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Abstract

Foraminifera are eukaryotic unicellular microorganisms inhabiting all marine environments.

The study of these protists has huge potential implications and benefits. They are good indicators of global change and are also promising indicators of the environmental health of marine ecosystems. Nevertheless, much remains to be learnt about foraminiferal ecology.

In this chapter we intend to introduce the main issues in the study of foraminifera in the Mediterranean Sea and the state-of-the-art developments in the study of these organisms. The aims of this chapter are: (1) to provide a brief history of the study of foraminifera and (2) to review recent developments in the study of modern foraminifera, particularly as they apply to Mediterranean faunas. Our intention is to describe the development of the use of foraminiferal assemblages in Mediterranean applied ecological studies up to their possible use as bio-indicator for the monitoring of marine ecosystems.

Keywords

Benthic foraminifera • Hard and soft-shelled taxa • Methodology • Ecology • Bioindicator • Mediterranean Sea

Introduction

Foraminifera were first described and illustrated in the eighteenth and nineteenth centuries (von Linnaeus 1758; Fichtel and Moll 1798; De Montfort 1808), but it was the French naturalist Alcide d'Orbigny who established a firm foundation for their study. In his 1826 work “Tableau Méthodique de la Classe des Céphalopodes”, d'Orbigny made the same mistake as earlier authors in describing

these microscopic shells as those of minute cephalopods. He believed that the granuloreticulopods of living specimens were tiny tentacles, and also, like von Linnaeus (1758), recognized that many of the planispiral shells resembled *Nautilus* (Lipps et al. 2011). However, d'Orbigny's major contribution was to establish these organisms as a distinct order (“Foraminifères”) because the chambers had apertures (*foramina*) that ensured the communication between different parts of the test instead of the siphons found in typical

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cephalopods. D'Orbigny's (1826) ascribed 544 species to his Order Foraminifères; 335 were new species names that were published without descriptions. Since then, these minute organisms have become interesting objects of study by both geologists and biologists (Cifelli 1990).

For many years, fossil foraminiferal faunas have been used to date sediments and to reconstruct paleo-environments (Haq and Boersma 1998). The resulting knowledge of climatic and oceanographic changes in the geological past has been used to predict and model future environmental change (Sen Gupta 2002). However, in recent years there has been renewed interest among the scientific community in foraminifera as indicators of modern global change, i.e. global warming, rising sea levels and loss of biodiversity (Hillaire-Marcel and de Vernal 2007; Ingels et al. 2012) and as bioindicators of environmental health (Hallock et al. 2003; Gooday et al. 2009; Frontalini and Coccioni 2011). This last applied use of foraminifera involves the study of the existing faunas and their actual ecology. The application of biochemical and molecular techniques, normally applied to other organisms, are making scientists aware that foraminifera can be used in ecological studies and/or protocols for biomonitoring programs, in the same way as the larger metazoan meiofaunal and macrofaunal assemblages, and with similar or even better results.

The aims of this chapter are: (1) to provide a brief history of the study of foraminifera and (2) to review recent developments in the study of modern foraminifera, particularly as they apply to Mediterranean faunas. Our intention is to describe the development of the use of foraminiferal assemblages in Mediterranean applied ecological studies up to their possible use as bio-indicator for the monitoring of marine ecosystems. We highlight (1) the heterogeneous nature of the existing body of data that cannot be easily integrated to produce an overall synthesis of foraminiferal community parameters and (2) the consequent need for a standardised methodology. The latter will lead to an improved understanding of the role of foraminifera in the functioning of Mediterranean Sea ecosystems and aspects of their biology that are beyond the scope of environmental studies.

What Are Foraminifera?

Foraminifera are single-celled eukaryotic organisms (protists) with tests (shells) that are present as fossils in the sediments of the last 545 million years, as well as in modern oceans. Tests may be made of organic material, sand grains or other particles cemented together ('agglutinated'), or crystalline CaCO_3 (calcite or aragonite). The hard tests are commonly divided into chambers that are added during growth, although the simplest forms are open tubes or hollow spheres.

Fully grown individuals range in length size from about 100 μm or less to almost 20 cm. Some have a symbiotic

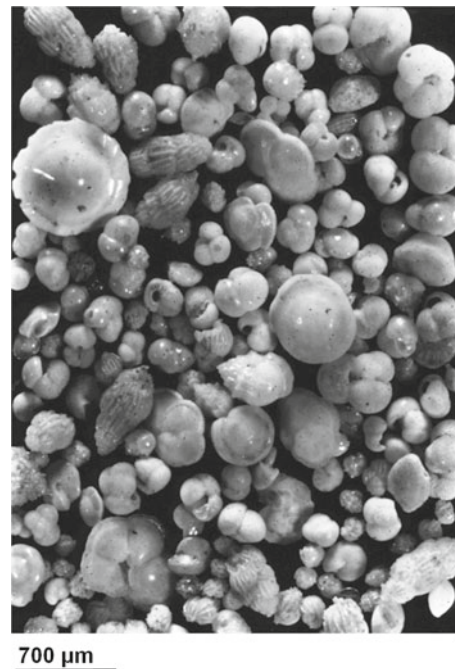


Fig. 13.1 Benthic and planktonic foraminiferal assemblages of deep sediment from tropical Atlantic Ocean (From Morigi 1999) (Scale bar=700 μm)

relationship with algae. They consume food ranging from dissolved organic molecules, bacteria, diatoms and other single-celled algae, to small animals such as copepods. They catch their food with a highly mobile network of thin pseudopodia (called reticulopodia) that extend from one or more apertures in the shell. Foraminifera also use their pseudopodia for multiple other functions including locomotion, respiration and test building.

