

# Vegetation and fire history of coastal north-eastern Sardinia (Italy) under changing Holocene climates and land use

Giorgia Beffa<sup>1,2</sup> · Tiziana Pedrotta<sup>1,2</sup> · Daniele Colombaroli<sup>1,2</sup> · Paul D. Henne<sup>1,2</sup> ·  
Jacqueline F. N. van Leeuwen<sup>1,2</sup> · Pascal Süssstrunk<sup>1,2</sup> · Petra Kaltenrieder<sup>1,2</sup> ·  
Carole Adolf<sup>1,2</sup> · Hendrik Vogel<sup>2,3</sup> · Salvatore Pasta<sup>4</sup> · Flavio S. Anselmetti<sup>2,3</sup> ·  
Erika Gobet<sup>1,2</sup> · Willy Tinner<sup>1,2</sup>

Received: 19 April 2015 / Accepted: 3 October 2015  
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**Abstract** Little is known about the vegetation and fire history of Sardinia, and especially the long-term history of the thermo-Mediterranean belt that encompasses its entire coastal lowlands. A new sedimentary record from a coastal lake based on pollen, spores, macrofossils and microscopic charcoal analysis is used to reconstruct the vegetation and fire history in north-eastern Sardinia. During the mid-Holocene (c. 8,100–5,300 cal BP), the vegetation around Stagno di Sa Curcurica was characterised by dense *Erica scoparia* and *E. arborea* stands, which were favoured by high fire activity. Fire incidence declined and evergreen broadleaved forests of *Quercus ilex* expanded at the beginning of the late Holocene. We relate the observed vegetation and fire dynamics to climatic change, specifically moister and cooler summers and drier and milder winters after 5,300 cal BP. Agricultural activities occurred since the Neolithic and intensified after c. 7,000 cal BP. Around 2,750 cal BP, a further decline of fire incidence and

*Erica* communities occurred, while *Quercus ilex* expanded and open-land communities became more abundant. This vegetation shift coincided with the historically documented beginning of Phoenician period, which was followed by Punic and Roman civilizations in Sardinia. The vegetational change at around 2,750 cal BP was possibly advantaged by a further shift to moister and cooler summers and drier and milder winters. Triggers for climate changes at 5,300 and 2,750 cal BP may have been gradual, orbitally-induced changes in summer and winter insolation, as well as centennial-scale atmospheric reorganizations. Open evergreen broadleaved forests persisted until the twentieth century, when they were partly substituted by widespread artificial pine plantations. Our results imply that highly flammable *Erica* vegetation, as reconstructed for the mid-Holocene, could re-emerge as a dominant vegetation type due to increasing drought and fire, as anticipated under global change conditions.

Communicated by J.-L. de Beaulieu.

**Electronic supplementary material** The online version of this article (doi:10.1007/s00334-015-0548-5) contains supplementary material, which is available to authorized users.

✉ Giorgia Beffa  
giorgia.beffa@gmail.com

- <sup>1</sup> Institute of Plant Sciences, University of Bern, Altenbergrain 21, 3013 Bern, Switzerland
- <sup>2</sup> Oeschger Centre for Climate Change Research, University of Bern, Falkenplatz 16, 3012 Bern, Switzerland
- <sup>3</sup> Institute of Geological Sciences, University of Bern, Baltzerstrasse 1, 3012 Bern, Switzerland
- <sup>4</sup> Institute of Biosciences and BioResources (IBBR), Division of Palermo, National Research Council (CNR), Corso Calatafimi, 414, 90129 Palermo (PA), Italy

**Keywords** Mediterranean · *Erica scoparia* and *E. arborea* · *Quercus ilex* forests · Pollen · Macrofossils · Charcoal

## Introduction

Little is known about the Holocene vegetation and fire history of the evergreen broadleaved thermo-Mediterranean belt. This is particularly true for Sardinia, from which only one fragmentary Holocene record is available (Di Rita and Melis 2013). Sardinia has a wide thermo-Mediterranean vegetation belt, which encompasses the entire island. This belt is characterised by evergreen drought-adapted woodlands, maquis and garrigues. The woodlands are dominated by *Quercus ilex*, *Q. suber*, *Olea*

*europaea* ssp. *sylvestris* or, under peculiar edapho-climatic conditions, by *Juniperus* (Bacchetta et al. 2009). Mixed maquis, garrigues (often rich in Lamiaceae, *Cistus* and *Erica* spp.), grasslands and other plant communities often occur under strong fire disturbance and dry climatic conditions (Chiappini 1985; Bacchetta et al. 2009). The thermo-Mediterranean vegetation makes Sardinia comparable to other large Mediterranean islands, such as Sicily and Crete or any other coastlands at 30–40°N between Portugal and Turkey, including the near east and Mediterranean coastlands of Northern Africa. However, this vegetation belt is lacking in neighbouring Corsica, which lies north of 40°N (Lang 1994).

Currently, it is unclear when the thermo-Mediterranean belt of Sardinia established and if the timing of its establishment was connected to the vegetation dynamics in other areas. Being the warmest and driest environment of the Mediterranean, the thermo-Mediterranean belt is particularly suited to test the so-called “aridification” hypothesis, which suggests that Mediterranean environments became gradually drier during the course of the mid and late Holocene (e.g. Ariztegui et al. 2000; Sadori et al. 2008; Jalut et al. 2009; Mercuri et al. 2012). The location of Sardinia at 39–41°N is of particular interest, as it has been hypothesised that sites north and south of 40°N experienced contrasting Holocene moisture dynamics (Magny et al. 2007) and fire regimes (Vanni re et al. 2011). New evidence from Sicily also suggests that vegetation history south of c. 40°N was remarkably different from that in more northern areas; for instance, afforestation in the thermo-Mediterranean belt at the coast occurred only during the mid-Holocene, millennia later than at higher altitudes or latitudes (Noti et al. 2009; Tinner et al. 2009).

Sardinia, the second largest island in the Mediterranean Sea, possesses a unique flora. Sardinian endemics represent 10–15 % of the whole vascular flora of the island (>2,400 taxa, Conti et al. 2005); this high value issues from a rather long history of isolation, the uneven topography and the high geological and pedological variability (Bacchetta et al. 2005, 2012). On the other hand, the land bridge that persisted until c. 10,000 years ago between Sardinia and Corsica (Lambeck et al. 2004) explains why these two islands share c. 30 % of endemic flora (Arrigoni et al. 1977–1991). A rich cultural history also contributes to the uniqueness of Sardinia. Humans have inhabited the island since the Palaeolithic. Initially, they were living in caves while hunting and fishing; then, with the onset of the Neolithic (c. 8,000 cal BP), people started to cultivate fields and breed livestock (Lilliu 2002). Because of Sardinia’s central position in the Mediterranean Sea, its population has been in contact with other Mediterranean populations since the Neolithic. Thus, its cultural history is characterised by the influence of different African, Asian and

European cultures such as Greeks, Phoenicians, Punics and Romans. Many archaeological sites such as caves, catacombs and *nuraghi* (typical Sardinian tower-like stone constructions dating back to the Bronze Age) are present throughout the island (Kriek 2014) suggesting that, as has been observed in other areas of the Mediterranean, humans may have substantially altered their environment since the advent of the Neolithic, in particular the vegetation and the fire regime (e.g. Andri  2007; Carri n et al. 2007; Colombaroli et al. 2007, 2008; Tinner et al. 2009; Turner et al. 2010).

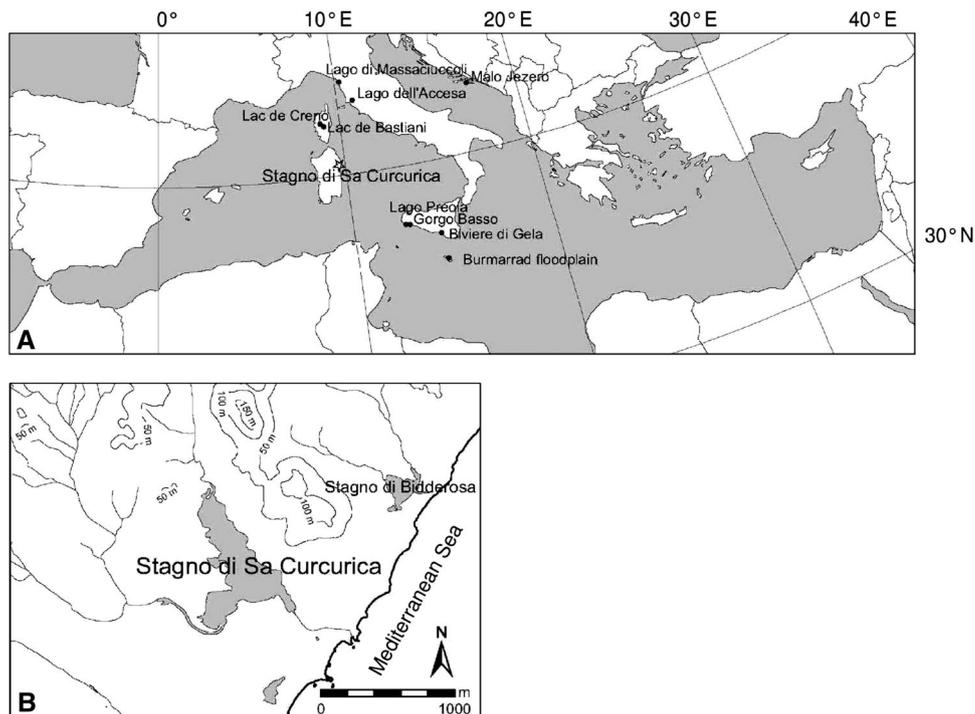
The main goals of our study are (1) to provide the first continuous mid to late Holocene record of the vegetation and fire history of Sardinia, and (2) to reconstruct the timing and causes of the formation of the thermo-Mediterranean vegetation at Sa Curcurica, a coastal salty lake. In order to reach these goals we use pollen and spore analysis to reconstruct extra-local to regional vegetation dynamics, terrestrial macrofossil analysis to reconstruct local vegetation dynamics, and microscopic charcoal analysis to reconstruct regional fire history. To provide a robust chronology, we use AMS radiocarbon dating on terrestrial plant macrofossils. We apply our results to check existing (partly contrasting) hypotheses about environmental change in the Mediterranean (e.g. the “aridification” hypothesis), and pay particular attention to human impact on vegetation and fire regimes. In order to disentangle climate from human impact, only non-pollen or non-charcoal evidence is used as a climate proxy in the discussion. X-ray fluorescence (XRF) analysis is used to assess sediment properties such as relative element abundances of bromine (Br), titanium (Ti), iron (Fe) and manganese (Mn) as a proxy for detrital input, lake productivity and oxygenation, while the bulk sedimentary total organic carbon/total sulphur (TOC/TS) ratio is used as a proxy for paleosalinity (marine vs. freshwater environments).

