Aquatic Botany 113 (2014) 72–82

Contents lists available at ScienceDirect

Aquatic Botany

journal homepage: www.elsevier.com/locate/aquabot

Environmental factors explaining the distribution and diversity of vascular aquatic macrophytes in a highly heterogeneous Mediterranean region

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ARTICLE INFO

Article history:
Received 13 August 2012
Received in revised form
18 November 2013
Accepted 25 November 2013
Available online 7 December 2013

Keywords:
Aquatic macrophytes
Species richness
Ionic content
Sediment texture
Altitude
Local factors
CCA
GAM
Variance partitioning
Temporary pools
Mountain lakes
Coastal lagoons
Mediterranean
Catalonia

ABSTRACT

The study of the relationships between vascular aquatic macrophyte occurrence, species richness and the local environment are central for suitable ecosystem quality assessments, freshwater bodies management and assistance for macrophyte restoration. Here we quantify the importance of the local factors, both water column and sediment, to provide tools for lentic water systems management and conservation in a Mediterranean region. We surveyed 90 water bodies along a 2500 m altitudinal gradient in Catalonia (NE Spain). Despite its relatively small scale, the area of study exhibits large-scale environmental gradients mainly related to a diverse geology and climate. In consequence, the response of aquatic macrophytes to a broad range of environmental conditions can be studied without interference of biogeographical clines. We identified all vascular aquatic macrophytes and analyzed 35 environmental variables at each site. Local environmental factors accounted for only 19% of variance in aquatic macrophyte distribution. Even though water column variables explained more variance than sediment variables in a variance partitioning analysis (pCCA), a mixed model integrating variables of both compartments performed better. The most important variables driving aquatic macrophyte distribution were water conductivity, water DOC, water K, water pH, water Na, sediment organic matter, sediment Na and water nitrate. CCA between species and water and sediment variables clearly segregated coastal lagoons, temporary pools and alpine lakes over two main gradients: ionic content and water body productivity. Species richness was low (4.2 species per water body on average) and GAM showed weak correlations with sediment and most water column variables. The best factor explaining species richness was the geomorphological typology, but only temporary pools were significantly different from the other types and had the highest species richness. Thus, temporary pools were unique and displayed a high biodiversity, strengthening the need for their preservation.

1. Introduction

The general relationships among aquatic macrophytes and local environmental characteristics have long been studied (e.g. Grillas, 1990; Heegaard et al., 2001; Onaindia et al., 2005). They are of key interest for management and conservation purposes, since the survival of aquatic macrophytes depends largely on local environmental factors and thus, they are susceptible to changes in land use (Akasaka et al., 2010) and other human pressures (Aznar et al., 2003; Goldyn, 2010; Chappuis et al., 2011b). The argument is nowadays particularly relevant because the EU Water Framework Directive (WFD; European Parliament, 2000) includes the use of aquatic macrophytes as bioindicators and, at present, many macrophyte-based indices are being developed and tested (e.g. Thiebaut et al., 2002; Pall and Moser, 2009; Testi et al., 2009; Bolpagni et al., 2012). Most of these indices are based on the relationship between aquatic macrophyte distribution and the water column characteristics in lakes from Central and Northern Europe (e.g. Rørslett, 1991; Palmer et al., 1992; Murphy, 2002; Duigan et al., 2007). In contrast, these relationships have been less studied in the Mediterranean Basin, a recognized biodiversity hot spot (Myers et al., 2000; Coll et al., 2010; Chappuis et al., 2012).

Overall, water column ionic content and eutrophication are general factors driving the distribution of aquatic macrophytes in continental waters (e.g. Gacia et al., 1994; Lehmann and Lachavanne, 1999; Heegaard et al., 2001; McElarney and Rippey, 2009). However, correlation with water chemistry may sometimes be low when looking at narrow ranges of the physicochemical gradient (Schneider and Melzer, 2004; Gacia et al., 2009). Some studies have highlighted the role of sediment composition and organic matter nature for aquatic macrophyte presence and distribution in lakes (e.g. Bini et al., 1999; Gacia et al., 2009; Pulido et al.,

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http://dx.doi.org/10.1016/j.aquabot.2013.11.007

2012a). Specifically, several studies found that pore water phosphorus concentration in the sediment was an important factor (Bini et al., 1999; Schneider and Melzer, 2004; Pulido et al., 2012a). Yet, macrophyte occurrence is both the cause and effect of local environmental conditions as they play an important role in the control of biogeochemical cycles such as seasonal nutrient retention and release (Jeppesen et al., 1998; Smolders et al., 2002; Rooney et al., 2003), pulses of DOC (Anesio et al., 1999; Stets and Cotner, 2008; Duarte et al., 2010), daily rhythms in oxygen and carbon dioxide production and demand both in water column (Frodge et al., 1990; Caraco et al., 2006) and eventually sediments (e.g. isoetid species; Pedersen et al., 1995; Smolders et al., 2002), and by enhancing sediment and organic matter deposition and retention (Gacia and Duarte, 2001; Gacia et al., 2002; Rooney et al., 2003).

