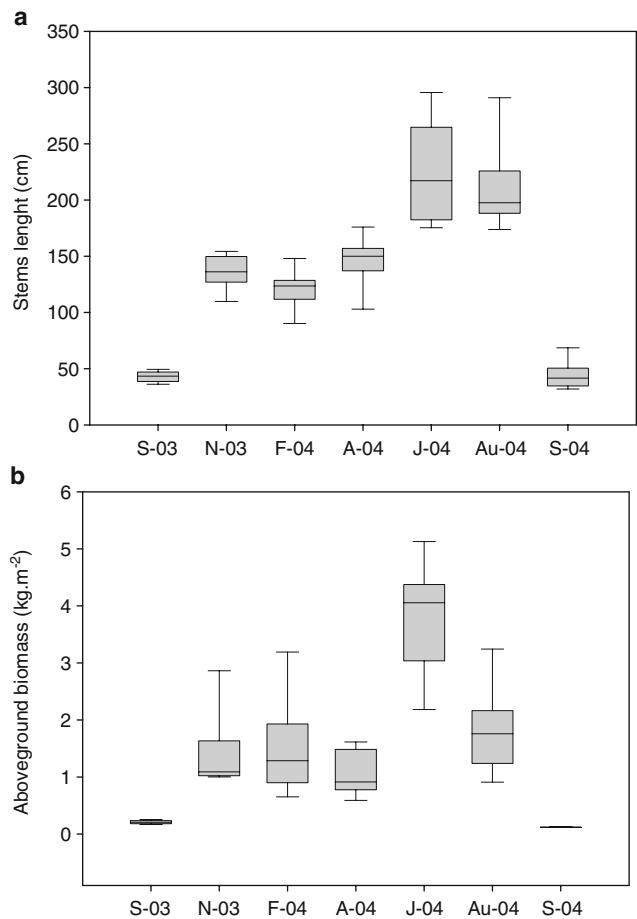
**Fig. 2** Phenology of *P. australis* at the Albuñón rambla during the study period

Fig. 3 Seasonal changes in stems length (a) and above-ground biomass (b) of *P. australis*. Plots the median, 10th, 25th, 75th and 90th percentiles as vertical boxes with cross bars



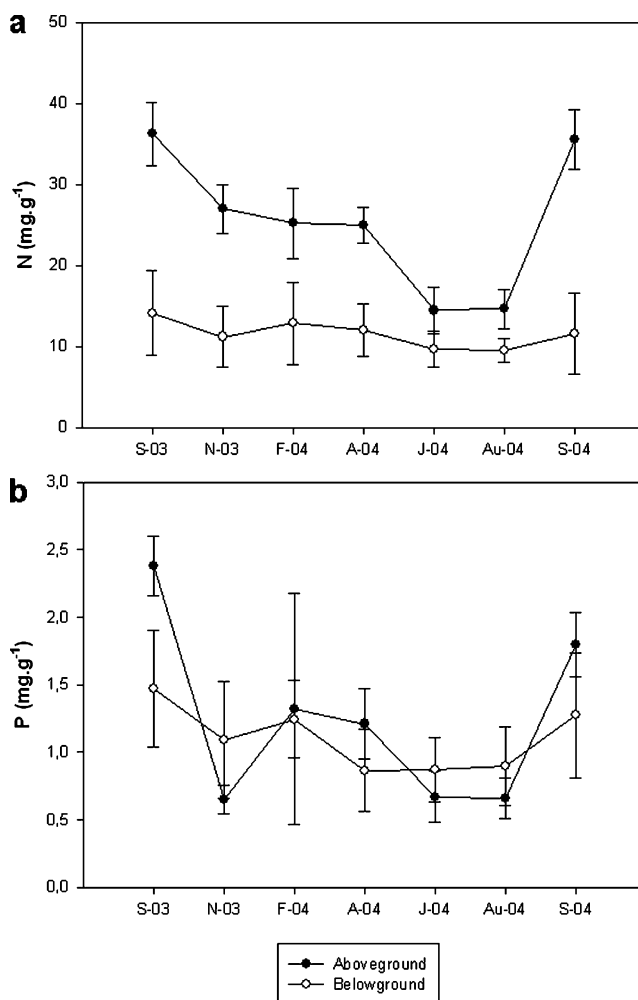
N g⁻¹ and 2.38 mg P g⁻¹, in September 2003). The dynamics of the nitrogen content followed a similar pattern in aboveground and belowground biomass, although variations were bigger in the aerial part (Fig. 4 a). During the cold period, N levels decreased in both parts, and no clear evidence of N translocation was observed. Later, during the spring growing season, a small increase in the N content occurred in the new stems and then fell in summer to reach the