### Study site

The Stagno di Sa Curcurica is a small coastal salty lake (38 ha) located in north-eastern Sardinia (40°27′19″N, 9°47′17″E, 0 m a.s.l.) in the province of Nuoro (Fig. 1). The site is protected by a regional natural reserve managed by the “Ente Forestale della Sardegna”. This zone, together with the surrounding area (14 km along the coast), was proposed to the European Commission as the “Site of Community Importance of Berchida and Bidderosa”. Several archaeological sites such as caves, catacombs and *nuraghi* are located in the surrounding region, testifying to active human presence since the pre-Neolithic (Kriek 2014).

Quaternary deposits, including gravel, sand and silt with a granitic Carboniferous/Permian substratum and massive

**Fig. 1** **a** Map showing the location of important Mediterranean study sites. **b** Topographical map of the area around the study site Stagno di Sa Curcurica. *Source* Sardegnaportale (2014)

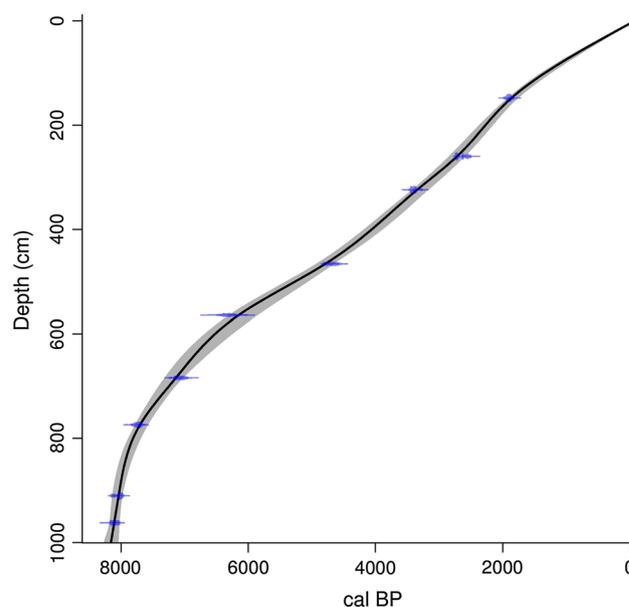


taken on average every 14 cm. In the central part, at a depth of c. 500 cm, we found the most important vegetational change of the sequence; hence subsamples were taken at a higher resolution of 4–8 cm. In the upper part, from 392 to 0 cm, subsamples were on average collected every 18 cm.

In order to make pollen and spores identifiable under the light microscope, subsamples were treated chemically (HCl, KOH, HF and acetolysis) and physically (0.5 mm sieving and decanting) and stored in glycerine following standard methods (Moore et al. 1991). *Lycopodium* tablets were added to the subsamples before the treatment, for

**Table 1** Lithology

Depth (cm)	Age (cal BP)	Lithology
0–629	–100 to 6,750	Silty gyttja
629	6,750	Tephra
629–706	6,750–7,300	Silty gyttja
706–708	7,300	Dark silty gyttja
708–759	7,300–7,600	Silty gyttja
759–761	7,600–7,650	Sandy gyttja
761–780	7,650–7,750	Gyttja
780–783	7,750	Sandy gyttja
783–812	7,750–7,850	Gyttja
812–813	7,850	Sandy gyttja
813–842	7,850–7,950	Gyttja
842–850	7,950	Sandy gyttja
850–857	7,950	Gyttja
857–864	7,950	Sandy gyttja
864–910	7,950–8,050	Gyttja
910–929	8,050	Sandy gyttja
929–932	8,050	Sand
932–936	8,050	Gyttja
936–963	8,050–8,100	Sandy gyttja
963–970	8,100	Fine gravel
970–1004	8,100–8,150	Gravel



**Fig. 2** Age-depth model of Stagno di Sa Curcurica. Points represent 9 calibrated ages on terrestrial macrofossils (Table 2). The model (smooth spline 0.2, black line) was developed with the program clam 2.2 (Blaauw 2010), which take into account 2 $\sigma$ -confidence range of calibrated ages (grey areas)

estimation of pollen and microscopic charcoal concentration (particles cm<sup>-3</sup>) and influx (particles cm<sup>-2</sup> year<sup>-1</sup>) (Stockmarr 1971). Using the reference collection of the Institute of Plant Sciences of the University of Bern as well as palynological keys and atlases (Moore et al. 1991; Reille 1992a; Beug 2004), pollen and spores were identified and counted under the light microscope at a magnification of 400 $\times$  or, occasionally, 1,000 $\times$ . *Filago*-type corresponds to *Gnaphalium*-type according to Beug (2004); we chose to call it *Filago*-type because in Sardinia *Filago* is more abundant than *Gnaphalium* and other genera (*Antennaria*, *Helichrysum*) that are included in this pollen type (Pignatti 2003). *Erica arborea*-type pollen determination follows Mateus (1989) and Ramil Rego et al. (1992) and includes

**Table 2** Radiocarbon dates and calibrated ages

Lab. code	Depth (cm)	Material	<sup>14</sup> C age (year BP)	Age (cal BP)	Age (cal BP, 2 $\sigma$ range)
Poz-59763	148–154	<i>Erica</i> leaves, charcoal	1,950 $\pm$ 30	1,890	1,797–1,935
Poz-59764	260–262	<i>Erica</i> leaves, flower	2,540 $\pm$ 30	2,726	2,616–2,841
Poz-59765	324–326	<i>Erica</i> leaves, flower	3,170 $\pm$ 40	3,355	3,192–3,420
Poz-59766	466–470	<i>Erica</i> leaves, flower	4,145 $\pm$ 35	4,815	4,694–4,942
Poz-59767	564–566	<i>Erica</i> leaves	5,510 $\pm$ 100	6,161	5,879–6,298
Poz-59768	684–686	<i>Erica</i> leaves	6,170 $\pm$ 50	7,144	7,047–7,310
Poz-59769	774–776	<i>Erica</i> leaves	6,900 $\pm$ 50	7,706	7,590–7,773
Poz-56289	910–912	Partially burned leaves	7,220 $\pm$ 40	8,038	7,989–8,131
Poz-56290	962–964	Twigs	7,290 $\pm$ 40	8,109	8,033–8,175

*E. arborea* and *E. scoparia*. Aside from the deepest slides (984 cm), within which the pollen concentration was very low, a minimum of 400 pollen grains per slide were counted. Microscopic charcoal particles ( $>10\ \mu\text{m}$ ) were counted using a magnification of  $400\times$  following Tinner and Hu (2003) and Finsinger and Tinner (2005).

The pollen diagram was plotted using the program Tilia 1.5.12 and TGView 2.0.2. Local pollen assemblage zones (LPAZs) were identified using the method of optimal sum of squares partitioning (Birks and Gordon 1985) with the program ZONE 1.2. Statistically significant zones were defined through the program BSTICK (Bennett 1996).

### Macrofossil analysis

We sampled 30 levels with a thickness of 2 cm and a volume of  $8\text{--}14\ \text{cm}^3$  for macrofossil analysis between the depths of 985 and 24 cm. The average interval among the samples is 30 cm between 985 and 235 cm depth, while in the upper part of the sequence the mean resolution of sampling is 53 cm. In order to isolate macrofossils from smaller sediment particles, subsamples were sieved with a mesh size of  $200\ \mu\text{m}$ . Macrofossils were then analysed under the binocular microscope using a magnification of  $6\text{--}50\times$  and identified using standard keys of vegetation morphology (e.g. Cappers et al. 2006; Arrigoni 2006–2010), along with the reference collection of the Institute of Plant Sciences of the University of Bern. Considering that pollen of the two main *Erica* species (*E. scoparia* and *E. arborea*) present in the sediments cannot be differentiated, we estimated the past abundance of the two species from macrofossils (specifically leaves). Morphological traits to distinguish *E. scoparia* and *E. arborea* were identified from fresh leaves under the binocular microscope (see ESM). Macrofossil concentrations were standardised to  $10\ \text{cm}^3$  and plotted using the programs Tilia 1.5.12 and TGView 2.0.2.