There are an estimated 4,000 benthic species of foraminifera living in the world's oceans today (Murray 2007) on and in the sediment, on rocks and on macroalgae at the sea bottom, while only 40 species are planktonic (Hemleben et al. 1989). Foraminifera are found in all marine environments, from the intertidal to the deepest ocean trenches, and from the tropics to the poles, from brackish to hyper-saline waters. Recent studies suggest that they are present in fresh-water and even in terrestrial habitats (Meisterfeld et al. 2001; Holzmann and Pawlowski 2002; Holzmann et al. 2003). Foraminifera are among the most abundant shelled organisms in many marine environments (Hayward et al. 2011). A cubic centimetre of sediment may yield hundreds of living individuals, and many more dead shells. In some habitats their shells are an important component of the sediment. For example, the pink sands of some beaches get much of their colour from the pink to red-colour shells of a particular species of foraminifer. In regions of the deep ocean far from land, the bottom sediment is often made up almost entirely of the shells of foraminifera (Fig. 13.1).

How Foraminifera Can Be Used in Applied Science

The study of fossil foraminifera has many practical applications beyond expanding our knowledge of the diversity of life. In particular they are useful in the field of stratigraphy, paleoenvironmental reconstruction, and oil exploration. The earliest foraminifera occurred in the Precambrian-Cambrian boundary, 545 million years ago (McIlroy et al. 1994) and they show a continuous evolutionary development up to present time, so that different species are found at different times. This, together with the fact that they are abundant in all marine environments, and easy to collect, even from deep oil wells, explains why they have been extensively used for dating marine sedimentary rocks. Foraminifera are sensitive to environmental conditions and often associated with particular environmental settings (Haq and Boersma 1998; Sabbatini et al. 2002; Panieri 2005, 2006a, b; Gooday et al. 2010). This allows paleontologists to use foraminiferal fossils to reconstruct environments in the geological past. In this way, foraminifera have been used to map the former planetary distributions of the tropics, locate ancient shorelines, and track global ocean temperature changes during the ice ages (Hillaire-Marcel and de Vernal 2007). To reconstruct ancient environments, paleontologists employ metrics that are similar to those used to characterize modern assemblages. These include species diversity, the relative numbers of planktonic and benthic species, the ratios of different shell types, and shell chemistry (Murray 1991; Hillaire-Marcel and de Vernal 2007). One widely used set of proxies for environmental conditions in ancient oceans is provided by the ratios of stable isotopes present in the shell carbonate. Although modified by physiological (“vital”) effects, these ratios reflect the chemistry of the water in which foraminifera grew. For example, in 1955, Cesare Emiliani discovered that the ratio of stable oxygen isotopes depends on the water temperature, because warmer water tends to evaporate off more of the lighter isotopes. Since then, measurements of stable oxygen isotopes in planktonic and benthic foraminiferal shells from hundreds of deep-sea cores worldwide have been used to map past surface and bottom-water temperatures (Rohling and Cooke 2002). These data helps us understand how climate and ocean currents have changed in the past and may change in the future.

Many geologists work as biostratigraphers and use foraminifera extracted from drill cuttings recovered from oil wells to date sediments and reconstruct past environments. The stratigraphic analyses made using foraminifera as descriptors is so precise that these fossils are even used to direct sideways drilling within an oil-bearing horizon in order to increase well productivity. Since the 1920's the oil industry has been an important employer of paleontologists specialised in the study of these microscopic fossils. As a result of their potential “economical significance”,

foraminifera are better known for their spectacular fossil record than for their variety and abundance in modern marine environments. But, at the same time, curiosity-driven research, and the need to understand the present in order to interpret the past, has recently propelled paleontologists to learn more about the ecology of these protists.

Ecology of Benthic Foraminifera

Ecological studies of modern foraminifera (especially benthic taxa) started in the 1950s (Phleger 1960) and have increased over the past 60 years. Nevertheless, the main interest of the scientific community in this group remains focused on the use of their excellent fossil record to understand marine environmental changes in the geological (and historical) past. This leads to the paradox that the paleoecology of fossil foraminifera (based on some pioneer studies performed by geologist in the second half of the nineteenth century), is often better known than the ecology of modern species. Little is known about life cycles and lifestyles of most species of foraminifera. Reasonably complete life cycles are known for fewer than 30 of the 4,000 extant species. The few species that have been studied show a rich diversity of foraminiferal life cycles (i.e. involving alternating generations, apogamic, binary fission, different type of gametes and mode of fertilization) and a wide range of behaviours and diets. The classical life-cycle (i.e. gametogamy) in *Elphidium crispum* has been shown to be environmentally sensitive (Myers 1943). The whole life-cycle (both sexual and asexual phases) is completed in 1 year in temperate regions such as the Mediterranean basin.

