

Mediterranean limnology: current status, gaps and the future

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ABSTRACT

The current ecosystem paradigm in limnology is represented by the cold temperate, stratifying lake and the single-channelled river. However, the variety of inland water ecosystems is much higher, and so is the ecological complexity of many of them. Most Mediterranean limnosystems are quite distinct from the contemporary limnological paradigm. This overview will deal with the striking and exciting differences between Mediterranean and other temperate limnosystems. For example, most are very small, their catchment area is much larger than their size, and they experience both a longer vegetation period and a strong seasonality in water supply which occurs outside the hot season, often from groundwater sources. In addition, we encourage research on the often poorly known limnological processes taking place in Mediterranean regions by pointing at insufficiently covered research fields. Furthermore, competition for water among different users, arising from population increase in fertile and/or tourist areas, is certainly limiting the ability of many Mediterranean limnosystems to survive at present and in the near future, particularly in the face of the harsher environmental conditions that climatic change is triggering. A new paradigm on Mediterranean limnology is thus necessary. This will enable us to predict and mitigate more accurately the unstoppable effects of man-made change in these beautiful and still largely ignored ecosystems.

Key words: state-of-the-art, cold temperate and tropical limnosystems, climate change, mitigation measures

Mite letargo d'acque
[Lukewarm lethargy of water]
Salvatore Quasimodo
(Italian poet and Nobel laureate for Literature 1959)

1. INTRODUCTION

Monsieur Jourdain's character of Molière was amazed whenever he spoke prose (Act II, Scene 4, 1670). So are many of the limnologists when they deal with aquatic ecosystems. This metaphor reflects especially what Mediterranean limnologists feel when they try to unravel the many current enigmas around the ecology of the aquatic world in Mediterranean areas, and try fitting their results into current limnological paradigms. This is no easy task, however, because Mediterranean limnology as a science historically lags behind the traditional limnology of temperate lake and river ecosystems. As a consequence, the application of contemporary intellectual frames to Mediterranean limnology is likely not very appropriate (Alvarez-Cobelas *et al.* 1992a; Harris 1999; and a large etc.). Furthermore, we are beginning to see that Mediterranean limnology does not meld well with many concepts of temperate limnology, as the many "exceptions to the rule" statements in discussions of scientific papers by Mediterranean limnologists highlight (Angeler & Rodrigo 2004; Ortega-Mayagoitia *et*

al. 2002a). It is time therefore to appreciate that Mediterranean limnology cannot be forced ad hoc in current conceptual frameworks. We must begin to create a Mediterranean limnology paradigm, thereby widening the general paradigm of this science. This short, unavoidable subjective, overview is a first step in this direction.

2. BRIEF HISTORY AND CURRENT STATUS

First surveys of Mediterranean freshwater ecosystems can be dated back to Forel's (1889) studies in Lombardy lakes. Some scattered efforts were carried out in the first third of the 20th Century (Hutchinson *et al.* 1932; Stanković 1931), but only after World War II a strong impulse has been given by Italians at the Palianza's Istituto Italiano di Idrobiologia (Bertoni & De Bernardi 1997), the earlier Yugoslavian limnologists (Stanković, Ocevski) and the solitary figure of Margalef in Spain (Ros 1991) to be followed later by the outburst and strong development of Australian, Israeli and South-African limnology.

The wealth of Mediterranean limnology is reflected by the words which different languages of Mediterranean cultures use when referring to Mediterranean aquatic ecosystems. A non-exhaustive list is shown in table 1. The reader will notice that we intentionally omitted words such as "lake", "river", "stream" and their translations because we wish to emphasize the existence of other, often ignored limnosystems (e.g., temporary pools and streams, etc.) that are worthwhile for research

Tab. 1. Mediterranean lexikon on limnosystems. Words and translations are from González-Bernáldez (1992), Luigi Naselli Flores (Univ. Palermo, Italy), Lourdes Domingo (School of Modern Languages, Murcia, Spain), Said Messari, Maria Leitao (Bi-Eau, Angers, France), Radovan Erben (Univ. Zagreb, Croatia) and Rose Angeler (Grafenbach, Austria). In brackets, the language of each word is given. As an Italian motto says, *traduttore: traditore* [translator: traitor], so we assume responsibility for any mistake when attempting word equivalence. The languages are the following: afr = Afrikaan; alb = Albanian; ar = Arabic; au = native Australian; ber = Bereber; cat = Catalan; cro = Croatian; en = English; fr = French; gr = Greek; ir = Irish; it = Italian; mt = Maltese; pt = Portuguese; sa = Sardo; sic = Sicilian; sp = Spanish; tu = Turkish.