### Geochemical analysis

Major element analysis was executed with a Cr-tube equipped ITRAX XRF core scanner (Cox Ltd., Sweden) at the Institute of Geological Sciences of the University of Bern. Measurements were performed at 5 mm resolution using an integration time of 10 s at 30 kV and 40 mA. Results for relative intensities of bromine (Br), titanium (Ti), chlorine (Cl) and the ratio of manganese to iron (Mn/Fe) were considered respectively as proxies for organic matter (Ziegler et al. 2008), terrigenous detrital sediment delivery from the watershed (Peterson et al. 2000; Haug et al. 2001), seawater intrusion and/or water–rock interaction (Mongelli et al. 2013) and redox-related diagenesis (Haberzettl et al. 2007). Low Mn/Fe ratios are used as a

proxy of reducing conditions at the sediment/water interface. We assume that high Mn/Fe ratios are a consequence of low lake levels and/or high wind speed causing mixing (Haberzettl et al. 2007).

Total carbon (TC) and total sulphur (TS) were analysed on  $\sim 100\ \text{mg}$  dried and ground sample aliquots by means of combustion at  $1,300\ ^\circ\text{C}$  in an oxygen atmosphere. For determination of total inorganic carbon (TIC), samples were combusted at  $1,300\ ^\circ\text{C}$  in a pure nitrogen atmosphere. Total organic carbon (TOC) was calculated by subtracting TIC from TC. All analyses were conducted on a Bruker G4 ICARUS CS analyser equipped with an infrared detector set for  $\text{CO}_2$  and  $\text{SO}_2$ . We use the bulk sedimentary TOC/TS ratio as an indicator for sediment deposition under marine versus freshwater conditions with lower values representing a stronger marine influence or more saline waters at Sa Curcurica (Berner and Raiswell 1984).

### Ordination, XRF and biodiversity analysis

Ordination analyses were performed on pollen percentages with Canoco 4.5 (Ter Braak and Šmilauer 2002) to identify species and sample distributional gradients. The gradient length of the first DCA (detrended correspondence analysis, see ESM Fig. 1) axis is 1.59; hence, we selected two linear models, principal components analysis (PCA) and redundancy analysis (RDA), for the following ordination analyses (Birks and Gordon 1985; Ter Braak and Prentice 1988). For RDA, five environmental variables were included as possible explanatory factors. Three abiotic environmental variables were obtained from the X-ray fluorescence (XRF) analysis (Br, Ti and Mn/Fe; see above). Two biotic environmental variables, microscopic charcoal influx and influx of *Sporormiella* spores (a genus of coprophilous fungi), were used as proxies for fire (Colombaroli et al. 2009) and the presence of grazing mammals (Davis and Shafer 2006; see also Etienne and Jouffroy-Bapicot 2014), respectively. Influx values at the base are highest for pollen, spores and microscopic charcoal. This may point to depositional effects unrelated to past fire or browsing activity. To investigate if such effects affected the analyses we recalculated RDA with microscopic charcoal and *Sporormiella* spores as pollen percentages (excluded from the pollen sum). Moreover, we reanalysed RDA omitting the samples older than 7,750 cal BP. Both analyses confirmed the results obtained with microscopic charcoal and *Sporormiella* spore influx values, suggesting that the influx based RDA results are ecologically robust.

The statistical significance and the amount of pollen percentage data variance explained by each single environmental variable independently were calculated by means of Monte Carlo permutation tests (Lepš and

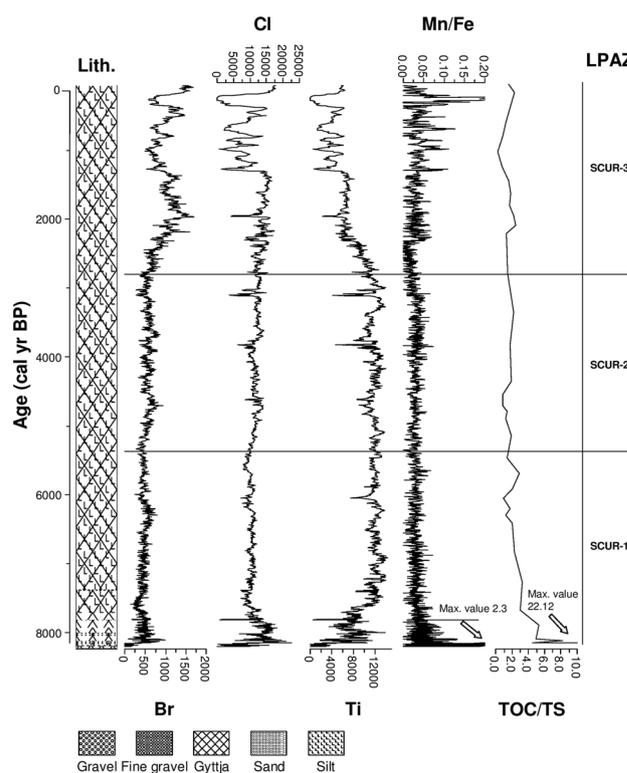
Šmilauer 2003) using the program Canoco 4.5. The effect of each environmental variable on pollen data variance was considered independently in order to avoid the variance partitioning effect (see Lepš and Šmilauer 2003).

Palynological richness (PRI), a proxy for species richness (Birks and Line 1992), and probability of interspecific encounter (PIE) (Hurlbert 1971) as a proxy of palynological evenness were calculated to investigate mid and late Holocene biodiversity dynamics near Sa Curcurica. Rarefaction analysis with a minimum pollen sum of 216 (Birks and Line 1992) was achieved using the Vegan package (Dixon 2003) of the statistical software R (R Development Core Team 2011, see Colombaroli and Tinner 2013). In order to assess possible alterations of PRI due to evenness influence, we also calculated evenness-detrended palynological richness (DE-PRI; see Colombaroli and Tinner 2013). PRI is regarded as to be unaffected by palynological evenness if both PRI and DE-PRI show similar temporal trends (Colombaroli and Tinner 2013).

## Results and interpretation

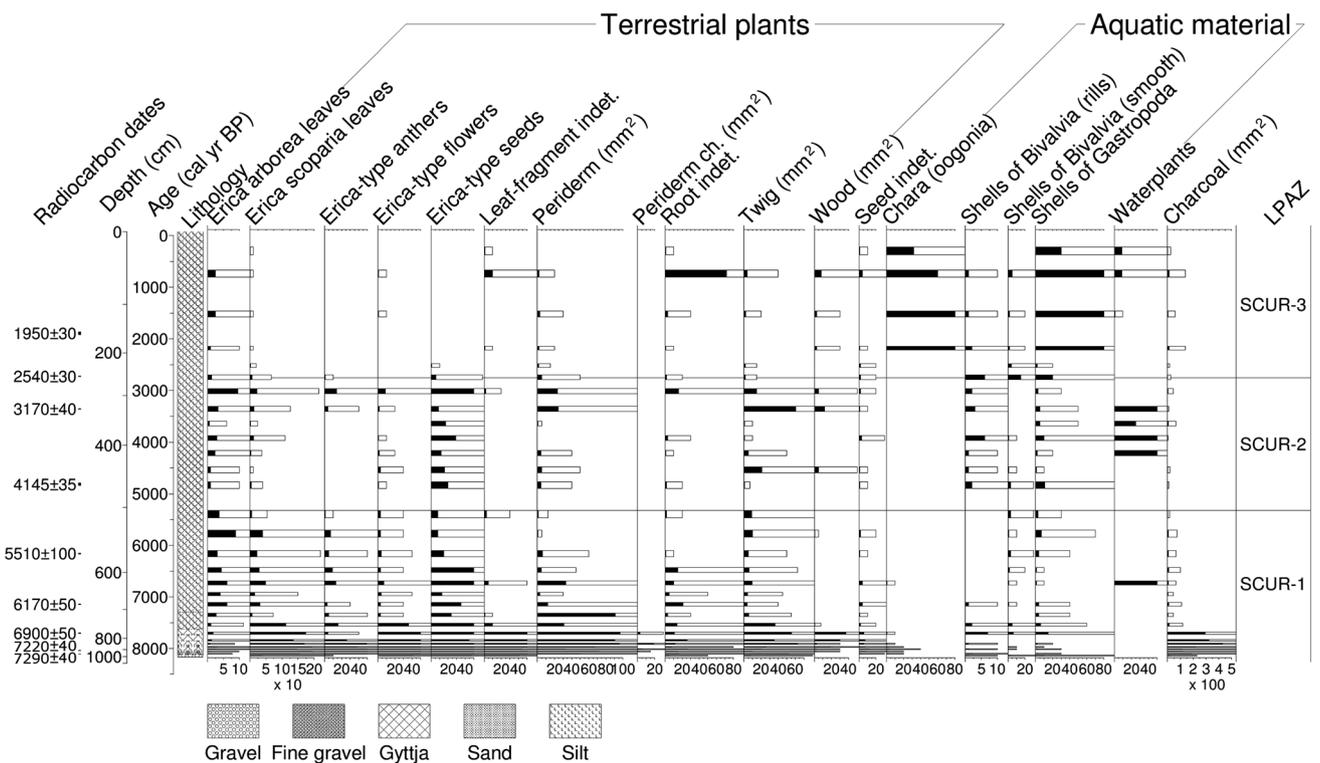
### Lithology and chronology

The lowest part of the sediment core, from 1,004 to 963 cm (8,150–8,100 cal BP, see Table 1), is composed mainly of gravel and fine gravel. Further up, from 963 to 932 cm (8,100–8,050 cal BP), alternate layers of gyttja and sandy gyttja are observed, overlaid by a sandy layer from 932 up to 929 cm (c. 8,050 cal BP). Although the gravel, sandy deposits and basal age suggest a link to the marine transgressions observed around 8,200 cal BP on the Italian coast (e.g. Masciacucoli; Colombaroli et al. 2007), this assumption is not supported by the high values resulting from the TOC/TS-ratio (Fig. 3), which suggest the presence of freshwater during this period. However, in the lowest part of the sequence, TOC/TS values could be influenced by the shortage of iron (see ESM Fig. 2) in the coarse grained basal deposits that consequently acts as the limiting factor, instead of sulphate, for pyrite formation (Bernier and Raiswell 1984). From 929 to 759 cm (8,050–7,600 cal BP) again, alternate layers of gyttja and sandy gyttja are present. Hence, the coarse grained sediments within the lower part of the core may suggest considerable lateral sediment transport of soil or shore deposits, possibly due to a generally low lake-level. This interpretation is in agreement with high Mn/Fe ratio values (Fig. 3). At a depth of 629 cm (6,750 cal BP), a tephra layer was detected using smear slides. Shells of gastropods and bivalves are spread uniformly throughout the core in varying concentrations (slightly higher in the upper part; Fig. 4).