These relatively large, shell-bearing protists typically constitute half or more of the deep-sea meiobenthos and are often an important constituent of the larger (>300 µm) macrofaunal size fraction as well. Together with bacteria, they are key players in the functioning of deep-sea benthic ecosystems. Some benthic species burrow actively through sediment at speeds up to 1 cm per hour, while others attach themselves to the surface of rocks or marine macroalgae. Many species feed at a low trophic level and play a crucial role in the long-term processing of fresh, photosynthetically-produced organic material that is transported to the ocean-floor as rapidly-sinking aggregates (Gooday 1993; Gooday et al. 2008). At least in some environmental setting, they collectively, process the same amount of labile organic matter as bacteria, although their biomass is a tiny fraction of that of bacteria (Moodley et al. 2002). Foraminifera are abundant enough to be an important part of the marine food chain, and their predators include scaphopods, isopods, marine snails, sand dollars and small fishes (Lipps 1983).

Studies conducted during the last decades have led to a better understanding of the biology of modern foraminifera (Le Cadre and Debenay 2006; Bentov et al. 2009; de Nooijer

et al. 2009). However this group is scarcely used in monitoring studies because a standardization of protocols has not been achieved to date. Recently Schönfeld (2012) tackled this issue and reviewed the development of field and laboratory methods, their constraints and consequences for faunal and data analyses evidencing that much work remain to do.

The most important requirement is to discriminate between living and dead assemblages (Murray 2000). Over the last 20 years, new methods have been developed for this purpose, each one having a different degree of accuracy and based on a different rationale. Rose Bengal (RB), a non-vital stain that binds proteins and other macromolecules, is still the most widely used in ecological studies to recognize presumably dead (unstained) foraminifera from their living (stained) counterparts (Walton 1953; Murray and Bowser 2000). However, it does not discriminate between viable and recently dead organisms. Therefore, it becomes very important to effectively recognize the cell metabolism. In this context, the *Fluorescent In Situ Hybridization technique* (FISH), complementary to the CellTracker Green method (Bernhard et al. 2006), represents a new and useful approach to identify living cells possessing an active metabolism and also able to discriminate their grade of activity (Borrelli et al. 2011).

The Early Works on Mediterranean Foraminifera

The earliest work on Mediterranean foraminifera, dating from the late eighteenth and early nineteenth centuries, was descriptive and focused on taxonomic inventories (Soldani 1789, 1795; d'Orbigny 1826). During the last century, local faunal assemblages or selected species from the Western and Eastern Mediterranean were described; these included the works of Buchner (1940) and Hofker (1960) in the Gulf of Naples, Colom (1974) in the Balearic Sea, Le Calvez and Le Calvez (1958) in the Gulf of Lyon; Cherif (1970) in the Aegean Sea (Miliolacea), Fornasini (1902, 1904, 1905, 1906a, b) and Wiesner (1923) in the Adriatic Sea. Studies of benthic foraminiferal distributions in the Mediterranean started in the late 1860s when Jones and Parker (1860) proposed a synoptical table of the fossil and Recent species and varieties of benthic foraminifera (littoral to intertidal) from the Tyrrhenian, Adriatic and Levantine basins. More recent investigations, starting in the 1950s, have extended from shallow water down to abyssal (4,500 m) depths.

Parker (1958), Todd (1958), Blanc-Vernet (1969) and Colom (1974) were the first to conduct qualitative studies of modern bathyal benthic foraminiferal fauna in the Mediterranean Sea. In particular, Parker (1958) studied the distribution of 110 benthic and 18 planktonic species in the Eastern Mediterranean and Aegean Sea and described four bathymetric faunal boundaries for the benthic species. Blanc-Vernet (1969) investigated living benthic foraminifera

from the Aegean Sea, off Rhodes, Crete and Peloponnesus, along the coast of Marseille and Corsica and described their biogeographic, seasonal and habitat-specific distribution. Parisi (1981) worked on samples from bathyal depths (1,003–3,593 m) in the Tyrrhenian Sea and Straits of Sicily. Bizon and Bizon (1983) reported on the geographic and bathymetric distribution of species down to 2,000 m off Marseille, Corsica, and in the Ligurian Sea. Two studies have analysed samples from both the Eastern and Western Mediterranean. Cita and Zocchi (1978) worked in the Alboran, Balearic, Tyrrhenian, Ionian, and Levantine basins (166–4,625 m), while Cimerman and Langer (1991) provided a comprehensive review of the distribution and morphology of benthic foraminifera from numerous localities in the Adriatic Sea and from various sample stations in the Tyrrhenian Sea.