Abankor (ber) = Banco de areia (pt) = Mallada (cat) = Pješčana jama (cro) = Sand pit (en) = Sablière, Sablonnière (fr) = تليمر تيرت (Turba ramliyya, ar)
Acquitrino (it) = Almarcha (sp) = Almagem (pt) = Imxarba (mt) = Livada (cro) = Márgiu (sic) = Meadow (en) = Moçal (alb) = Nava (sp) = Paul (pt) = Vlei (afr)
Agerman (ber) = Bara, Lokva, Mlaka (cro) = Charca (sp) = Charco (pt) = Gandott (mt) = Polla (it) = Pool (en) = Toll (cat) = تليمر (Berka, ar)
Aguelman, Ayerman (ber) = Krška jama (cro) = Rock pool (en)
Aiguamoll (cat) = Bataklik (tu) = Biviere (or "Viviere", sic) = Élos (gr) = Humedal, Pantano (sp) = Kënetë (alb) = Marjal (cat) = Marsh, Swamp, Wetland (en) = Močvara (cro) = Palude, Pantano (it) = حرم (Marý, ar)
Albañal, Darro, Esgueva (sp) = Ditch (en) = Jama, Jarak (cro) = Regueira (pt) = Rigole (fr) = عالب (Balla'a, ar)
Albina (sp) = Ghadira mielha (mt) = Playa lake, Salt pan (en) = Solište, Solana (cro) = طش / عاق (Šaṭṭ / Qa'a, Sebkha, ar)
Albufeira (pt) = Albufera (cat, sp) = Étang (fr) = Lagoon (en) = Laguna (cro, mt) = Limnothálassa (gr) = فري حب (Buhaira, ar)
Arroyo (sp) = Creek (en) = Dere (tu) = Ilma gieri (mt) = Potok, Zaton (cro) = Riacho (pt) = Rierol (cat) = Ru (fr) = جيلخ (Jaliý, ar)
Backswamp (en) = Banco, Cilanco, Galacho, Madre vieja (sp) = Močvara nastala naplavljivanjem (cro) = Méandre (fr) = Oxbow (en) = يلمر طش (Šaṭṭ ramli, ar)
Baisse (fr) = Graba, Glib (cro) = Meander scrolls, Slough (en) = جرعت (Ta'arruý, ar)
Bárceña, Cibanca, Vega (sp) = Bega (sa) = Billabong (au) = Callow (ir) = Floodplain (en) = Ova (tu) = Plaine aluviale (fr) = Poplava (cro) = Várzea, Veiga (pt) = قور (Raqqá, ar)
Balsa (sp) = Bassa (cat) = Cisterna, Tanque (pt) = فوط / تليمر (Berka, Ṭuf, Ramaz, ar)
Bara (cro) = Estanque (sp) = Ggebbia (sic) = Pellg (alb) = Stagno (it) = جيرااص (Sahara, ar)
Bog, Carr (en) = Marais, Marécage (fr) = Močvara, Tresetište (cro)
Bulvar (tu) = Creek (au) = Fiumara (it) = Ilma korrenti (mt) = Marigot (fr) = Përrua (alb) = Rambla (sp) = Riera (cat) = دو (Wadi, ar)
Burim (alb) = Fawwara (mt) = Fuente, Manantial, Ojo (sp) = Izvor, Vrelo (cro) = Kaynak (tu) = Nascente (pt) = Pigi (gr) = Sorgente (it) = Source (fr) = Spring (en) = Ullal (cat) = نيع (*Ayn, ar)
Canal (pt) = Canal, Cauce, Caz (sp) = Channel (en) = Chenal (fr) = Corso (it) = Kanal (cro, mt) = Kanali (tu) = Korito (cro) = ضوح (Hawd, ar)
Ciénaga (sp) = Ghadira bit tajn (mt) = Mollera (cat) = Mudflat (en) = Muljevita obala od oseke (cro) = Placa de lodo (pt) = Triemula (sic) = عقم (Manqa', ar)
Craie lacustre (fr) = Marna, Gesso (pt) = Sedra, Travertin (cro) = Travertí (cat) = Travertine, Tufa (en) = Travertino, Toba (sp) = فوط / فس يلف (Falisa, Ṭaffa, Ṭufa, ar)
Delta (cro, gr, it, pt, sp)
Estany (cat) = Ibón, Lucio (sp)
Fen (en) = Močvarno tlo (cro) = عقم نس م (Mustanqa', ar)
Gnamma (au) = Gurgu (sic)
Gölet (tu) = Lacuna (it) = Lagoa (pt) = Laguna (cro, sp) = Lagunë (alb) = Limnowla (gr) = Llacuna (cat)
Jeimarros (gr) = Potok (cro) = Sel (tu) = Torrente (it, pt, sp) = Wied (mt) = ليس (Sayl, ar)
Mire (en) = Torbiera (it) = Tremedal, Turbera (sp) = Tresetište (cro) = Tourbière (fr) = Turfeira (pt) = موشخ / موشخ (Mawýal, Majazza, ar)
Raso, Tabla (sp) = Table (fr, en) = Tablica (cro)

because of their enormous scientific and social interest. So in addition to lakes and rivers, which have been studied exhaustively in cold temperate climates, there are other, often more abundant, ecosystem types in Mediterranean regions of the world, which make the aquatic habitat more diverse.

The Mediterranean climate is experienced in the Mediterranean basin (*sensu stricto*), the south-western part of South Africa, Southern California, the south-western and southern part of Australia and Central Chile (Bolle 2003). It is not easy to place boundaries of Mediterranean climate in the Mediterranean basin (Jeftić *et al.* 1992; Bolle 2003). As a compromise for France, we have chosen to use river catchments draining

to the Mediterranean Sea as the northern boundary (Biro 1970); so the Rhône and the minor watersheds of the Gulf of Lion are included in the Mediterranean limnological area. Mediterranean climate is characterized by a strong seasonality of rainfall and air temperature (Fig. 1), which are out of phase. Rainfall occurs mostly in spring and autumn (Bolle 2003). Also, the annual rainfall-to-potential evapotranspiration ratio ranges from 0.12 to 1, resulting in water shortages and droughts in many Mediterranean landscapes for considerable time of the year.

This section will be devoted to outline some features that make Mediterranean inland waters different from cold temperate and tropical limnosystems. We have

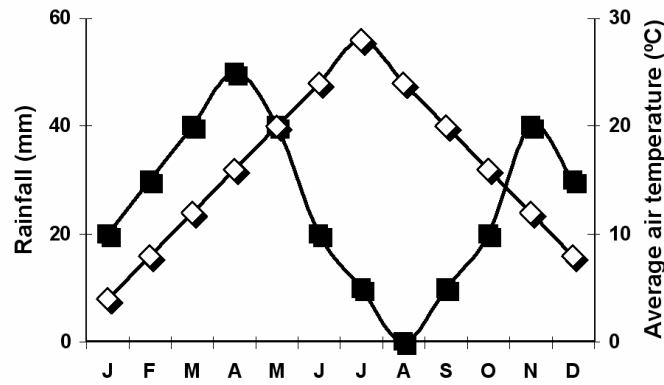


Fig. 1. Average air temperature and rainfall in 2003 in Ruidera Lakes (Central Spain). Data source: Lagunas de Ruidera Natural Park.