**Fig. 3** Comparison of X-ray fluorescence (XRF) data of bromine (Br), chlorine (Cl), titanium (Ti) and manganese over iron (Mn/Fe) ratio and total organic carbon over total sulphur (TOC/TS). Data for Br, Cl and Ti are displayed in counts. The TOC/TS ratio was calculated from percent weight data for both elements. LPAZ: local pollen assemblage zones (analyst: Hendrik Vogel)

The uppermost section of the sediment core, from 759 to 0 cm (7,600 cal BP—present), consists of silty gyttja, suggesting less erosional input. This interpretation is corroborated by elemental analyses. The Mn/Fe ratio decreases at c. 738 cm (7,500 cal BP) suggesting deeper, poorly oxygenated mixed water conditions until 205 cm (2,300 cal BP). Subsequently, the Mn/Fe ratio increases again pointing to lower, better oxygenated waters. Cl and Br values show pronounced shifts and trends which may be related to salinity changes more than to productivity. Ti values, as a proxy of erosional activity, decrease between 290 and 164 cm (3,000–2,000 cal BP), stay relatively constant until c. 90 cm (1,200 cal BP) and thereafter they show high variability (Fig. 3). The age-depth model (Fig. 2) is relatively linear, although sedimentation rates for the lower coarse-grained deposits (1,004–774 cm; 8,150–7,700 cal BP) are significantly higher when compared to the upper, more fine grained deposits (on average 7 vs. 1 mm/year), confirming the increased in-wash of detrital constituents in the lowest part of the section.



**Fig. 4** Plant-macrofossil concentration diagram of Stagno di Sa Curcurica (per  $10\text{ cm}^3$ ). The *empty bars* are  $5\times$  exaggerations. ch.: charred. LPAZ: local pollen assemblage zones (analysts: Pascal Süssstrunk and Giorgia Beffa)

### Pollen and macrofossil analysis: vegetation history

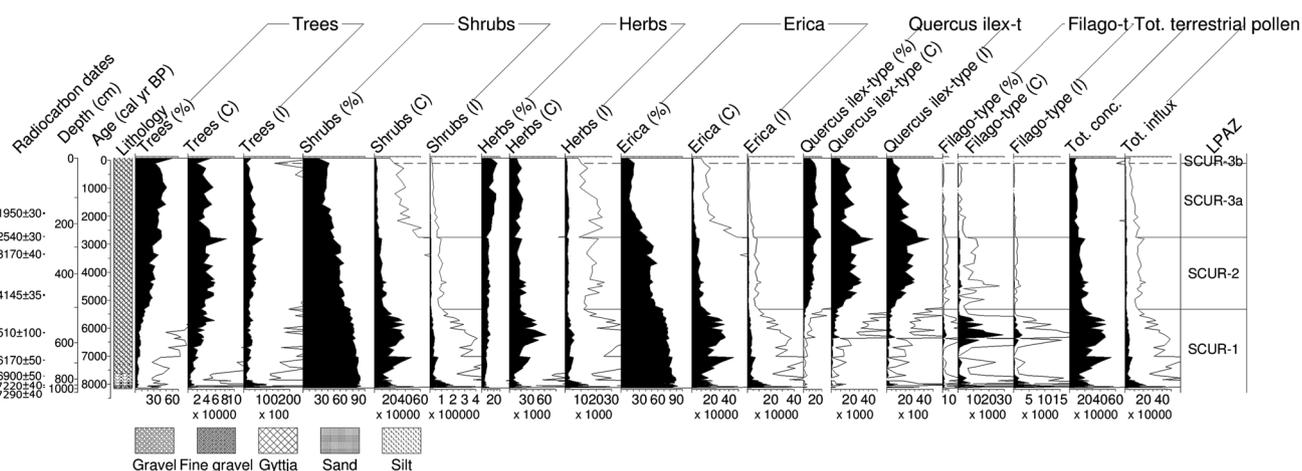
Along the sequence, three statistically significant local pollen assemblage zones (LPAZ) have been identified (Figs. 5, 6, 7, SCUR-1 to SCUR-3). In order to divide the modern *Pinus* spp. plantations of the last century from periods in which *Pinus* spp. were not locally abundant and exotic plant species such as *Eucalyptus* spp. were absent, the zone SCUR-3 has been subdivided into two subzones (SCUR-3a/b; Figs. 5, 6, 7). In general, pollen percentages, concentration and influx have similar trends for trees and shrubs. The increasing trend of herb percentages is not mirrored in the concentration and influx values. This might point to distortion effects as for instance a percental underrepresentation of herb pollen in the oldest zone SCUR-1.

#### SCUR-1: 8,150–5,300 cal BP

Pollen data suggest that vegetation around Sa Curcurica was characterised by shrublands or woodlands, composed mainly of *Erica* (65–89 % of the pollen sum), during zone SCUR-1 (8,150–5,300 cal BP; Fig. 6). The attribution of *Erica* species to shrublands is not unequivocal, since *E. scoparia* and *E. arborea* can grow up to 10–20 m and form dense forest canopies (Arévalo et al. 1999). Pollen of other

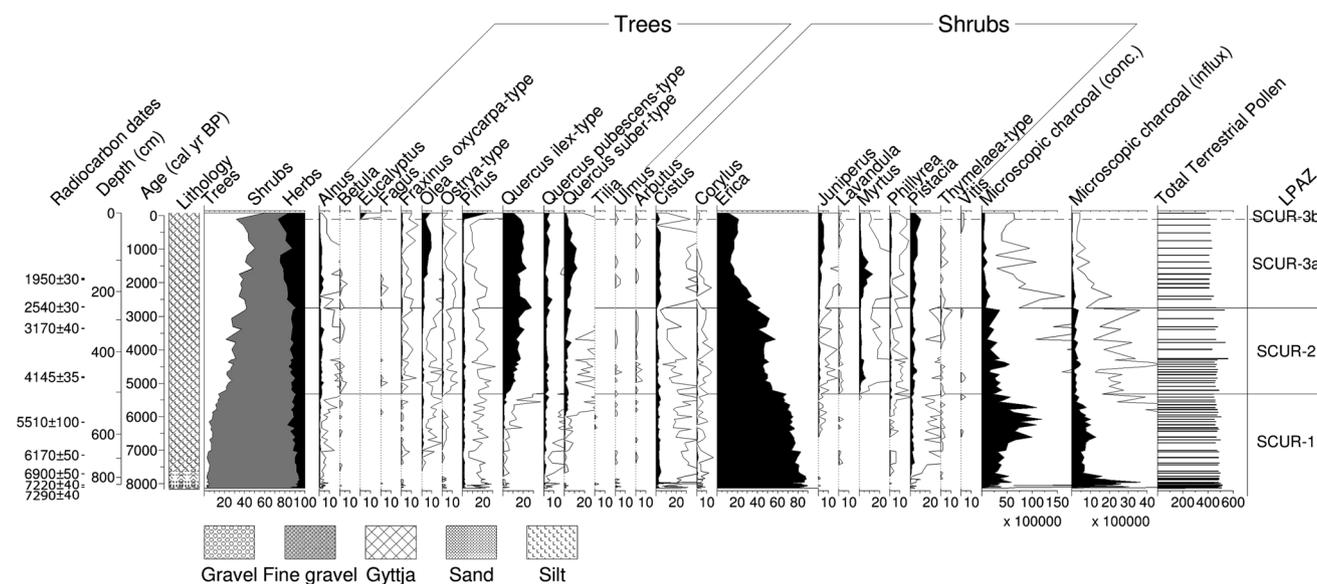
arboreal species such as *Pinus*, *Quercus pubescens*-type, *Alnus*, *Cistus*, *Pistacia* and *Corylus* are present, though with low values, suggesting that they were rather rare vegetation components. Pollen of upland herbs comprises Poaceae, *Aster*-type, Chenopodiaceae, *Filago*-type and Cichorioideae. After c. 7,050 cal BP, pollen of trees such as *Olea*, *Fraxinus oxycarpa*-type, *Q. suber*-type and *Q. ilex*-type slightly increases, suggesting the establishment of small tree stands in the area around Sa Curcurica. Nevertheless, pollen belonging to these plant species, together with that of herbs such as *Artemisia*, *Asphodelus*, *Rumex acetosella*-type and Brassicaceae, remains  $<21\%$  of the pollen sum until the end of the zone SCUR-1.