Moreover, the distribution of organisms is the result of both processes related to species dispersal and survival at a regional scale and to local species sorting associated with abiotic conditions (environmental constraints) and biotic interactions (e.g. competition, herbivory). The importance of local factors versus regional factors driving aquatic plant species distribution and richness has been approached in riverine and lacustrine systems indicating that both scales (local and regional) are relevant and that the weight of environment *versus* history may vary depending on species (Capers et al., 2010) or plant functional forms (e.g. floating leaved macrophyte diversity depends more on the connectivity among systems while submerged macrophytes diversity is more related to water chemistry in artificial ponds; Akasaka and Takamura, 2011).

Environmental studies do not only focus on the distribution of aquatic macrophyte species but also on the species richness of water bodies or sites. Species richness has been related to a variety of environmental factors and, despite some contradictory results, the most frequent correlations with species richness have been found with water transparency (Toivonen and Huttunen, 1995; Vestergaard and Sand-Jensen, 2000; Akasaka et al., 2010), ionic content (Vestergaard and Sand-Jensen, 2000; Hinden et al., 2005), trophic state (Rørslett, 1991; Toivonen and Huttunen, 1995; Akasaka et al., 2010), human pressures (Li et al., 2006; Hicks and Frost, 2011), altitude (Jones et al., 2003), latitude (Hinden et al., 2005; Heino and Toivonen, 2008), and water body area (Rørslett, 1991; Vestergaard and Sand-Jensen, 2000; Jones et al., 2003; Sondergaard et al., 2005). Correlations are not always linear and richness may have intermediate optima along environmental gradients (e.g. trophic gradient; Rørslett, 1991; Toivonen and Huttunen, 1995).

Catalonia is a small (32,000 km^2) Mediterranean area situated in North-eastern Spain exhibiting a high diversity of continental water body types and a high aquatic macrophyte richness at regional scale (Chappuis et al., 2011a). It is therefore an excellent area to assess patterns of species richness at a water body level. In addition, and because Catalonia has steep environmental gradients, it offers the possibility of studying the response of aquatic macrophytes to a broad range of environmental conditions without interference of biogeographical clines.

In this work, we aim to understand the distribution and richness of vascular aquatic macrophytes in relation to main local environmental factors (water column and sediment) and measure the relevance of both compartments to provide elements for the management and protection of lentic water bodies, as well as preservation of biodiversity in Mediterranean areas. To achieve this goal the manuscript is structured in three specific goals: (1) to identify the main environmental gradients in lentic water bodies of Catalonia, (2) to identify the main environmental variables driving aquatic macrophyte distribution and quantify their relative importance (water *versus* sediment, and total explained variance by both compartments) and (3) to study species richness patterns in relation to the local environment. We hypothesized that: (1) the main environmental gradient was related to altitude, (2) macrophyte distribution was mainly driven by variables from the water compartment, especially the water ionic content, and (3) species richness was higher in remote water bodies such as alpine lakes because of a reduced human pressure. We also hypothesized that the weight of the environment may also vary depending on the typology of stagnant water systems and that local factors explaining aquatic plant distribution and richness may differ in small and more diverse aquatic systems than previously acknowledged.

2. Methods

2.1. Field sampling

A survey of 215 water bodies distributed over Catalonia was conducted from 2005 to 2009 (extended study area description in Chappuis et al., 2011a,b). A subset of 90 water bodies with aquatic macrophytes (Fig. 1) was sampled once for aquatic macrophyte species, water and sediment. The remaining 125 water bodies were not included in the current analysis as no vascular aquatic macrophytes were found or the water bodies were dried up.

Altitude of the sampled water bodies ranged between 0 and 2573 m a.s.l. averaging 824 m a.s.l. The study also covered a wide range of water body surface area, from a tiny pond of 18 m^2 to extensive coastal lagoons of up to 416.6 ha; the average being 13.7 ha and the median 0.5 ha. Up to 8 geomorphological types were included in the study to encompass all the aquatic diversity hold by this area (Chappuis et al., 2011a,b). The geomorphological types were as follows: alpine lakes (at high altitude with oligotrophic soft-waters, $n = 21$), alpine reservoirs (at high altitude with

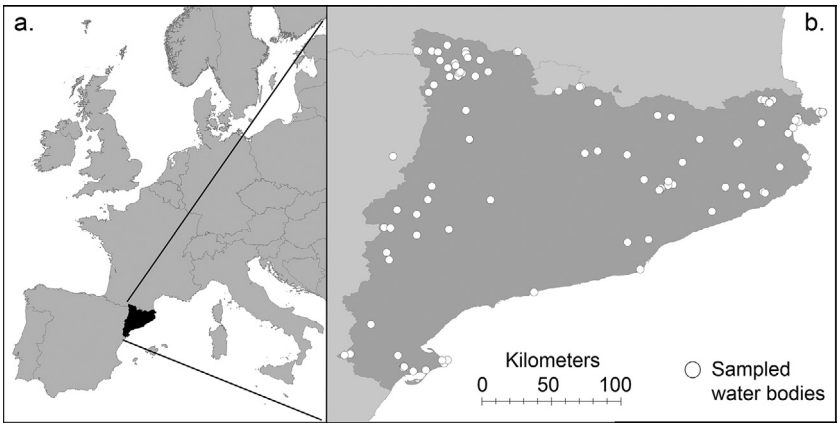

Fig. 1. Study area in Catalonia (NE Spain; a) and distribution of the different sampled water bodies (b).