In general, earlier studies have focused on restricted areas. For instance, Albani and Serandrei Barbero (1982, 1990), Serandrei Barbero et al. (1989) and Albani et al. (1991) worked on recent benthic foraminifera in the Venice Lagoon (Northern Adriatic Sea) and recognized areas characterized by similar hydrographic conditions basing on these faunas. Sgarrella et al. (1983) studied modern benthic foraminifera from the Gulf of Policastro in the southern Tyrrhenian Sea in order to determine the influence of fresh-water discharge on the assemblages. In an important study covering a much wider geographical area, Jorissen (1987, 1988) analysed the distributions of benthic foraminiferal taphocoenoses found in 285 grab samples and piston-core tops from the Adriatic Sea. For the first time, he correlated the distribution and the morphology of these organisms to environmental parameters, such as the input of nutrients and suspended load from Italian rivers (mainly from the Po outflow) and the surface circulation responsible for the transport and distribution of these products to the bottom.

The relatively few studies of modern planktonic foraminifera in the Mediterranean include those of Blanc-Vernet (1969), Cifelli (1974), Thunell (1978), Blanc-Vernet et al. (1979), Vénec-Peyré (1990). Of particular note is the later work of Pujol and Vergnaud-Grazzini (1995) which is the most accurate study so far of the distribution of living planktonic foraminifera along a NW-SE transect across the Mediterranean Sea. Their observations indicated that geographical distributions and living depths are related to regional hydrography and productivity of the Mediterranean basins.

The Last 30 Years of Efforts in the Study of Benthic Foraminifera

In the past 30 years, research in this field has increased greatly, prompted by the need to understand modern foraminiferal distributions in order to interpret marine environmental changes in the historical past. This led to an increased

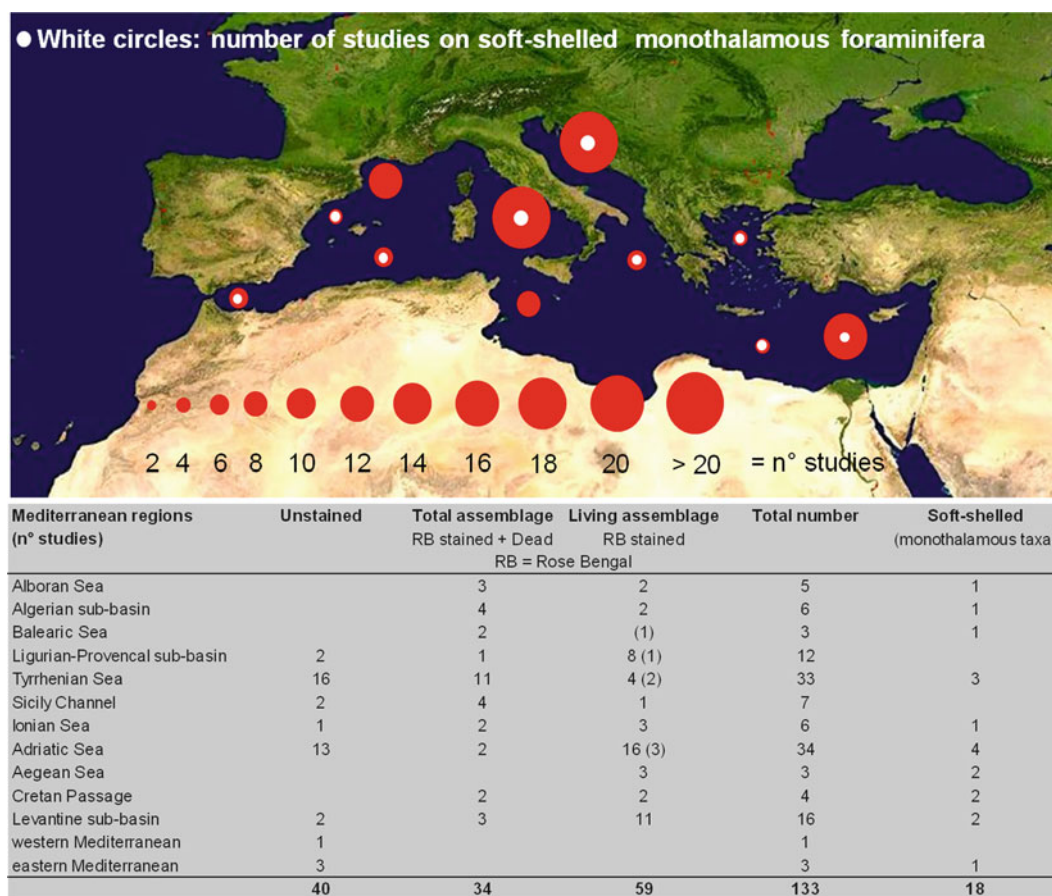


Fig. 13.2 Geographical distribution of total foraminiferal studies in the Mediterranean Sea. The *red circle* diameter is proportional to the number of total foraminiferal studies and the *white circle* indicate the number of

studies on soft-shelled monothalamous taxa. The number between parenthesis in the column of the living assemblage indicates experimental studies where foraminifera are observed alive. *RB* Rose Bengal

emphasis on trying to understand the ecological requirements of modern foraminifera. In addition, benthic foraminifera have emerged as reliable indicators of the state of marine environments, in particular in shallow-water settings (Gooday et al. 2009; Balsamo et al. 2010, 2012; Frontalini and Coccioni 2011). In order to address these aims, different approaches were used, including the study of both unstained assemblages (i.e. the total assemblage comprising live and dead individuals without differentiating them) and living (Rose Bengal stained = RB stained) assemblages (Fig. 13.2).