minimum values in both parts of the plant. However, P dynamics showed evidence of translocation processes related to growth activity (Fig. 4 b). In November and in summer, the periods when aerial growth stops because of the harsh conditions, the P concentration in rhizomes was higher than in stems, while in spring and in September, the periods of maximum growth, the reverse relation was found. In February, both concentrations were very similar.

Table 4 Basic descriptive statistics of nutrients concentrations in aboveground and underground tissues of *P. australis* and results of analysis of variance (ANOVA-one factor)

	Aboveground tissues				Underground tissues				F	P
	N	Mean ± SE	Min.	Max.	N	Mean ± SE	Min.	Max.		
N (mg g ⁻¹)	65	25.77±2.64	14.45 (J-04)	35.86 (S-03)	63	11.57±0.05	9.57 (Au-04)	14.12 (S-03)	163.01	0.0000
P (mg g ⁻¹)	63	1.24±1.1	0.65 (N-03)	2.38 (S-03)	63	1.10±0.05	0.86 (A-04)	9.57 (S-03)	0.10	n.s.

Fig. 4 Seasonal changes in nitrogen (a) and phosphorus (b) concentrations in aboveground and underground tissues of *P. australis*. Vertical bars represent standard error ($n=9$)



The highest total amounts of the two elements in the aboveground biomass were reached in July (0.54 TmN ha^{-1} and $0.025 \text{ TmP ha}^{-1}$) but decreased to approximately half in August (Table 5).

Nonsignificant differences in the concentrations of P and N between the two studied stands of

P. australis were found in August 2004, just before cutting (Table 6). However, in September 2004, after reed cutting, the levels of these elements in the young stems and of P in rhizomes were significantly greater in stand 1 than in the mature stand 2.

Table 5 Aboveground biomass (mean \pm standard error) of *P. australis* and nutrient accumulation during the study period

Date	Biomass (kgDW m^{-2})	N (Tm ha^{-1})	P (Tm ha^{-1})
9-09-2003	0.21 ± 0.01	0.08	0.005
7-11-2003	1.39 ± 0.20	0.38	0.009
13-02-2004	1.49 ± 0.26	0.38	0.02
22-04-2004	1.07 ± 0.13	0.27	0.013
16-06-2004	3.72 ± 0.31	0.54	0.025
19-08-2004	1.80 ± 0.24	0.26	0.012
13-09-2004	0.12 ± 0.001	0.04	0.02

Table 6 Summary of analysis of variance (ANOVA-one factor) comparing nutrient content of aboveground and underground tissues between the two studied reaches, before (August) and after (September) reed cutting in 2004

	Date	Tissue	F	P
N	19-08-2004	Aboveground	1.31	n.s.
		Belowground	3.02	n.s.
	13-09-2004	Aboveground	107.6	0.0005
		Belowground	1.05	n.s.
P	19-08-2004	Aboveground	0.0007	n.s.
		Belowground	0.07	n.s.
	13-09-04	Aboveground	49.51	0.00006
		Belowground	5.12	0.05

3.5 Nutrient Bioaccumulation in Relation to Environmental Variables

The N concentration in stems showed a positive correlation with the ammonium of the water of floodplain and channel and the N/P of sediments, while it showed the inverse relation with the C_{org}/N of sediments (Table 7). Phosphorus retention in the aboveground tissues was highly correlated with phosphate concentration of channel water. Ammonium of the channel water was also positively correlated with the P concentration both in the aboveground and belowground tissues. The nitrate content of water in the channel and the air temperature also showed a positive correlation with P concentrations in the stems, while P retention in the rhizomes was negatively correlated with nitrates in the floodplain water (Table 7).

Predictive models of nutrient concentration in the aboveground biomass obtained are shown in Table 8. The N content in the aboveground tissues was highly dependent on ammonium and nitrate content of water from the channel (with positive sign) and the C_{org}/N ratio of sediments (with negative sign). The P model accounts for 70% of its variability and was defined by the ammonium, nitrate, and phosphate concentrations of water of the rambla besides the salinity as independent variables, all with positive sign. As regards the nutrient levels in the underground part, no significant model was found.