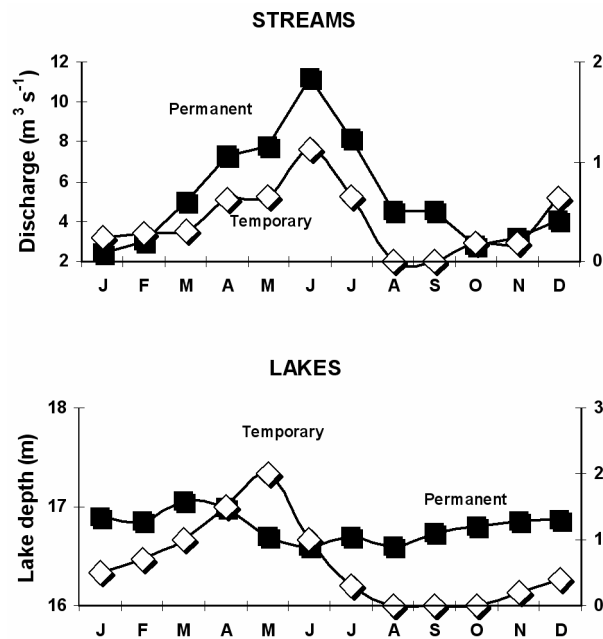


Fig. 2. Upper panel. Seasonal discharge in a permanent (Pinilla River, left ordinate) and a temporary (Upper Gigüela River, right ordinate) stream in Central Spain. Data sources: Alvarez-Cobelas (unpublished data) and Guadiana Water Authority. **Lower panel.** Seasonal lake levels in a permanent (Lake del Rey, left ordinate) and a temporary lake (Manjavacas Lake, right ordinate) in Central Spain. Data sources: Lagunas de Ruidera Natural Park and Alvarez-Cobelas (unpublished data).

selected only a few examples for which we are beginning to understand underlying mechanisms and processes of functioning. Obviously (read hopefully) the range of examples can be widened with the increase of our understanding of Mediterranean ecology in the future.

The strong seasonality of rainfall has important implications for water availability in Mediterranean limnosystems. As data from Central Spanish streams and lakes show (Fig. 2), a delayed response to rainfall patterns is evident in water discharge in streams and water levels in lakes. Depending on the availability of water and biophysical settings, Mediterranean aquatic ecosystems occur on a permanence gradient, and

include ephemeral to permanent water bodies (Boulton & Brock 1999).

Another key feature for Mediterranean limnosystems is that of landscape structure which can be useful for regional studies (Kalff 1991). Many limnological processes have been shown to depend partly on landscape features, an index of which is extension. Figure 3 shows the striking difference between the catchment:lake ratio for cold temperate and Mediterranean lentic systems. The data for temperate ecosystems are taken from the book by Kalff (2002), whereas those from the Mediterranean have been gathered from the extensive study on Sicilian reservoirs by Calvo *et al.* (1993). The regional differences are

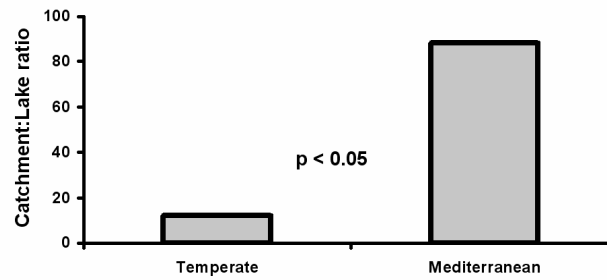


Fig. 3. Comparison of catchment:lake area ratios in cold temperate and Mediterranean limnosystems. Data sources: Kalff (2002, table 9-3) and Calvo *et al.* (1993). A Mann-Whitney test was performed to check the otherwise easily seen difference between both data sets.

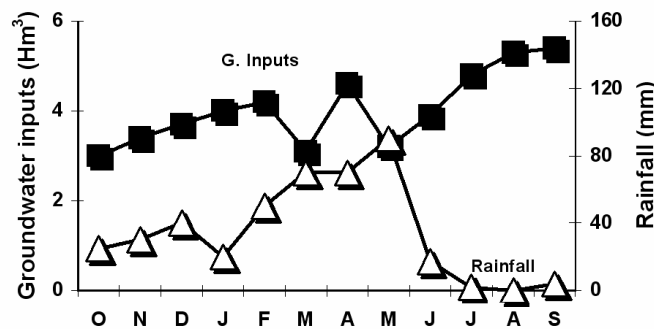


Fig. 4. Groundwater inputs to and rainfall over Lake La Colgada (Lagunas de Ruidera Natural Park) in the hydrological year 2003-2004. Data sources: Montero (unpublished data) and Lagunas de Ruidera Natural Park.

appreciable at one glance. Mediterranean limnosystems should experience stronger catchment effects than those in most cold temperate and tropical climates. Many Mediterranean studies acknowledge the influence of regional landscape characteristics but they have been scarcely used to explain local ecological phenomena. Studies such as those by Likens (1985) or Johnson *et al.* (1997) for other climatic regions will need to be designed for Mediterranean areas.

Furthermore, many Mediterranean environments are shallow, thus increasing the importance of emergent and submerged plants and the benthic-pelagic interactions for overall limnological functioning (Moss *et al.* 2004). Processes related to vegetation and the benthic-pelagic coupling should more importantly regulate ecosystem processes in the Mediterranean compared with cold temperate limnosystems. However, these phenomena are only beginning to be explored in Mediterranean aquatic ecology.

In Mediterranean areas groundwater hydrology is as important as surface hydrology for the persistence and functioning of aquatic ecosystems. In many stagnant and flowing Mediterranean limnosystems, water availability depends a great deal on groundwater discharge, which is either lagged from rainfall seasonality or lacks any seasonality because it depends in turn upon the hydrogeologic features of the subterranean aquifer. In Central Spanish Ruidera lakes,

despite a seasonal rainfall, the discharge of groundwater to the lakes is not seasonal at all (Fig. 4). In addition to water availability, groundwater can be a source of nutrients to limnosystems, as is often the case in agriculturally-used areas (Alvarez-Cobelas *et al.* 2004; Lamontagne 2002).