The question of whether total or living assemblages best reflect the average environmental conditions is extensively debated by researchers (Murray 1982; Bergamin et al. 2003). For instance, Scott and Medioli (1980) assessed the validity of using the total (RB stained and dead) assemblage in ecological studies. They found that the high seasonal variability of the living (RB stained) assemblage may be attributed to seasonal climatic changes rather than changes in the prevailing marine environment. Murray (1982, 2000), however, argued that ecological studies must be based on the living assemblage, analysed over a period of time, in order to determine the relationships between living and dead assemblages.

Alve and Murray (1994) found that, due to post-mortem processes influencing the dead (unstained) assemblage, such as dissolution of calcareous tests or transport, only results based on the living assemblage are reliable. Murray and Bowser (2000) emphasized that the main problem with total assemblages is that data on living assemblages (biocoenoses, not influenced by taphonomic changes) are combined with those on dead assemblages (tanathocoenoses or even taphocoenoses modified by taphonomic processes). In addition, the proportion of live and dead tests is influenced by several factors such as the thickness of sampled sediment layer, temporal variations of standing crop and the sedimentation rate. From this discussion it is clear that living assemblages, although certainly autochthonous, are affected by substantial temporal changes due to the high irregular foraminiferal life cycles and patchily distributed populations. Consequently, only samples collected during different seasons of the year can be considered to reflect the overall environment. On the other hand, total assemblages are affected by post-mortem processes, but they have the advantage that they represent the average environmental conditions during the time span corresponding to the deposition of the sediment

sample. This approach is simpler, more practical and less costly and therefore may be preferred in environments where taphonomic processes are limited and autochthonous/allochthonous specimens can be recognized.

Various authors have used these different approaches to investigate modern Mediterranean benthic foraminiferal faunas during the last 30 years. During the 1980s and 1990s, a number of researchers described the relationships between the distribution of the unstained (live and dead individuals without differentiating them) benthic foraminiferal assemblages and the main environmental variables, i.e. oxygen, temperature, salinity, organic matter and grain size (Table 13.1, Fig. 13.3a). In the Adriatic Sea, Albani and Serandrei Barbero (1982, 1990), Albani et al. (1984, 1991, 1998, 2007, 2010) and Serandrei Barbero et al. (1989, 1999) thoroughly described modern benthic foraminifera on the continental shelf of the northern basin and the lagoon of Venice, interpreting them as indicators of different environmental settings, from intertidal to shallow water. Other studies based on unstained samples were conducted in the Tyrrhenian Sea and the Strait of Sicily. In these areas, where the human impact due to the presence of major ports (Naples and Augusta harbours) and industries (Bagnoli Bay) is high, work on benthic foraminifera has focused principally on possible links between pollution and assemblage characteristics, including changes in density and biodiversity, sensitive species, deformation of the shell (Bergamin et al. 2005; Ferraro and Lirer 2006; Ferraro et al. 2006, 2009; Di Leonardo et al. 2007; Valenti et al. 2008; Romano et al. 2008, 2009a; Carboni et al. 2009).

Other recent studies that use benthic foraminifera for environmental characterization have analysed the total fauna (Rose Bengal stained + dead) (Table 13.1, Fig. 13.3b). The majority of sampling sites are located in the Tyrrhenian Sea where authors anticipated that the presence of heavy metals would drive changes in benthic foraminiferal assemblages and cause test deformations (Bergamin et al. 2009; Cherchi et al. 2009; Romano et al. 2009b; Aloulou et al. 2012; Caruso et al. 2011). This approach was used by Coccioni (2000) in the Adriatic Sea and Samir and El-Din (2001) in the Levantine basin (Fig. 13.3b). Studies based on live plus dead assemblages have also addressed foraminiferal distributions (Donnici and Serandrei Barbero 2002; Buosi et al. 2012). De Rijk et al. (1999, 2000) analysed the distribution of Recent benthic foraminifera along a west–east bathyal and abyssal transect in the Mediterranean and their relation to the organic matter flux to the seafloor. Other papers document the impact of different environmental parameters (physical or chemical) on foraminiferal assemblages. For example, Milker et al. (2009) examined the influence of temperature on the distribution of modern shallow-water faunas, whereas Carboni et al. (2004) and Frezza and Carboni (2009) describe assemblages in the Tyrrhenian Sea influenced by the outflow of the river Ombrone, and Panieri

(2005, 2006b) described the adaptation of benthic foraminifera to extreme environments (i.e. hydrothermal vent).