The clear dominance of *E. scoparia* between c. 8,150 and 7,500 cal BP is recorded locally through macrofossils, which show a very high quantity of *Erica* leaves; of these, c. 98–99 % are of *E. scoparia*, while only 1–2 % are of *E. arborea* (Fig. 4). Moreover, *Erica* flowers, seeds and stamens occur as well. This vegetational situation coincides with a period that was probably characterised by soil erosion and thus possibly poorly developed and shallow soils (see above). Between 7,500 and 5,400 cal BP, counts of *Erica* macrofossils markedly decrease, although their presence remains considerable. During this phase, the *E. arborea* component becomes more important (on average 23 % of the *Erica* leaves sum). Then, comparable to the



**Fig. 5** Comparison between pollen percentages, concentrations and influx of selected pollen sub-sums (trees, shrubs, herbs, *Erica*, *Quercus ilex*-type, *Filago*-type and total terrestrial pollen) of Stagno

di Sa Curcurica. Empty curves show 10× exaggerations. LPAZ: local pollen assemblage zones. *Unbroken lines* statistically significant zone limits. *Dashed lines* statistically non-significant zone limits



**Fig. 6** Arboreal pollen (AP) percentage and microscopic charcoal diagram of Stagno di Sa Curcurica. Only selected taxa shown; for further explanations see Fig. 5 (analyst: Giorgia Beffa)

trend of *Erica* observed in the pollen diagram (Fig. 6), *Erica* macrofossils further decrease around 5,300 cal BP, suggesting that local and sub-regional vegetation dynamics were comparable. Today, *Erica* communities can be considered as an early-successional phase towards late-successional *Q. ilex* forests (Chiappini 1985); yet, it is impossible to attribute this plurimillennial zone to a transient pioneer or early-successional stage. More likely this phase represents a late-successional stage with *Erica* species as for example observed on the Canary Islands (Arévalo and Fernández-Palacios 2003). Alternatively, special environmental conditions such as recurrent fire disturbance and/or drought-stress may have led to a dominance of the

two shrub species over millennia. Neolithic land-use intensified after 7,000 cal BP (e.g. increase of *Cerealia*-type, *Plantago lanceolata*-type), but remained relatively weak as suggested by low non arboreal pollen (NAP) abundance (10–15 %). The presence of salt-intolerant (Pignatti 2005) *Isoetes* (1–3 %) suggests freshwater conditions in the lake, or freshwater wetlands nearby. Towards the end of the zone at c. 6,300–5,500 cal BP *Ruppia*, a genus which can tolerate salty conditions but also occurs in fresh waters (Pignatti 2005), expanded. Accordingly, a TOC/TS decline suggests increasing salinity (Berner and Raiswell 1984) at 8,000–7,000 cal BP, with conditions similar to today established after c. 6,500 cal BP (Fig. 3). Microfossils and



SCUR-3: 2,750 cal BP: present (AD 2012)

At the beginning of zone SCUR-3, *Erica* and *Q. ilex*-type are the major AP constituents (AP = 91 %), indicating the dominance of these two woody taxa in the surrounding landscape. By 1,400 cal BP AP declines, reaching 75 % and NAP including *Artemisia*, Poaceae, *Rumex acetosella*-type, Cichorioideae, *Plantago lanceolata*-type and Cerealia-type increases, likely as a result of agricultural activities. Cerealia-type shows very low pollen percentage values suggesting low local cereal production. During the past c. 2,750 years, pollen of *Q. ilex*-type remains relatively constant, while that of *Erica* continues to decrease (from 42 down to 13 % of the total pollen sum in an interval of c. 1,350 years). Pollen data suggest that, in addition to herbaceous taxa, some arboreal species expanded during the late Holocene, forming a less natural, but more diverse and open landscape. Pollen of *Q. suber*-type, *Cistus* and *Pistacia* increases c. 2,750 cal BP, and decreases again around 750, 300 and 100 cal BP, respectively. The increase of pollen of *Q. suber*-type after 2,800 cal BP might result from human activities related to cork production (Dettori et al. 2001). Pollen of *Juniperus* and *Myrtus* increases around 2,500 cal BP and the latter shows a peak (13 % of the pollen sum) around 1,750 cal BP and decreases c. 750 years later. Pollen of *Olea* increases after 1,900 cal BP, possibly as a result of human activities. The most recent part of the sequence, which corresponds to the last century, records an expansion of exotic plants such as *Eucalyptus*, an important increase of *Pinus*, as well as the presence of other plant genera such as *Pistacia*, *Olea*, *Erica*, *Cistus*, *Juniperus* and *Artemisia*. This is consistent with survey data related to the current vegetation composed of *Pinus* spp. plantations, *Oleo-Ceratonion* communities and exotic species. Spores and pollen of the vascular aquatic plants *Isoetes* and *Ruppia* show a striking increase around 2,750 cal BP and remains abundant until the present. After 2,500 cal BP, *Chara* macrofossils (oogonia) occur in the sediments, possibly due to increasing freshwater supply, given that most *Chara* species prefer oligotrophic, clear and nutrient-poor freshwater conditions (Ellenberg 2009).

### Microscopic charcoal analysis and fire history

With exception of a basal peak which is probably over-expressed in the microscopic charcoal influx, microscopic charcoal concentrations and influx values show similar trends. Interestingly enough, major changes in the microscopic charcoal trend correspond to zonation results (LPAZ, Figs. 5, 6, 7), suggesting a close link between fire regime and vegetation composition (Fig. 6). Maximum microscopic charcoal influx values between c. 8,150 and 7,780 cal BP are not reflected in concentrations and may

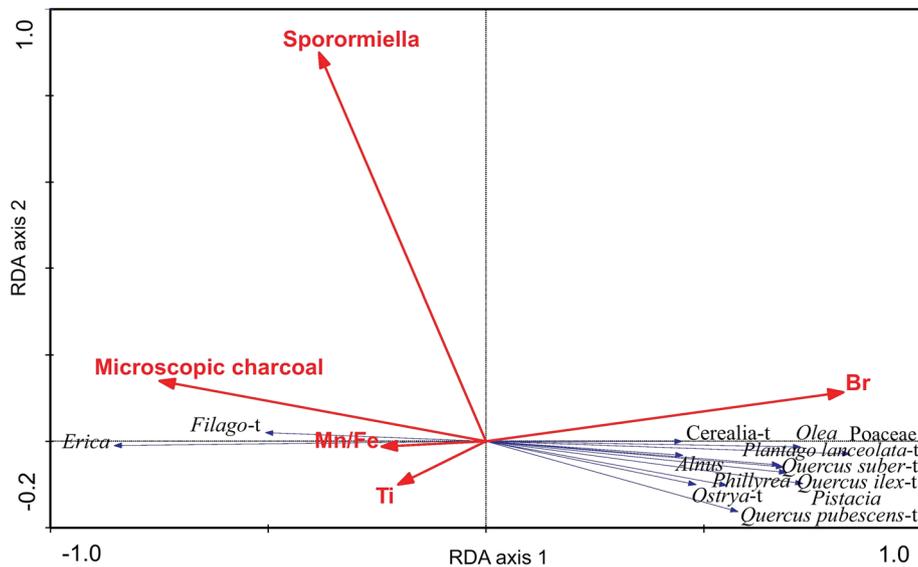
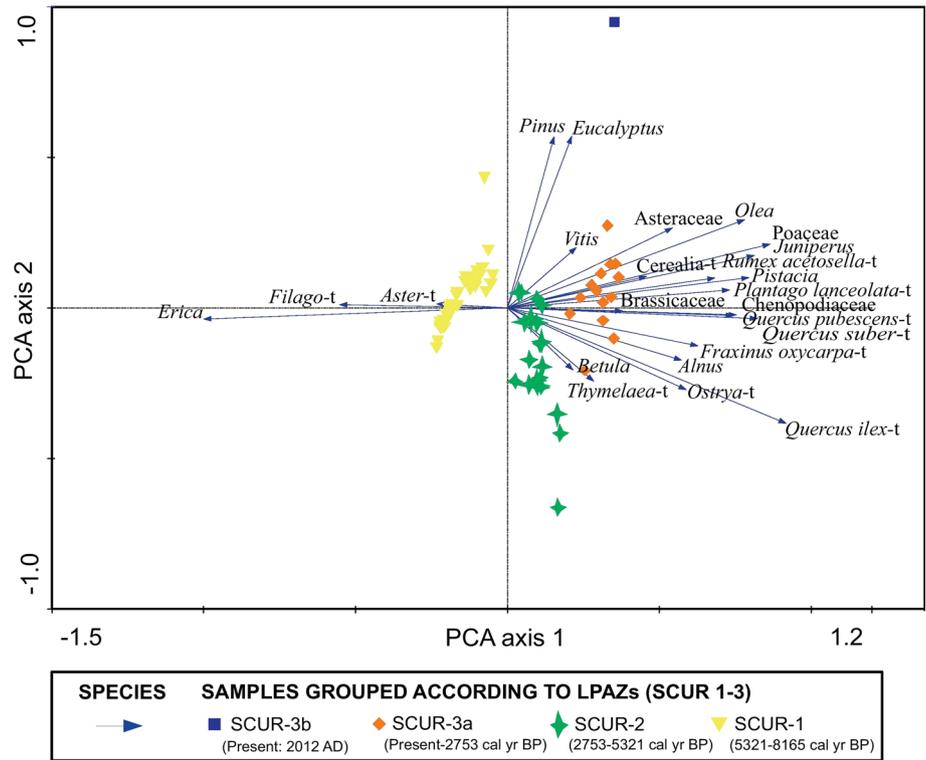
suggest very high fire activity or alternatively (but less likely) be the result of taphonomical processes (e.g. in-wash of reworked charcoal with erosional material) at the base of the sequence (Fig. 2). Subsequently, microscopic charcoal influx stays relatively high (e.g. 363,885 particles  $\text{cm}^{-2} \text{year}^{-1}$  at 7,381 cal BP; 659,949 particles  $\text{cm}^{-2} \text{year}^{-1}$  at 6,690 cal BP; 549,856 particles  $\text{cm}^{-2} \text{year}^{-1}$  at 5,727 cal BP) during the entire zone, indicating frequent regional burning while *Erica* woodlands were dominant. Accordingly, microscopic charcoal concentration and influx peak at c. 7,000 to 5,300 cal BP, preceding the *Q. ilex* expansion. Microscopic charcoal influx decreases in zone SCUR-2 (e.g. 101,329 particles  $\text{cm}^{-2} \text{year}^{-1}$  at 4,590 cal BP) meaning reduced fire activity when *Q. ilex* forests expanded around Sa Curcurica (zone SCUR-2; 5,321–2,753 cal BP). In the more recent part of the sequence (SCUR-3; 2,753 cal BP—present), microscopic charcoal influx reaches minimum values (e.g. 20,494 particles  $\text{cm}^{-2} \text{year}^{-1}$  at 1,574 cal BP) indicating low fire activity when *Erica* woodlands further decreased and the regional landscape became more open in response to human impact.