Another significant Mediterranean climate effect on limnosystems is the number of sunny hours in the year, which affects the length of the vegetative season positively and hence the variability of annual phytoplankton biomass. Figure 5 represents the ratio between maximal phytoplankton and average phytoplankton biomass in stratifying lakes of tropical, cold temperate and Mediterranean areas. Data for tropical and cold temperate lakes are reported in Lewis (1990), data for Mediterranean systems have been gathered from Greek, Italian and Spanish lakes. Mediterranean and tropical lakes have higher ratios than cold temperate lakes, which imply a response to the longer growing season. Mediterranean systems, however, show higher variability of that ratio than cold temperate and tropical lakes. Unfortunately the underlying mechanisms of this variability cannot be explained accurately at the present moment.

Chlorophyll responses to total phosphorus, a fundamental topic in applied limnology, also appear to be functionally distinct between temperate and Mediterranean areas, as these relationships show.

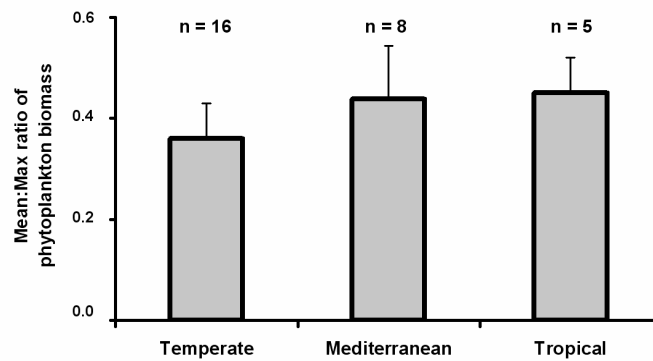


Fig. 5. Mean-to-max ratio of seasonal phytoplankton biomass in cold temperate, tropical and Mediterranean lakes. Only data sets with monthly sampling throughout an entire year have been used. Data sources: Alvarez-Cobelas (unpublished data, El Lakes Campillo and Las Madres, Spain), Alvarez-Cobelas *et al.* (1992, El Porcal Lake, Spain), Lewis (1990), Moustaka-Gouni (1993, Lake Volvi, Greece), Moustaka-Gouni & Nikolaidis (1990, Lake Vegoritis, Greece), Naselli-Flores & Barone (1998, Lakes Arancio and Rosamarina, Italy) and Planas (1973, Lake Banyoles, Spain).

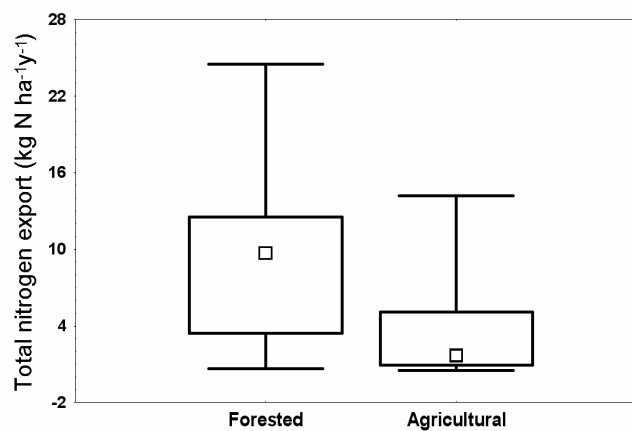


Fig. 6. Nitrogen export in forested and non-forested catchments of Alto Guadiana basin (Central Spain) in 2003. Data source: Alvarez-Cobelas (unpublished data).

$\text{Chl-}a_{\text{MAX}} = 0.74 \text{ TP}_{\text{AVE}}^{0.97}$ $r = 0.91$; $n = 20$
(OECD 1982, Shallow lakes and reservoirs Project)

$\text{Chl-}a_{\text{MAX}} = 0.45 \text{ TP}_{\text{AVE}}^{0.64}$ $r = 0.62$; $n = 68$
(Spanish reservoirs, Alvarez-Cobelas, unpublished)

$\text{Chl-}a_{\text{MAX}} = 0.54 \text{ TP}_{\text{LOADING}}^{0.72}$ $r = 0.87$ $n = 20$
(OECD 1982, Shallow Lakes and reservoirs Project)

$\text{Chl-}a_{\text{MAX}} = 1.43 \text{ TP}_{\text{LOADING}}^{0.40}$ $r = 0.65$ $n = 25$
(Spanish reservoirs, Ortiz-Casas & Peña 1984)

where $\text{Chl-}a_{\text{MAX}}$ is averaged epilimnetic chlorophyll "a" during stratification, TP_{AVE} is averaged total phosphorus in the water-column at late mixing, and $\text{TP}_{\text{LOADING}}$ is TP_{AVE} corrected for the Vollenweider & Kerekes' loading term (OECD 1982). In a straightforward way, the epilimnetic chlorophyll "a" in summer has a flatter response to average phosphorus content of the water column in Spanish reservoirs than in the OECD shallow lakes and reservoir study. Also, the explained variability is lower (around 40%) suggesting that other variables than phosphorus more importantly mediate chlorophyll variability in Mediterranean limnosystems compared

with cold temperate lakes and reservoirs. The same happens if we consider the classical loading term of P studies which in the case of Mediterranean aquatic ecosystems, may be influenced by the smaller size of catchments (see above).

In a cross regional comparison, perplexity can also arise when we focus on nutrient metabolism in streams. Unfortunately, there are few studies on this topic in Mediterranean areas as compared with those in temperate zones, and this is a gap to which we will refer later. For now, our own data show that forest catchments appear to export more nitrogen than agricultural areas in Central Spanish streams (Fig. 6), while the converse happens in cold temperate streams (e.g. Mayer *et al.* 2002). Concerning phosphorus, however, no statistically difference has been found between agricultural and forested catchments in our streams. This is another topic that deserves a closer scrutiny in view of the increasing concern on nitrogen effects worldwide (Vitousek *et al.* 1997).