Finally, ecological studies of live (RB stained) assemblages have focused on their distribution and diversity, as well as their utility in biomonitoring (Table 13.1, Fig. 13.3c). Studies performed either in shallow areas or at deep sites (Fig. 13.4) have ranged from the description of foraminiferal microhabitats within the first 7 cm of sediment at a single shallow site close to the Po outlets (Barmawidjaja et al. 1992) to the spatial micro-distributions in the shallow subtidal zone in the northernmost Adriatic Sea (Hohenegger et al. 1993). Fontanier et al. (2008) compared samples from the Gulf of Lion slope (343–1,987 m) and one site located at 920 m in the Lacaze-Duthier Canyon, while Mojtahid et al. (2009, 2010) and Goineau et al. (2011, 2012) explored environmental control on live benthic foraminifera in a river-dominated shelf setting in their study of the Rhône prodelta (15–100 m). Pancotti (2011) conducted the only existing study of live assemblages in samples from the Eastern to Western Mediterranean. Her data provided new insights into foraminiferal diversity in the Mediterranean deep-sea, in particular, an apparent east-to-west increase in species richness corresponding to the productivity gradient, as well as indicating future research directions regarding factors controlling and threatening deep-sea biodiversity (Danovaro et al. 2010).

A number of authors have addressed the temporal variation (seasonal and/or inter-annual) of foraminiferal faunas, in terms of density and biodiversity, in relation to changes over time in key environmental parameters (i.e. oxygen, grain size, organic matter) (Soetaert et al. 1991; Jorissen et al. 1992; Pranovi and Serandrei Barbero 1994; Donnici et al. 1997; Schmiedl et al. 2000; Jannink 2001; Serandrei Barbero et al. 2003; Duijnsteet et al. 2004; Panieri 2006b; Lampadariou et al. 2009; Sabbatini et al. 2010, 2012; Frontalini et al. 2011). A few papers consider the use of live (RB stained) foraminifera as environmental pollution indicators. Among these, Bergamin et al. (2003), Frontalini and Coccioni (2008), Coccioni et al. (2009), Frontalini et al. (2009, 2010), Buosi et al. (2010) used the FAI index (Foraminiferal Abnormality Index) to detect, on the basis of foraminiferal test morphology, the degree of ecosystem contamination in the central Adriatic and along the Italian coast of the Tyrrhenian Sea. Also of note are the studies of Yanko et al. (1999) describing the response of benthic foraminifera to heavy metal pollution along Mediterranean coast of Israel.

Others authors (e.g. Arieli et al. 2011) evaluated the potential long-term effect of rising sea-surface temperature caused by a thermal pollution from a power station on living benthic foraminifera, while Hyams-Kaphzan et al. (2009) and Elshanawany et al. (2011) explored the effects of anthropogenic eutrophication in the Eastern Mediterranean Sea.

Unfortunately, the numerous foraminiferal studies conducted in the Mediterranean have utilised different

Table 13.1 Methodological features of foraminiferal studies in the Mediterranean Sea listed for Unstained, Total (Rose Bengal stained + dead) and living (Rose Bengal stained) assemblages