### Ordination, XRF and diversity analysis

The first PCA axis explains 93.6 % of data variance, while the second axis explains only 2.2 % (Fig. 8). Low PCA axis 1 values are associated with *Erica* and *Filago*-type, while high values are reached for *Quercus ilex*-type, *Q. suber*-type, *Q. pubescens*-type, *Olea*, *Alnus*, *Myrtus*, *Juniperus*, Poaceae, *Plantago lanceolata*-type, *Artemisia* and *Rumex acetosella*-type. The distribution of samples forms clusters following the LPAZs with samples belonging to the zone SCUR-1 (i.e. yellow triangular symbols; Fig. 8) showing low values, while samples belonging to the zones SCUR-2 and SCUR-3 (i.e. green stars and orange rhombuses; Fig. 8) show higher values. Therefore, species and sample distributions on PCA axis 1 follow the long-term development of vegetation composition around Sa Curcurica through the mid and late Holocene. PCA axis 2 shows low values for taxa such as *Q. ilex*-type, *Ostrya*-type, *Fraxinus oxycarpa*-type and *Alnus* and high values for taxa such as *Eucalyptus*, *Pinus*, Cerealia-type, *Olea*, *Vitis*, *Rumex acetosella*-type and Poaceae, most likely indicating a separation between more natural and more disturbed/human influenced vegetation communities.

Three RDA environmental variables (microscopic charcoal, *Sporormiella* and Br) significantly influence pollen data variance according to the performed significance test (Monte Carlo permutation; Lepš and Šmilauer 2003). Ti and Mn/Fe, on the other hand, are not statistically significant. RDA (Fig. 9) with microscopic charcoal influx suggests that fire influences 37.9 % of the vegetational data

**Fig. 8** PCA scatterplot of samples and selected species. The first axis explains 93.6 % of data variance, while the second axis only 2.2 %. Samples are grouped according to the local pollen assemblage zones (SCUR 1-3; see legend of Fig. 7)



**Fig. 9** RDA biplot of selected species and 5 explanatory variables. Microscopic charcoal influx and spores of the dung fungus *Sporormiella* are used as proxies for fire (which influences 37.9 % of data variance) and “presence of grazing mammals” (which influences 10.5 % of data variance), respectively. Abiotic variables

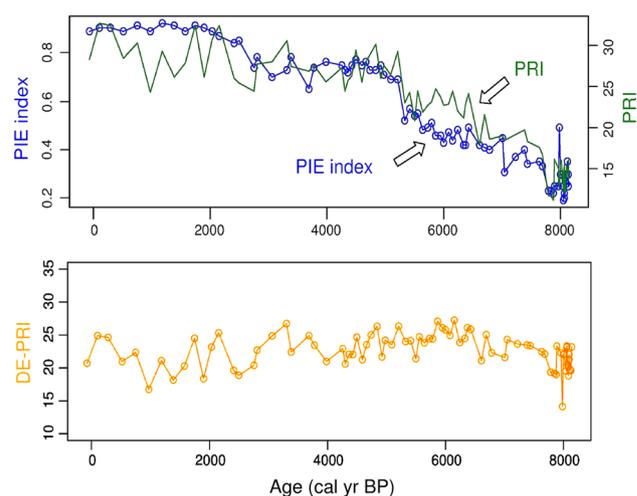
were obtained from the X-ray fluorescence (XRF) analysis. Bromine (Br), titanium (Ti) and manganese over iron (Mn/Fe) were respectively chosen as proxies for organic input. Br influences 45.3 % of data variance, while Ti and Mn/Fe are not statistically significant

variance. Microscopic charcoal is positively correlated with *Erica* and *Filago*-type and correlates negatively with many other taxa, including *Quercus ilex*-type, *Q. suber*-type, *Q. pubescens*-type, *Olea*, *Pistacia*, *Ostrya*-type, *Juniperus*, *Artemisia* and *Poaceae*. This implies that the

dominance of *Erica* during the mid-Holocene may have been partly favoured by high fire activity, while *Q. ilex*-*Olea europaea* vegetation caused low fire activity. Spores of dung fungus *Sporormiella* influence 10.5 % of data variance and are positively correlated with *Erica* and

*Filago*-type. This suggests that during the mid-Holocene, grazing mammals were present near the lake so that they could have access to a rare source of water along the coast, given that *Filago* and *Helichrysum* usually prefer fields, disturbed and dry areas (e.g. maquis) and/or pastures (Pignatti 2003; Keeley and Brennan 2012). Influence of Ti on data variability is not statistically significant; nevertheless, it negatively correlates with most of the taxa, likely suggesting higher soil erosion during the early period, before vegetation became more diverse. Br influences 45.3 % of data variance and correlates negatively with *Erica* and *Filago*-type and positively with for example *Q. ilex*-type, Poaceae as well as many other species. Its trend (Fig. 3) is very similar to that of aquatic plants such as *Ruppia* and salt-intolerant (Pignatti 2005) *Isoetes* (Fig. 7), which increased sharply around 2,750 cal BP. The rather high abundance of *Isoetes* (c. 11–12 %), together with evidence of high salinity (low TOC/TS, Berner and Raiswell 1984) suggests that *Isoetes* expanded in nearby freshwater wetlands or that increased freshwater inflow produced a marked horizontal or vertical salinity gradient in the lake (Stevenson et al. 1993; Lardicci et al. 1993; Barke et al. 2011). This latter interpretation is supported by the expansion of *Chara*, which prefers freshwater environments (Ellenberg 2009), after 2,500 cal BP. The Mn/Fe ratio (although not statistically significant) may help to refine the causes of water quality changes. Mn/Fe shows an opposite trend to Br, indicating better oxygenation as a result of lower water levels (i.e. higher Mn/Fe ratio values; Davison 1993) c. 8,200–7,500 cal BP, when *Erica* woodlands were dominant and fire activity was particularly high (Figs. 3, 6). Mn/Fe values, which are relatively low from c. 7,500 to 2,300 cal BP, slightly increase again during the last two millennia (Fig. 3), suggesting a better oxygenation of the water column and surface sediment due to a low water level that enabled deeper mixing of the water column. Lowering water tables may explain the expansion of aquatic plants such as *Myriophyllum alterniflorum* and *Ruppia* close to the coring site. Considering the rise of anthropogenic indicators after 2,750 cal BP (see above), it might well be that the water table lowering reflects human use of water or draining of wetlands from Roman times to the present. Similar dynamics of Br and Cl (see Fig. 3) after c. 1,800 cal BP may be related to rapid changes in salinity rather than productivity. Declining Br and Cl values during this period may indicate that people blocked the channel to the sea for irrigation purposes to avoid freshwater loss and inflow of marine water into the lake.

Since palynological richness (PRI) and palynological evenness (PIE) show largely comparable trends throughout the entire sequence, we assume that PIE has an effect on PRI (Fig. 10; Colombaroli and Tinner 2013), which is confirmed by the difference between PRI and PIE-detrended PRI (DE-



**Fig. 10** Top Comparison of palynological richness (PRI, green line) and evenness (PIE, blue line with points) estimated on a constant sum of 216 pollen grains. Bottom Evenness-detrended palynological richness (DE-PRI, orange line)

PRI) curves. PRI and PIE show low values at the beginning of the sequence, suggesting the predominance of few taxa during the mid-Holocene, when *E. scoparia* and *E. arborea* were dominant and high fire incidence persisted (Figs. 6, 10). Subsequently, from c. 7,900 to c. 5,500 cal BP, PRI and PIE continuously increase to remain relatively constant until c. 2,800 cal BP (LPAZ boundaries 1–2). Around 2,800 cal BP, palynological evenness increases again until c. 2,000 cal BP and remains high until present, while palynological richness shows high variability. At 5,500 and 2,800 cal BP, regional fire activity decreased, while *Q. ilex* and other tree taxa increased, probably advantaging species evenness. Detrended palynological richness (DE-PRI) shows higher values than PRI from c. 8,100 to c. 5,500 cal BP (when *Erica* woodlands were dominant), implying that low evenness at this time may have lowered PRI (Colombaroli and Tinner 2013). After 5,500 cal BP, on the other hand, DE-PRI shows lower values than PRI, indicating that high evenness probably inflated PRI during the late Holocene (Colombaroli and Tinner 2013). Consequently, it seems that though PRI and PIE increase together, most of these diversity changes can be attributed to increasing evenness rather than to increasing richness.