Differences between cold temperate and Mediterranean limnosystems can also be found in

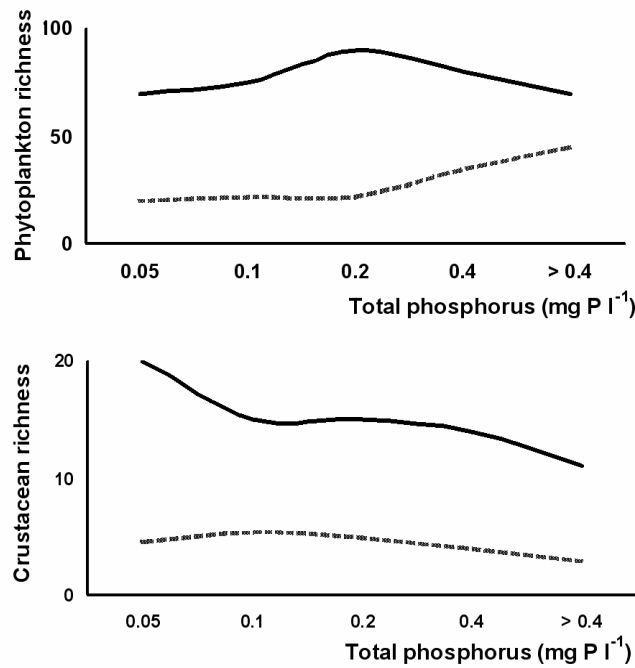


Fig. 7. Patterns of planktonic species richness vs total phosphorus in Spain (dashed line) as compared with those of Danish lakes (solid line). Data sources: Spanish phytoplankton (Alvarez-Cobelas, unpublished data), Spanish crustaceans (Alonso 1998), Danish plots (adapted from Jeppesen *et al.* 2000).

species richness, the highest concern of taxonomically-oriented limnologists. If we plot the trend of phytoplankton and crustacean richness along a phosphorus gradient in Danish lakes (Jeppesen *et al.* 2000), phytoplankton richness peaks at intermediate phosphorus concentrations, but Crustaceans do so in oligotrophic sites (Fig. 7). In Spain, however, phytoplankton richness correlates positively with phosphorus and Crustaceans peak at intermediate concentrations of phosphorus. It seems that the threshold of highest richness at intermediate nutrient concentrations (Connell 1978; Carney & Elser 1990) was shifted towards higher TP values in Mediterranean limnosystems, but again no sound explanation can be advanced yet.

In the last thirty years there has been a growing interest regarding limnetic food webs, often linked to biomanipulation as a tool for improving water quality. Some useful concepts, such as the trophic cascade (Carpenter & Kitchell 1993) or the alternative stable states (Scheffer 1998), have emerged based on studies in cold temperate climates. Though useful for Mediterranean areas, it may happen that processes inherently associated with climate add further complexity. As shown in several studies, including ours (King *et al.* 1997; Angeler *et al.* 2002a, b; Ortega-Mayagoitia *et al.* 2002a, b), the role of cyprinids, the dominant (often non-planktivorous) fishes in Mediterranean ecosystems (Doadrio 2002), can importantly affect interactions between sediments and the water column, including food web characteristics. Although they clearly influence food web dynamics, no generalizations can be made on the magnitude and importance of influence. Ontogenetic

shifts in habitat and food selection with fish age (Mittelbach & Persson 1998) and the benthic feeding of most adult cyprinids (Doadrio 2002) truncate the pelagic trophic cascade. Therefore, sediment-pelagic interactions modify species richness and water quality features that, in turn, impinge on trophic cascade functioning in a feedback response that has not been studied yet. Recent research also suggests that the influence of bottom-up forces is higher in Mediterranean limnosystems (Moss *et al.* 2004).

Until now, we have provided a few examples that highlight differences between cold temperate and Mediterranean limnosystems indicating that the latter merit further research with independent models. Most Mediterranean limnology has been undertaken in Italy, Australia, Israel, California and Spain, with interesting contributions from Chile, South Africa, France and Greece. Unfortunately, contributions by the Arabic countries of the Mediterranean basin, including Turkey, are scarcer and frequently published in journals with very restricted distribution. Table 2 shows a short account of studies on Mediterranean limnology where we have intended to include studies from most countries experiencing Mediterranean climate.

We can summarize the current status of Mediterranean limnology as the following: it is an underdeveloped branch of limnology. Many of its current models (either conceptual or mathematical) are unsatisfactory and many studies are compromised by the fact that researchers forced their results inappropriately into contemporary conceptual frameworks valid only for other climatic regions.

Tab. 2. Some limnological studies from Mediterranean areas of the World. Despite much of it is included in grey literature, we have only included published studies with ordinary distribution to make it easier for the concerned reader to dig deeper. In addition to the whole proceedings of the Societas Internationalis Limnologiae, some Mediterranean-specific limnology serials have been checked in its entirety, such as *Memorie dell' Instituto Italiano di Idrobiologia* (now *Journal of Limnology*), *Limnetica* and *Marine and Freshwater Research*. Also, the worldwide web has been searched for. An attempt has been made to search for limnological papers of all Mediterranean countries, but success was not always achieved. Since there are many studies in some areas, we have had to perform a selection which (it is obvious) will not satisfy everybody, but we think it is very representative of current knowledge on Mediterranean limnosystems and its gaps. Some recent EU research projects on limnology partly devoted to the Mediterranean basin are also reported at the end of the overview.