Area	Sampling technique	Replicates	Thickness (cm)		Standardization	Staining	Wet vs Dry	Sieve-size fraction (µm)		Soft vs Hard	Author(s)
			Surficial	0–3; 0–4				Unstained	Dry		
Adriatic Sea	n.a.	No	Surficial	0–3; 0–4	No	Unstained	Dry	>125	Hard		Albani and Serandrei Barbero (1982)
Adriatic Sea	Grab sample	No	0–3; 0–4	^a		Unstained	^a	n.a.	^a		Albani and Serandrei Barbero (1990)
Adriatic Sea	Hand-scraping	No	0–1; 1–2	No	No	Unstained	Dry	n.a.	Hard		Albani et al. (1984)
Adriatic Sea	Grab sample	No	0–3; 0–5	No	No	Unstained	Dry	n.a.	Hard		Albani et al. (1991)
Adriatic Sea	Grab sample	No	Surficial	No	No	Unstained	Dry/floatations in CCl ₄	>63	Hard		Albani et al. (1998)
Adriatic Sea	Grab sample	No	0–5; 0–7	No	No	Unstained	Dry	>125	Hard		Albani et al. (2007)
Adriatic Sea	Grab sample	No	0–5; 0–7	No	No	Unstained	Dry/floatations in CCl ₄	>125	Hard		Albani et al. (2010)
Tyrrhenian Sea	Core	No	0–3; 0–5	^a g ⁻¹ Dry sediment		Unstained	Dry	>125	Hard		Bergamin et al. (2005)
Tyrrhenian Sea	Grab sample	No	0–2	No	No	Unstained	Dry	>63	Hard		Carboni et al. (2009)
Adriatic Sea	Core	No	0–40			Unstained	^a	>63	Hard		Chierici et al. (1962)
Tyrrhenian Sea	Box-core	Yes	n.a.	^a g ⁻¹ Dry sediment		Unstained	Dry	>90	Hard		Di Leonardo et al. (2007)
Tyrrhenian Sea	Box-core	No	0–1; 0–3	No	No	Unstained	Dry	>90	Hard		Ferraro and Lirer (2006)
Tyrrhenian Sea	Vibro-core	Yes	0–20	No	No	Unstained	Dry	>125	Hard		Ferraro et al. (2006)
Tyrrhenian Sea	Vibro-core	No	0–20	^a g ⁻¹ Dry sediment		Unstained	Dry	>90	Hard		Ferraro et al. (2009)
Levantine basin	Box-core	^a	^a	^a	^a	Unstained	^a	^a	^a		Hyams-Kaphzan et al. (2008)
Adriatic Sea	Grab sample/ piston core	No	n.a.	n.a.	n.a.	Unstained	Dry	150–595	Hard		Jorissen (1987, 1988)
Tyrrhenian Sea, Sicily Channel	Gravity core	No	0–1	no	no	Unstained	Dry	>63	Hard		Parisi (1981)
Eastern MediterraneanPiston/gravity core Sea		No	^a	^a	^a	Unstained	Dry	>150	Hard		Parker (1958)
Tyrrhenian Sea	Grab sample	No	Surficial	^a g ⁻¹ Dry sediment		Unstained	Dry	>125	Hard		Romano et al. (2008)
Tyrrhenian Sea	Grab sample	No	0–2	^a g ⁻¹ Dry sediment		Unstained	Dry	>63	Hard		Romano et al. (2009b)
Adriatic Sea	Grab sample	No	0–3; 0–4	^a		Unstained	^a	n.a.	^a		Serandrei Barbero et al. (1989)
Adriatic Sea	Grab sample	No	Surficial	No	No	Unstained	Dry	>63	Hard		Serandrei Barbero et al. (1999)
Tyrrhenian Sea	Grab sample	No	0–3; 0–4	No	No	Unstained	Dry	>63	Hard		Valenti et al. (2008)
Strait of Sicily	Grab sample	No	0–1; 0–2	50 cm ³		RB + Dead	Dry	>63	Hard		Aloulou et al. (2012)
Tyrrhenian Sea	Grab sample	No	0–2	^a g ⁻¹ Dry sediment		RB + Dead	Dry	>63	Hard		Bergamin et al. (2009)

(continued)

Table 13.1 (continued)

Area	Sampling technique	Replicates	Thickness (cm)	Standardization	Staining	Wet vs Dry	Sieve-size fraction (μm)	Soft vs Hard	Author(s)
Tyrrhenian Sea	Grab sample	No	0–1	g^{-1} Dry sediment	RB + Dead	Dry	>50	Hard	Buosi et al. (2012)
Tyrrhenian Sea	Grab sample	No	n.a.	g^{-1} Dry sediment	RB + Dead	Dry	>125	Hard	Carboni et al. (2004)
Tyrrhenian Sea	Grab sample	No	0–4	g^{-1} Dry sediment	RB + Dead	Dry	>63	Hard	Caruso et al. (2011)
Tyrrhenian Sea	Hand coring	Yes	0–2	10 cm^3	RB + Dead	Dry/floatation ZnBr_2^a	63–125; >125	Hard	Cherchi et al. (2009)
Adriatic Sea	Grab sample	No	n.a.	^a	RB + Dead	^a	>125	^a	Coccioni (2000)
Mediterranean Sea	Box-core	No	0–2	No	RB + Dead	Dry	>125	Hard	de Rijk et al. (1999)
Mediterranean Sea	Box-core	No	0–2	No	RB + Dead	Dry	>125	Hard	de Rijk et al. (2000)
Adriatic Sea	Grab sample	No	0–7	No	RB + Dead	Dry	>125	Hard	Donnici and Serandrei Barbero (2002)
Tyrrhenian Sea	Grab sample	No	0–5; 0–7	No	RB + Dead	Dry	>125	Hard	Frezza and Carboni (2009)
Western Mediterranean Sea	Grab sample/box core	No	0–1; 0–2	10 cm^3	RB + Dead	Dry	>125	Hard	Milker et al. (2009)
Tyrrhenian Sea	Box-core/gravity core	No	0–1	10 cm^3	RB + Dead	Dry/floatation sodium polytungstate	>63	Hard	Panieri (2005)
Tyrrhenian Sea	Scuba diving	Yes	0–2	10 cm^3	RB + Dead	Dry/floatation sodium polytungstate	>63	Hard; Soft only qualitative	Panieri (2006b)
Tyrrhenian Sea	Grab sample	No	0–2	g^{-1} Dry sediment	RB + Dead	Dry	>63	Hard	Romano et al. (2009a)
Eastern Mediterranean Sea	Grab sample	No	0–1; 0–2	g^{-1} Dry sediment	RB + Dead	Dry	>63; >125 geochemistry	Hard	Samir and El-Din (2001)
Tyrrhenian Sea	Grab sample	No	n.a.	No	RB + Dead	Dry	>106	Hard	Sgarrella et al. (1983)
Levantine basin	Hand-scraping	Yes	surficial	g^{-1} Dry sediment	RB	Dry	63–1000	Hard	Arieli et al. (2011)
Adriatic Sea	Box-core	No	0–2	g^{-1} Dry sediment	RB	Dry	>63	Hard	Barnawidjaja et al. (1992)
Tyrrhenian Sea	Grab sample	No	n.a.	g^{-1} Dry sediment	RB	Dry	>125	Hard	Bergamin et al. (2003)
Aegean Sea	Grab sample	No	0–1	g^{-1} Dry sediment	RB	Dry	>63	Hard	Bergin et al. (2006)
Tyrrhenian Sea	n.a.	No	surficial	g^{-1} Dry sediment	RB	Dry	>63	Hard	Buosi et al. (2010)
Adriatic Sea	Box-core	No	0–10	cm^2	RB	Dry	63–150; >150	Hard	De Stigter (1996)
Adriatic Sea	Grab sample	No	Surficial	200 cm^3	RB	Dry/floatations in CCl_4	>63	Hard	Donnici et al. (1997)
Adriatic Sea	Sediment core	Yes	0–2	no	RB	Wet	>63	Hard	Duijnste et al. (2004)