4 Discussion

4.1 Nutrient Dynamics

Numerous studies have provided data of nutrient levels in aquatic plant tissues and growth rates in relation to nutrient concentrations in the environment, particularly with regard to the use of macrophyte species in the control of eutrophication (e.g. Carignan and Kalff 1980, Fernández-Alaet et al. 1999). Plants displayed a significantly higher P content in nutrient-rich sites than in nutrient-poor ones (Garbey et al. 2004), growing deficiently in conditions of nutrient shortage. Romero et al. (1999), in hydroponic culture in the laboratory, showed that nitrogen and phosphorus concentration in the *P. australis* tissues generally increased with N level in the root solution and significantly affected the relative growth rate of the plants. Similar results have been obtained by other authors (Ulrich and Burton 1985; Rickey and Anderson 2004). Tylová et al. (2008) experimentally demonstrated that nutrient enrichment affects plant growth, phenology, and the accumulation of N storage compounds in belowground organs.

In streams under heavy influence of agriculture, such as the Albuñón rambla, nitrate is the predominant N form. Nevertheless, during summer months, it is common to find high phosphate and ammonium concentrations due to the increase in the discharge of

Table 7 Pearson correlation coefficients between nutrient concentrations and environmental variables for aboveground and underground tissues

	N	P
Aboveground tissues		
Temperature	n.s.	0.38*
N-NH ₄ ⁺ floodplain water	0.33*	n.s.
N-NH ₄ ⁺ channel water	0.35*	0.59***
N-NO ₃ ⁻ channel water	n.s.	0.42*
P-PO ₄ ³⁻ channel water	n.s.	0.60***
C_{org}/N sediments	-0.33*	n.s.
N/P sediments	0.38*	n.s.
Underground tissues		
N-NO ₃ ⁻ floodplain water	n.s.	-0.38*
N-NH ₄ ⁺ channel water	n.s.	0.31*

* $p=0.05-0.01$; ** $p<0.01-0.001$; *** $p<0.001$

Table 8 Multiple linear regression models for nutrient concentration in the aboveground tissues of *P. australis* (data $\log(x + 1)$ transformed)

	R^2 adjusted	F, p	SE
$N_{\text{aboveground tissues}} = 1.26 - 0.15 (C_{\text{org}}/N_{\text{sediments}}) + 0.11 (N - NH_4^+_{\text{channel water}}) + 0.25 (N - NO_3^-_{\text{channel water}})$	0.49	$F(3.53) = 19.24$ $p < 0.00000$	0.11
$P_{\text{aboveground tissues}} = -1.14 + 0.17 (N - NH_4^+_{\text{channel water}}) + 0.53 (N - NO_3^-_{\text{channel water}}) + 0.76 (\text{Salinity}) + 0.06 (P - PO_4^{3-}_{\text{channel water}})$	0.70	$F(4.58) = 37.12$ $p < 0.00000$	0.07

wastewater. The mean content of nitrogen and phosphorus in water during the studied period corresponded to hypereutrophic conditions (Vollenweider 1968). Nutrient levels in *P. australis* were high in relation to the high nutrient concentrations in the environment and similar to those obtained by other authors in eutrophic systems: Lake Averno (Naples, Italy; Baldatoni et al. 2003), constructed wetlands in Queensland, Australia (Greenway and Woolley 1999), el Hondo wetland (Elche, Spain; Cirujano et al. 2005), and Pilica River (Poland; Kiedrzyńska et al. 2008).

Seasonal changes in N and P concentrations in the aboveground and belowground tissues of common reed were observed in relation with plant phenology and cutting. The greatest nutrient concentrations were reached in the newly emerging stems after cutting. N concentrations in the aboveground reed tissues were always greater than in the belowground tissues, with maximum levels in growth periods (autumn and spring) and minimum levels in winter and summer. The initial decline in concentrations of N and P in the aboveground tissues coincided with senescence of the stems in winter because of low temperatures, and the second decline was in July due to drought stress.