TOPIC	REFERENCES
Monographs and reviews	Akbulut (2004), Allanson (2004), Allanson <i>et al.</i> (1990), Alonso (1998), Alvarez-Cobelas & Cirujano (1996), Bonacina & Baudo (2001), Boulton & Brook (1999), Chergui <i>et al.</i> (1999), Davies <i>et al.</i> (1994, 1995), De Deckker & Williams (1986), Di Castri & Mooney (1973), Gagneur & Kara (2001), Gasith & Resh (1999), Grove & Rackham (2001), Guilizzoni <i>et al.</i> (1992), Jaouali (1995), Karaman & Beeton (1981), Lassere & Marzollo (2000), Montes & Duarte (1992), Peduzzi <i>et al.</i> (1998), Prat & Ward (1994), Prat <i>et al.</i> (1984), Rzöska & Talling (1976), Serruya (1978), Serruya & Pollinger (1983), Stanković (1960), VV.AA. (1989), Warner & Hendrix (1984)
Mediterranean floras, faunas and their distribution	Alonso (1996), Bunn & Davies (1990), Campaioli <i>et al.</i> (1994), Cirujano & Medina (2002), Cook (2004), Doadrio (2001), Margaritora (1985), Naselli-Flores <i>et al.</i> (1998), Stanković (1955), <i>Systematique des Organismes des Eaux Continentales Françaises</i> (1981-1993)
Studies on Mediterranean specific-sites	Bazzanti <i>et al.</i> (2000), Bayly (2002), Boix <i>et al.</i> (2000), Cianficconi & Moretti (1988), Cotta-Ramusino <i>et al.</i> (1991), Di Giovanni (1966), El Mezdi (1985), Ferrari <i>et al.</i> (1993), Gagneur (1994), Hillman & Shiel (1991), Hutchinson <i>et al.</i> (1932), Margalef (1948), Moretti (1949, 1953), Naselli-Flores & Barone (2002), Pevalek (1935), Ramón <i>et al.</i> (1993), Soria & Alfonso (1993), Stanković (1931, 1955, 1958)
Preliminary surveys and monitoring	Bahhou <i>et al.</i> (2000), Barbanti <i>et al.</i> (1971), Burgis & Symoens (1987), Calvo <i>et al.</i> (1993), Elster & Vollenweider (1961), Gessner (1957), Giudicelli <i>et al.</i> (1985), Margalef <i>et al.</i> (1976), Mitamura <i>et al.</i> (1997), Ramos <i>et al.</i> (1998), Rodrigues Capitulo <i>et al.</i> (1994), Saad (1978), Saad & Hemeda (2001), Sechi & Mosello (1985), Vicente <i>et al.</i> (1993)
Physical limnology	Ambrosetti & Barbanti (2002), Barbanti <i>et al.</i> (1981), Clark & Hudson (2001), Colomer & Casamitjana (1993), Colomer <i>et al.</i> (2001), Di Cola <i>et al.</i> (1977), Imberger (1985), Jellison <i>et al.</i> (1993), Kirk (1994), MacIntyre (1993), MacIntyre <i>et al.</i> (1999), Marcé <i>et al.</i> (2004), Piontelli & Tonolli (1964), Vila & Abella (1993)
Lake and wetland biogeochemistry	Adams <i>et al.</i> (2000), Astorga <i>et al.</i> (1993), Boon (2000), Boon <i>et al.</i> (2000), Callieri <i>et al.</i> (1986), Comin (1984), Corbella <i>et al.</i> (1956), Curco <i>et al.</i> (2002), Forés & Comin (1991), Golterman (1995), Golterman <i>et al.</i> (1998), Hambright & Eckert (2001), Lamontagne (2002), López <i>et al.</i> (2001), Mosello (1981), Petrović (1975), Vollenweider (1956, 1963)
Stream biogeochemistry, including decomposition	Butturini & Sabater (1998), Harris (2001), Hart <i>et al.</i> (1991), Maamri <i>et al.</i> (1994), Maltchik <i>et al.</i> (1998), Martí & Sabater (1996), Martí <i>et al.</i> (2004), McKergow <i>et al.</i> (2003), Mollá <i>et al.</i> (1998), Pattee <i>et al.</i> (2000), Robertson <i>et al.</i> (1999), Romani <i>et al.</i> (2004), Suárez & Vidal-Abarca (2000), Webster <i>et al.</i> (2001)
Plankton structure and dynamics	Albay <i>et al.</i> (2003), Aleem & Samaan (1969), Alvarez-Cobelas & Rojo (1994), Baldi (1943), Bertoni & Callieri (1999), Calderón-Paz <i>et al.</i> (1993), Callieri & Heinimaa (1997), Cassie (1967), De Bernardi (1974), Gasol <i>et al.</i> (2002), Guerrero <i>et al.</i> (1975, 1987), Hamza <i>et al.</i> (1993), Janasch (1958), Legendre & Trousselier (1988), Miracle (1975), Ocevski (1966), Padan & Shilo (1969), Peters (1985), Pirocchi (1947), Planas (1973), Pugnetti <i>et al.</i> (1992), Ravera (1954), Salmaso <i>et al.</i> (2003), Tafas & Economou-Amilli (1991), Tonolli & Tonolli (1951), Tonolli <i>et al.</i> (1967)
Benthos structure and dynamics	Aboal <i>et al.</i> (2000), Adams <i>et al.</i> (1978), Canteras (1985), Gell <i>et al.</i> (2002), Gomme & Muntau (1981), Habdija <i>et al.</i> (2000), Howard-Williams (1978), Metzeling <i>et al.</i> (2002), Prat & Bonada (2002), Prat & Rieradevall (1995), Resh <i>et al.</i> (1990), Rossi <i>et al.</i> (2003), Sabater <i>et al.</i> (2004), Sommer & Horwitz (2001), Stanković (1951)
Fish	Berg & Grimaldi (1966), Gasith <i>et al.</i> (1998), Granado-Lorencio (1991), Morgan <i>et al.</i> (2002), Moyle <i>et al.</i> (1982), Vargas & Sostoa (1996)
Food webs	Angeler <i>et al.</i> (2003), Balcombe & Closs (2004), Covich & Knežević (1978), De Bernardi & Giussani (1975), Giussani (1974), Giussani <i>et al.</i> (1990), Gophen & Serruya (1990), Gophen <i>et al.</i> (1991), King <i>et al.</i> (1997), Kitchell <i>et al.</i> (1978), Manca & Ruggiu (1998), Margaritora <i>et al.</i> (2001), Ortega-Mayagoitia <i>et al.</i> (2002a, b), Robertson <i>et al.</i> (1997), Točko (1966), Vighi <i>et al.</i> (1995)
Long-term studies	Berman <i>et al.</i> (1995), De Bernardi & Soldavini (1976), Morabito & Pugnetti (1999), Ruggiu <i>et al.</i> (1998a), Zohary (2004)

(to be continued)

Tab. 2. Continuation.