## Discussion

### Environmental conditions and dominance of *E. scoparia* and *E. arborea* during the mid-Holocene (8,100 to 5,300 cal BP)

*Erica* shrublands are generally considered early successional communities. In Sardinia they are regarded as a

dynamic stage toward the climax or end successional stage of *Quercus ilex* (Chiappini 1985). *E. scoparia* and *E. arborea* are found as dominant species in various vegetation communities. They form extended heathlands and shrublands, usually in disturbed areas, or grow associated with trees such as *Q. ilex* forming dense forests (e.g. Brullo et al. 1977; Ojeda et al. 2000; Lloret et al. 2004). Evidence for the potential of forest formation by *E. scoparia* and *E. arborea* comes from the Canary Islands, where they form part of the canopy in the late-successional laurel forests (10–20 m height, Arévalo et al. 1999). At our site the phase of *Erica* dominance was not a short (multi-decadal) early successional stage, given that the species dominated local and regional vegetation for millennia. Very similar mid-Holocene evidence comes from Corsica, where high abundances of *Erica* are interpreted as primeval forests which became extinct during the late Holocene (Reille 1992b).

The factors that allowed *Erica* species to dominate vegetation and form forests and/or tall shrublands for millennia in Sardinia and Corsica may be explained by considering the ecology of the species. In the Mediterranean, *E. scoparia* and *E. arborea* are advantaged by frequent and prolonged droughts during the spring and summer, which can cause severe damage to *Q. ilex* forests (Lloret et al. 2004; Nogués et al. 2014). After repeated drought events, *Erica* stands may replace *Q. ilex* forests (Lloret et al. 2004). This competition advantage is explainable by the higher resprouting capacity of the two *Erica* species after repeated strong droughts (Lloret et al. 2004). *E. scoparia* can also outcompete other species on sandy, shallow and nutrient-poor soils (i.e. sandstone; Ojeda et al. 2000). *E. scoparia* and *E. arborea* are highly combustible (Fernandes et al. 2000; Curt et al. 2011) and extremely fire-adapted, given that their underground lignotubers allow them to quickly resprout and regenerate aboveground biomass after frequent and intense fires (Ojeda et al. 2000; Keeley et al. 2012).

Microscopic-charcoal inferred regional fire activity (mainly frequency; see Tinner et al. 1998; Conedera et al. 2009) was highest during the period of *Erica* dominance and given the fire-ecology of the species involved, this may partly explain the mid-Holocene dominance of *Erica* communities. The high level of fire disturbance may have forced *Erica* to form shrublands rather than forests. On the other hand, *E. arborea* increases its resprouting capacity with size (e.g. Pausas et al. 2008) and thus it might well be that *Erica* formed forests during the mid-Holocene when fire disturbance was high. Our new pollen record suggests that *Q. ilex* was present in the area since at least 8,000–7,500 years ago (empirical limit) but never reached more than 1–2 % until 5,500 years ago. It seems unlikely that fire alone was so pervasive to prevent an expansion of

*Q. ilex* and other disturbance-adapted maquis species (e.g. *Phillyrea*, *Juniperus*, *Pistacia*) for more than two millennia. Thus, fire may have interacted with another cause to advantage *Erica* species over late successional *Q. ilex*.

In Italy north of c. 40°N lake-levels were lowest during the period 9,000–5,000 cal BP (Magny et al. 2007, 2011, 2012; Giraudi et al. 2011), suggesting dry conditions during the mid-Holocene. This finding is in contrast with oxygen isotope records suggesting humid conditions during the same period (Baroni et al. 2006, Giraudi et al. 2011; Roberts et al. 2011). This conflict is explainable by seasonal differences, with oxygen isotopes as a proxy for winter precipitation and lake-level records as a proxy for summer precipitation or evaporation (Giraudi et al. 2011). Thus, according to this interpretation the mid-Holocene was characterised by warmer and drier summers and cooler and wetter winters than today. Recent simulations confirm this seasonal pattern, which in the climatic models primarily results from orbital forcing (Tinner et al. 2013). We therefore hypothesise that the prolonged dominance of *Erica* and the absence of evergreen oak forests were related to warmer/drier summers and cooler/moister winters than today.

Cool mid-Holocene winter temperatures on the Sardinian coast probably played a marginal role in the absence of *Q. ilex* forests, since this species can grow at much higher altitudes and latitudes as for example in northern Italy or along the French Atlantic coast (Delzon et al. 2013). Instead, humid mid-Holocene winters may have affected *Q. ilex*, given that marked rainfall periods may restrict the germination of *Q. ilex* seeds to the same extent as water limitation in summer (Gómez-Aparicio et al. 2008), but promote *E. scoparia* (Zunzunegui et al. 1998). Moreover, growth of *Q. ilex* mostly depends on spring and summer precipitation, and enhanced winter precipitation has very little effect (Nijland et al. 2011). The mid-Holocene climatic setting might have also significantly affected the fire regime. We assume that the high fire activity observed during the mid-Holocene (Fig. 6) may have been driven by marked and prolonged summer heat and droughts, exacerbating the effects of climate by promoting stress- and disturbance-adapted *Erica* species at the expense of late-successional *Q. ilex*. Climatically and fire controlled shrubland dominance during the early and mid-Holocene are also recorded at other Mediterranean sites. For instance, on the southern Sicilian coast, *Pistacia* dominance persisted for several millennia under dry conditions and frequent fires, before the expansion of *Q. ilex*-*Olea europaea* forests and the decline of fire activity at 7,000 cal BP (Tinner et al. 2009; Noti et al. 2009; Calò et al. 2012). *Pistacia* shrublands also occurred on the island of Malta where they established around 7,000 cal BP in response to increased moisture availability (Djamali et al.

2013). Due to markedly xeric environmental conditions, they probably correspond to today's potential natural vegetation of the island (Djamali et al. 2013).

In our pollen record (Fig. 6) there is no unambiguous indication of agricultural activities until 5,300 cal BP. This finding is in excellent agreement with evidence from Corsica (e.g. Lac de Bastiani and Lac de Creno; Reille 1992b), where the *Erica* dominance persisted during the entire mid-Holocene in the absence of significant human impact. The high *Sporormiella* dung spore values since the beginning of the record may suggest presence of wild animals or cattle around the site; however, in the absence of a clear pollen signal of pastoralism (i.e. high AP and low NAP, see Figs. 6, 7) such as Poaceae, Cichorioideae, *Artemisia* and *Plantago lanceolata* it is difficult to attribute this evidence to livestock grazing. Nonetheless, it is very likely that such activities existed in the area during this period belonging to the Sardinian early Neolithic and early mid Neolithic (Lilliu 2002).

#### Climate and human impact on vegetation and fire between 5,300 and 2,750 cal BP

During the period 5,300–2,750 cal BP, evergreen oak forests gradually replaced *Erica* shrublands or woodlands around Sa Curcurica. *Q. ilex* expanded together with rather mesophilous taxa such as for example *Alnus*, *Ostrya* and *Selaginella denticulata* suggesting that (summer) moisture availability increased. This interpretation is supported by the expansion of salt-intolerant *Isoetes*, which most likely indicates increasing freshwater inflow into the saline coastal lake. Similar vegetation dynamics were observed at mountain sites (Creno and Bastiani; Reille 1992b) and coastal lagoons (Le Fango and Saleccia; Reille 1992b) of Corsica, where *Q. ilex* forests at the coast and stands of rather mesophilous taxa such as *Abies*, *Fagus* and *Betula* in the mountains replaced *Erica* dominated woodlands (Reille et al. 1999; Leys et al. 2014).

Further south, in Sicily, coastal evergreen oak-olive forests remained rather stable and closed (Tinner et al. 2009; Noti et al. 2009; Calò et al. 2012), inland forests opened (e.g. Sadori and Narcisi 2001) and mountain forests became more mesophilous (Bertolani Marchetti et al. 1984; Bisculm et al. 2012). At Dar Fatma, in the mountains of northern Tunisia, the dominant species *Q. canariensis* decreased, while *Q. suber* and *Erica* increased (Ben Tiba and Reille 1982). In Malta, Mediterranean arboreal ecosystems dominated until c. 5,600 cal BP, to be subsequently replaced by humanised herbaceous communities (Djamali et al. 2013). East of Sardinia, forest re-expanded and stabilized around 5,300 cal BP and fire incidence declined at Mediterranean coastal sites such as Lago di Massaciuccoli in Tuscany and Malo Jezero in southern

Croatia (Colombaroli et al. 2007, 2009; Jahns and van den Bogaard 1998), which is in good agreement with the pattern observed at Sa Curcurica. North and west of Sardinia, in southern France, Iberia and the Balearic islands, vegetation became more open during the late Holocene (Pérez-Obiol and Sadori 2007; Jalut et al. 2000; Pantaléon-Cano et al. 2003) and it is still debated if this vegetation shift was the result of human impact, climatic change or a combination of both (Carrión et al. 2010; Sadori et al. 2013; Mercuri and Sadori 2014).