The phosphorus dynamics was different, the decrease in P in the shoots and the increase in rhizomes at the end of the vegetation period showing downward translocation. At the end of autumn and winter, P is translocated of stems and leaves toward the rhizomes and roots, which can recycle and withdraw nutrients from senescing plant parts for reuse (Vitousek 1982). The belowground storage pools of P compounds provide essential amounts of nutrients that are used for the growth of young stems in early spring. In early spring, at the start of its natural growth cycle, a translocation occurred again but in the opposite direction: from rhizomes to aerial part. The nutrient translocation capacity (in this case of P) from some organs to others enables plants to face nutrient fluctuations and therefore be highly competitive in habitats with fluctuating resources (Garbey et al. 2004). The formation of N reserves in rhizomes was, however, negligible. This behavior is typical of relatively open nutrient cycles where, over the longer-term, net storage of incoming nutrients does not occur (Board 1996, Kuehl et al. 1997). Under high nitrogen levels, *P. australis* can allocate more resources to aboveground growth than to

rhizome growth because there is little or no competition for nitrogen (Minchinton and Bertness 2003). Common reed of the Albuñón rambla corresponds to the assimilation type described by Lippert et al. (1999) adapted to nutrient-rich habitats, which is characterized by a pronounced external N cycle. Internal reserves play a less important role. The reed stand is well supplied with external N pools, both from sediments and water, and is highly productive (great aerial biomass, with stems of great length and diameter, and with a high nutrient content).

4.2 Factors Controlling Nutrient Bioaccumulation

Nutrient accumulation in the aboveground reed tissue responded positively to N availability in the Albuñón rambla. Nitrate and ammonium concentrations of channel water contribute to the storage of P and N in stems. Salinity and phosphates from the water channel also positively affect P retention. However, high C_{org}/N values in sediments can limit microbial activity and, therefore, the mineralization processes of the organic matter, negatively affecting N accumulation in the stems. On the other hand, interactions between the N and P cycles in sediments may explain the negative relationships found between the P content in the rhizomes and the nitrate concentration of the floodplain water. High nitrate concentrations in the floodplain increase the denitrification process. Denitrification with FeS as the reducing agent produces FeOOH, which will strongly enhance P binding onto sediment. The overall result is a loss of N compounds and a stronger P fixation, which limits the P release of sediments and therefore its assimilation by the rhizomes (Golterman 2004). Andersen (1982) obtained similar results in lakes, finding a positive correlation between high nitrate concentration and low P release from sediment.

4.3 Proposed Management Plan

Several authors have proposed to control the flow of nutrients and heavy metals in lakes or reservoirs through reed harvesting, considering the dynamic cycling of nutrients and the seasonal changes in accumulation (Nikolaidis et al. 1996; Asaeda and Karunaratne 2000; Kiedrzyńska et al. 2008). Besides, the periodic cutting of common reed stimulates its

growth and increases nutrient content of new shoots (Greenway and Woolley 1999).

The high nutrient content of *P. australis* in the Albuñón rambla means it can be used as a “green filter” to reduce the pollution load reaching the Mar Menor lagoon, if the aboveground biomass is harvested when it contains the maximum amounts of nutrients. In the Albuñón rambla, the aboveground biomass reached the maximum value in July as did as the maximum standing stocks of N and P. However, in August, it decreased probably due to drought stress and high temperature conditions in the study area. Based on the obtained results, we propose that reed cutting be brought forward to the beginning of summer, instead of August, coinciding with the time of maximum aerial biomass, greatest nutrient retention, and less risk of high precipitation. A second harvest in November, before the autumn shoots began to die and before P translocation to rhizomes, could be recommended to maximize the nutrient reduction in nutrient-rich habitats because the following spring growth will not be limited. However, the effects of harvesting frequently on the plants need to be evaluated. We recommend removing the stems immediately after cutting to avoid nutrient leaching from shoots to sediments and water and that the use of heavy machinery for cutting be avoided because this alters the floodplain sediments and favors the P release (Golterman 2004). Traditional reed cutting in the Albuñón rambla at the end of summer and litter deposition on the floodplain lead to the rapid release of soluble compounds from leaves and stems, facilitated by the fragmentation to which they are subjected (Larsen 2003).

The correct management of common reed in coastal rambals and wetlands (cutting and removing the biomass from the floodplain) represents an economic and simple measure to reduce the contamination of the Mar Menor lagoon in conjunction with other watershed strategies (wastewater treatment plants, good agricultural practices, geomorphic stream restoration, etc). The stream restoration designed to reconnect stream channel with floodplains that promote flooding and dissipation of erosive force, increasing the residence time during floods, could increase the removal of nutrients by common reed and denitrification rates (Kaushal et al. 2008).

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