TOPIC	REFERENCES
Palaeolimnology	Aleem (1961), Guilizzoni & Oldfield (1996), Hutchinson (1970), Lami <i>et al.</i> (2000), Marchetto & Lami (1994), Margalef (1957), Ruggiu <i>et al.</i> (1998b) Schmidt <i>et al.</i> (2000), Valero-Garcés (2003)
Environmental problems including water pollution and eutrophication	Alvarez-Cobelas <i>et al.</i> (1992b), De Bernardi <i>et al.</i> (1996), Gaggino & Provini (1988), Gophen (2000), Lake (2003), Wynne & Parparova (2002)
Techniques for biological monitoring	Alba-Tecedor & Pujante (2000), Buffagni <i>et al.</i> (2001), Davies (2000)
Human culture and Mediterranean limnosystems	Alvarez-Cobelas & Cirujano (1996), Bayly (1999), Blasco Ibáñez (1901), Haslam (1991), Haslam & Borg (1998), Infante don Juan Manuel (1325), Snowden (1999)
EU Projects dealing (at least partly) with Mediterranean limnology	AL:PE, AQEM, AQUACON, BIOFILMS, BIOMAN, ECOFRAME, ERAS, EUREED I-II, EUROLIMPACS, FIRELAB, MOLAR, NICOLAS, PALICLAS, STAR, STREAMES, SWALE, TEMPQSIM

3. GAPS

The review of limnological literature (Table 2) has enabled us to find some gaps in Mediterranean limnology that could be arranged broadly within the following topics.

Gaps related to Mediterranean geography or ecosystems.- Some geographical areas have been insufficiently surveyed and their researchers are still engaged in enumerating their aquatic floras and faunas. Interestingly, many systems have high EVT:Rainfall ratios. Hence the most classical topics of ecology, i.e. the adaptations of organisms to environmental processes could be relatively new for Mediterranean limnology, and yield surprising results. We will need more information from areas and habitats with poor limnological knowledge. These are the following.

1. More studies from Northern Africa, the Arabic Middle-East, Mediterranean Chile and Turkey are needed.
2. There are few studies on temporary streams and Mediterranean specific limnosystems (gnammas, sebkhas, vleis, etc.; Table 1) and hence they must be increased.

Hydrology and biogeochemistry relationships.- Because water availability is essential for the survival of aquatic ecosystems, the regulation of their hydrological and biogeochemical processes must be studied jointly with more detail. More specifically, some research lines that are now poorly pursued will provide extremely interesting insights. These lines are the following:

1. The relationship between groundwaters and limnosystems has hardly been explored.
2. There are almost no studies on wetland biogeochemistry.
3. Very few studies exist on hyporheic biogeochemistry.

Biotic relationships.- The still poorly known aquatic floras and faunas of Mediterranean regions limit our understanding of biologically-mediated ecological proc-

esses. It is clear that updated taxonomic treatments of Mediterranean animals and plants must be prepared as a tool for sound ecological research in Mediterranean limnosystems. This will result in disclosing a high variety of yet overlooked biotic relationships, such as

1. The role of cyprinid fish in food webs that deserves more research.
2. Bacterial growth and diversity in wetlands and streams mostly unknown.
3. Plankton-benthos linkages still unknown.
4. The functioning of submerged and emergent vegetation and their influence on limnological processes.
5. The study of impacts of Mediterranean-alien species (e.g. *Dreissena*, *Procambarus*, *Eirocheir*) on food webs and ecological processes that has not been started yet or is poorly understood.

Overall approaches.- Limnology is a synthetic science and, from the very beginning (Forbes 1887), it has pursued an integrative view. Despite many holistic claims (e.g. Margalef 1983), Mediterranean limnology is still in its infancy concerning ecosystem approaches. It is time to start ecosystem, biome and even regional studies, linking processes across terrestrial and aquatic boundaries in Mediterranean areas of the World. Latitude has been shown to be a poor descriptor of overall limnological processes (Kalff 1991), but regional approaches will certainly produce surprising results and applications to tackle forthcoming threats, such as those of climatic change. Holistic topics to be considered are:

1. The landscape approach of limnosystem study, which is absent and has certainly proved to be very fruitful to explain overall processes, both in streams (Johnson *et al.* 1997) and in lakes (Riera *et al.* 2000).
2. The availability of limnosystem models, either heuristic or predictive, conceptual or numeric, which is still lower than the vast array of items from cold temperate areas (e.g. Reynolds *et al.* 2001; Sommer *et al.* 1986; Straskraba & Tundisi 1999).
3. Long-term studies exist in very low numbers, compared with long-term cold temperate surveys

(e.g. Talling 1993; Bäuerle & Gaedke 1998). Those studies will not only help to understand climate change but also illuminate shorter-term processes arising from seasonal and interannual environmental variability (Neale *et al.* 1991).

4. Climate change effects that can be hardly envisaged.

Applied topics.- These topics will not only aid in preserving Mediterranean limnosystems, but will provide also information on their economic value and the economic losses produced if they are impaired or even disappear. Some of them include:

1. Limnosystem services that have not been emphasized enough. This is an expanding topic throughout the world (Costanza *et al.* 1997) but remains to be carried out with Mediterranean limnosystems.
2. Measures for mitigating damage caused by climate change that will have to be developed for Mediterranean limnosystems.