Similarities among inland lake levels and glacier records in Italy suggest that (summer) precipitation increased during the late Holocene (Magny et al. 2007, 2012), while oxygen isotopes point to a decline of winter precipitation (Giraudi et al. 2011; Roberts et al. 2011). This change probably resulted from the orbitally-induced decline in summer insolation and rise in winter insolation, which accompanied the onset of the Neoglacial cooling in the Northern Hemisphere at the beginning of the late Holocene at c. 5,500–5,000 cal BP (Andersen et al. 2004; Magny et al. 2006). We therefore assume that the long-lasting expansion of *Q. ilex* was mainly the result of cooler, more humid and shorter summers during the late Holocene. Less humid and warmer winters may also have advantaged *Q. ilex*, given its sensitivity to frost and winter rainfall for seed germination (Lo Gullo and Salleo 1993; Gómez-Aparicio et al. 2008). Reduced interannual precipitation variability (e.g. Magny et al. 2007) and more stable environmental conditions may have contributed to this vegetational change as well, given that according to ecological literature, evergreen broad-leaved *Q. ilex* forests represent the current late-successional (or climax) vegetation type in the Sardinian lowlands (Chiappini 1985). The *Q. ilex* expansion may have partly advantaged the taller *E. arborea* (Ojeda et al. 2000; Arrigoni 2006–2010) over *E. scoparia* (see Fig. 4).

The onset of the late Holocene or Neoglacial period around 5,300 cal BP coincides with a considerable decline of fire activity around Sa Curcurica (Fig. 6). We hypothesise that lower fire incidence resulted from cooler and wetter summers and thus contributed to the expansion of *Q. ilex* forests, as observed in other sites in the Mediterranean (Colombaroli et al. 2009). Positive feedback processes may have further reduced fire activity, since holm oak forests tend to inhibit fires (Azevedo et al. 2013). Fire dynamics observed at Sa Curcurica during the mid- and late Holocene mirror the situation of other sites situated between 40 and 45°N in the western Mediterranean (Magny et al. 2007; Vannièrè et al. 2011), likely implying higher climatic similarity between north-eastern Sardinia and the northern rather than the southern Mediterranean realm.

Pollen indicative of land use (e.g. *Plantago lanceolata*-type, *Rumex acetosella*-type, *Artemisia*, Cerealia-type) and creation of open land (NAP increasing from c. 10 to 15 %)

suggest that agricultural and pastoral activities were increasingly practiced in the area. Open environments included maquis and garrigue, as suggested by the expansion of *Myrtus*, *Lavandula*, *Phillyrea* and *Pistacia*. This is consistent with the presence of several *nuraghi* dated to this period in the area between Orosei and Siniscola (Kriek 2014). Taken together we mainly attribute the forest dynamics (expansion of *Q. ilex*) to a shift to cooler and moister summers at the onset of the late Holocene, while the moderate vegetation opening (increase of NAP and cultural indicators) was mainly caused by human impact.

### **The increasing role of human impact as driver of vegetation and fire regime changes after 2,750 cal BP**

The expansion maximum of *Q. ilex* is dated at 2,750–2,600 and is associated with a drastic decline of *Erica*, a significant increase of open habitats (NAP) and of land use, as well as a marked decline of regional fire activity. Together with the change at 5,300 cal BP (first expansion of *Q. ilex* and decline of *Erica*), this vegetational change is the most important of the entire Sa Curcurica sequence (two statistically significant LPAZ boundaries). The unambiguous link with the increase of land use (e.g. Cerealia-type, *Plantago lanceolata*-type, *Rumex acetosella*-type, *Cannabis*-type, *Artemisia*, *Olea*) suggests that human impact controlled this main vegetation shift. Maquis and garrigue continued to expand, apparently unrelated to regional and local fire activity.

In Sardinia this period coincides with the increasing influence of the Phoenician period and the maximum development of the *nuragic* civilization (Lilliu 2002) at the Bronze Age–Iron Age transition and during the early Iron Age (c. 900–500 BC, c. 2,850–2,450 cal BP). Roman influence in Sardinia started around 200 BC (2,150 cal BP). Literary sources suggest that during the first centuries of Roman influence, fruit tree cultivation was prohibited, but subsequently the rule was annulled and fruit tree production was then promoted (Mastino 1995). In agreement, *Olea europaea* expanded at Sa Curcurica around AD 50 (1,900 cal BP), probably in response to increased oil production. Cork oak groves may have been established when *Q. suber* reached maximum values at around AD 300–400 (Dettori et al. 2001). Increasing forest disruption and land use during the past three millennia is documented in almost all Mediterranean pollen records (e.g. Reille 1992b; Colombaroli et al. 2008; Tinner et al. 2009; Noti et al. 2009) and coincides with early urbanization in the Mediterranean and adjacent areas (e.g. Celtic culture in Western and Central Europe).

During and after the *Q. ilex* expansion and *Erica* collapse at 2,750–2,600 cal BP, mesophilous taxa with rather high moisture needs remained abundant or even expanded

(e.g. *Alnus*, *Q. pubescens*-type, *Ostrya*-type, *Fraxinus oxycarpa*-type, *Selaginella denticulata*). Similarly, salt-intolerant freshwater vegetation (e.g. *Isoetes*) further expanded in and/or around the site. Similar vegetation dynamics occurred around 2,800 cal BP in North Africa (Algeria), where *E. arborea* collapsed and mesophilous *Alnus*, *Salix* and *Osmonda regalis* expanded (Benslama et al. 2010). Given the link between initial *Q. ilex* expansion and climatic change at 5,300 cal BP, it is tempting to relate this pattern to a shift towards cooler and more humid conditions at around 2,800 cal BP, which may have resulted from changes in atmospheric circulation as a consequence of decreasing solar activity (grand solar minimum; Martin-Puertas et al. 2012). Glacier advances (or less frequent recessions) and higher lake levels during the late Holocene probably resulted from this climatic shift (Holzhauser et al. 2005; Jörin et al. 2006).

### **Water level, salinity and moisture changes during the mid- and late Holocene**

After a disturbance event causing the deposition of sands in the Sa Curcurica basin at c. 8,200 cal BP, possibly a sea transgression (Colombaroli et al. 2007), freshwater conditions prevailed at Sa Curcurica. Increasing water salinity (i.e. low TOC/TS values) at 8,000–6,000 cal BP was probably related to incursions of seawater. The subsequent expansion of mesophilous terrestrial taxa (e.g. *Alnus*, *Fraxinus*, *Selaginella denticulata*) and freshwater plants (e.g. *Isoetes*) strongly argues against increasing (summer) evaporation or reduced precipitation as an alternative explanation for the observed high water salinity after 6,000 cal BP. To address this issue more carefully, additional pollen-independent Sardinian palaeoclimatic precipitation and temperature proxies such as lake-level, chironomids or oxygen isotopes would be needed. Human influences such as water-table lowering, for example for irrigation purposes or to permit early urbanization, may have affected the hydrology of Mediterranean natural archives since pre-Roman times (Calò et al. 2012). Other human activities such as the alteration of the connection between coastal lakes and the sea (as suggested by the joint Br and Cl evidence) may additionally complicate the reconstruction of natural palaeohydrological dynamics, for example for palaeoclimatic purposes. However, increasing summer moisture availability at c. 5,300 and 2,750 cal BP would explain the decline of fire activity directly (e.g. higher fuel moisture) or indirectly (e.g. reduction of vegetation flammability by further shift from *Erica* to *Q. ilex*). The latter explanation seems equally likely, because at other Mediterranean sites, anthropogenic fire activity reached its minimum (e.g. Colombaroli et al. 2008; Tinner et al. 2009) when *Q. ilex* forests were abundant (e.g. Colombaroli et al. 2007; Noti et al. 2009; Tinner et al. 2009; Calò et al. 2012).

## Conclusions

Pollen, microscopic charcoal and macrofossil analyses of sediments from Stagno di Sa Curcurica, a coastal salty lake located in north-eastern Sardinia, suggest that during the mid-Holocene, woodlands composed mainly of highly stress- and disturbance-adapted *E. scoparia* and *E. arborea*, were dominant. The unusual millennial persistence of today's early successional vegetation associations presents important similarities with the neighbouring, northern island of Corsica. There, *Erica* forests were dominant at different altitudes, from the coasts to the mountains (Reille 1992b). We hypothesise that the marked seasonality that characterised the mid-Holocene with particularly long, dry, hot summers and cool, humid winters may have had a central role promoting the expansion and persistence of highly stress-adapted shrub species (*E. arborea*, *E. scoparia*) and high summer fire activity, and then further inhibited the proliferation of *Q. ilex*. Around 5,300 and 2,750 cal BP *Q. ilex* forests expanded in the region near Sa Curcurica when moisture availability increased in response to climatic change. On the other hand, fire, which was decisive in maintaining *Erica* stands, markedly decreased. Our data indicate that agricultural activities were practiced in the region around Sa Curcurica since at latest the late Neolithic and increased significantly during the Phoenician and Roman periods (c. since 2,800 cal BP).

On the basis of our new palaeoecological record covering the last 8,000 cal BP, we conclude that open *Q. ilex* forests might be the potential natural vegetation around Sa Curcurica today. Our results imply that under global warming conditions (e.g. increase of extreme events, drought stress and high fire activity), *Q. ilex* may decline and *Erica* communities regain their former importance. Given that in contrast to *Q. ilex* forests and shrublands such communities are highly flammable, this may have serious implications for land use, infrastructure and human safety. Vegetation modelling may be used to investigate quantitatively this complex ecological issue (Henne et al. 2015). Further sampling sites are needed to evaluate whether the close link between vegetation and fire history is characteristic throughout Sardinia. Additional pollen-independent palaeoclimatic evidence from the Central Mediterranean would be decisive in refining the climatic interpretations presented here.

**Acknowledgments** We thank Willi Tanner for the field work, Massimo D'Angelo for helping with coring permits, Florencia Oberli for the laboratory instructions, Kathrin Studer for her help with the determination of morphological differences between *Erica scoparia* and *E. arborea* macrofossils, Andy Lotter for inspirational discussions and two anonymous reviewers for their very valuable suggestions. This study was supported by the Swiss National Science Foundation (SNF 200021\_134616/1).

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