4. THE FUTURE

The future of Mediterranean limnology as a science will depend on the survival of Mediterranean limnosystems which, in turn, will depend on water use and politics. The near future (roughly 100 years ahead) for Mediterranean limnology is not an optimistic one, however, as future scenarios of global climate change predict. In Mediterranean areas, lower and seasonally more irregular rainfall and higher air temperatures are expected (Bolle 2003), resulting in reduced water availability for surface and aquifer systems. Conversely, the socioeconomy of many Mediterranean areas will increasingly depend on agriculture and/or tourism, which are very water-demanding sectors (Gleick 1993). This will result in a conflict in which Mediterranean limnosystems will have the lowest societal priority. In the worst case many Mediterranean limnosystems and their invaluable cultural and biological legacy will be condemned to go extinct.

Prompt societal responses, including sustainable water use, to climate change are therefore key factors for the future of Mediterranean limnosystems. We acknowledge that only a few long-term data exist (but see the exceptional studies on Italian subalpine lakes and Lake Kinneret; table 2) on predicting the likely effects of climate change on our systems of interest but some prospective opinions reported by Spanish limnologists, working for at least 10 years in some systems that they know well, suggest that the effects of climate change will be very important in limnosystems (Alvarez-Cobelas *et al.* 2005). More specifically, the topics covered have been the persistence of the ecosystem (will it survive or not?), its size (will it stay permanent or become temporary?), its biogeochemistry and biota (will they be altered by climate change?). We have also asked about likely semiquantitative effects of climate change, and assigned them to categories from 0

(nil effect) to 4 (very strong effect). The overall conclusion is that the impacts generated by climate change will be very variable, and that streams appear to be less importantly affected in comparison with lentic water bodies (Fig. 8).

A strong argument to support more research on Mediterranean limnology comes from the fact that climate change will probably make cold temperate limnosystems more similar to what Mediterranean limnosystems are now (Arnell *et al.* 1996). So further improvement of Mediterranean studies will be very useful because it will provide reference conditions for cold temperate systems.

What about mitigation measures on the effects of climate change on Mediterranean limnosystems? Some could be the following:

- 1st) Mediterranean limnosystems should be given more priority in the societal needs.
- 2nd) Water-saving measures should be implemented immediately, instead of destructive and in terms of efficiency short-lived intercatchment water diversions, to supply Mediterranean tourist and agricultural sectors with water.
- 3rd) Developing and/or improving wastewater treatment and recycling.
- 4th) Increasing revegetation in catchments to mitigate pollution.
- 5th) Increasing environmental protection of valuable limnosystems, also enhancing connectivity among them.

5. CONCLUSIONS

Our preceding description of the current state, gaps and prospects of Mediterranean limnology allows us to arrive at some general conclusions.

- 1st) Mediterranean limnosystem types are very rich, but the ecology of most is poorly known.
- 2nd) Current models of cold temperate limnosystems have very restricted geographical application and Mediterranean limnosystems do not meld with them.
- 3rd) More research is urgently needed.
- 4th) More people and more funding must be devoted to Mediterranean limnology. These goals can be achieved partly by recruiting young and qualified personnel. A prerequisite, however, shall be a less burdensome and longer-term working perspective.
- 5th) Many endangered Mediterranean limnosystems will survive if, and only if, Mediterranean societies appreciate them (which is not the case right now).
- 6th) If Mediterranean societies continue to ignore the importance of their limnosystems, then it will occur what the great Sicilian writer Leonardo Sciascia (1983) so cleverly wrote more than 20 years ago: "*I fiumi sono mito e memoria, s'appartengono ai "verdi paradisi" dell'infanzia*" [rivers are myth and memory, they belong to the "green paradise" of childhood].

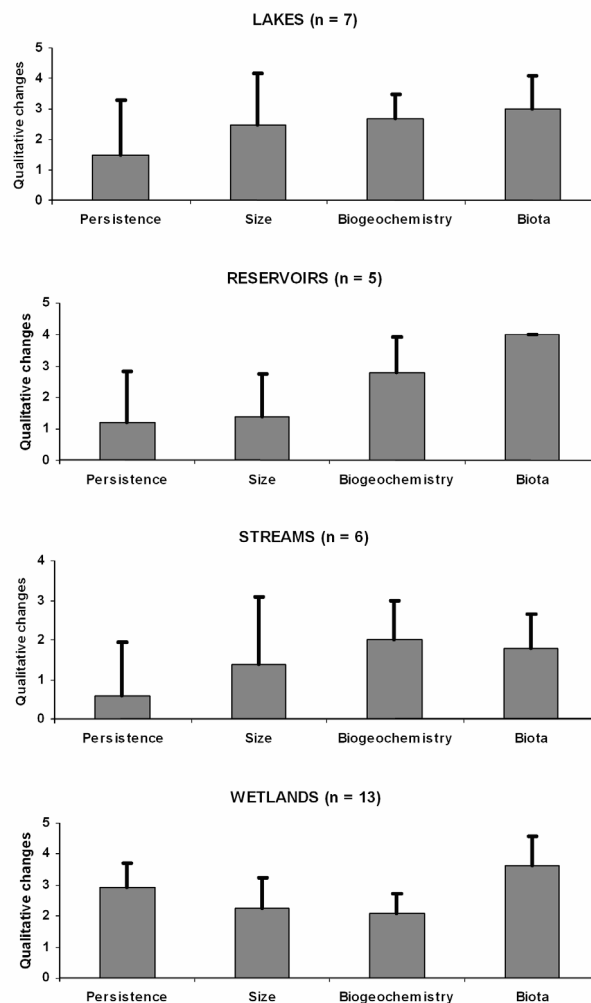


Fig. 8. Average and standard deviations of changes in response to climate change based on prospects of Spanish limnologists on the limnosystems they know best. The figure has been drawn from data reported in Alvarez-Cobelas *et al.* (2005). Qualitative changes after a century of climate change have been suggested for the persistence of ecosystems (change from permanent to temporary nature), even considering their disappearance (a value of 4), their size (0-no change; 4-very strong reduction in size), biogeochemistry (0-null change, 4-very strong change) and biotic communities (0-null change, 4-very strong change).

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