Eastern Mediterranean Sea	Grab sample	No	0–3	50 cm ³	RB	Dry	>63	Hard	Elshanawany et al. (2011)
Western Mediterranean Sea	Multi-core	Yes	0–10	50 cm ³	RB	Wet	>150	Hard	Fontanier et al. (2008)
Adriatic Sea	Grab sample	No	0–2	50 cm ³	RB	Dry	>63	Hard	Frontalini and Coccioni (2008)
Tyrrhenian Sea	Grab sample	No	n.a.	50 cm ³	RB	Dry	>63	Hard	Frontalini et al. (2009)
Tyrrhenian Sea – Adriatic Sea	Grab sample	No	n.a.	50 cm ³	RB	Dry	>63	Hard	Frontalini et al. (2010)
Adriatic Sea	Grab sample	No	0–5	50 cm ³	RB	Dry	>63	Hard	Frontalini et al. (2011)
Western Mediterranean Sea	Multi-core	No	0–5	100 cm ²	RB	Wet	63–150; >150	Hard	Goineau et al. (2011)
Western Mediterranean Sea	Multi-core	Yes	0–5	100 cm ²	RB	Dry	63–150; >150	Hard	Goineau et al. (2012)
Adriatic Sea	Core	Yes	0–5	90 cm ³	RB	Dry	>63	Hard	Hohenegger et al. (1993)
Levantine basin	Box-core	No	0–10	10 cm ³	RB	Wet	63–2000	Hard	Hyams-Kaphzan et al. (2009)
Levantine basin	Box-core	No	0–10	50 cm ³	RB	Wet	63–150; 150–595	Hard; Soft only qualitative	Jannink (2001)
Adriatic Sea	Box-core	No	n.a.	g ⁻¹ dry sediment	RB	Dry	>63	Hard	Jorissen et al. (1992)
Aegean and Levantine Sea	Multi-core	Yes	0–10	10 cm ²	RB	Wet	>32	Soft+Hard	Lampadariou et al. (2009)
Western Mediterranean Sea	Multi-core	No	0–5	100 cm ²	RB	Wet and dry	63–150; >150	Hard	Mojtahid et al. (2009)
Western Mediterranean Sea	Multi-core	No	0–5	100 cm ²	RB	Wet and dry	>150	Hard	Mojtahid et al. (2010)
Adriatic Sea	Grab sample	Yes	0–2	10 cm ²	RB	Wet	>63	Soft+Hard	Nardelli (2012)
Mediterranean Sea	Box-core	Yes	0–5	10 cm ²	RB	Wet	>63	Soft+Hard	Pancotti (2011)
Adriatic Sea	Scuba diving	No	0–1	no	RB	Wet	>63	Hard	Panieri (2006a)
Adriatic Sea	Grab sample	No	0–3; 0–4	^a	RB	^a	>63	^a	Pranovi and Serandrei Barbero (1994)
Adriatic Sea	Box-core	No	0–2	20 ml	RB	Wet	>63	Soft+Hard	Pucci (2006)
Adriatic Sea	Box-core	No	0–2	10 cm ²	RB	Wet	>63	Soft+Hard	Sabbatini et al. (2010)
Adriatic Sea	Grab sample	Yes	0–1	10 cm ²	RB	Wet	>63	Soft+Hard	Sabbatini et al. (2012)
Western Mediterranean Sea	Multi-core	No	0–10	g ⁻¹ dry sediment	RB	Dry	>125	Hard	Schmiedl et al. (2000)
Adriatic Sea	Grab sample/ box-core	No	0–10	^a	RB	^a	>125	^a	Serandrei Barbero et al. (2003)
Western Mediterranean Sea	Box-core	No	0–20	10 cm ²	RB	Wet/ludox	500; 250; 38	Xenophyophores	Soetaert et al. (1991)

n.a. not available

^aIndicate data not available; informations are referred to Frontalini and Coccioni (2011), Appendix A. Supplementary data. Frontalini and Coccioni (2011)

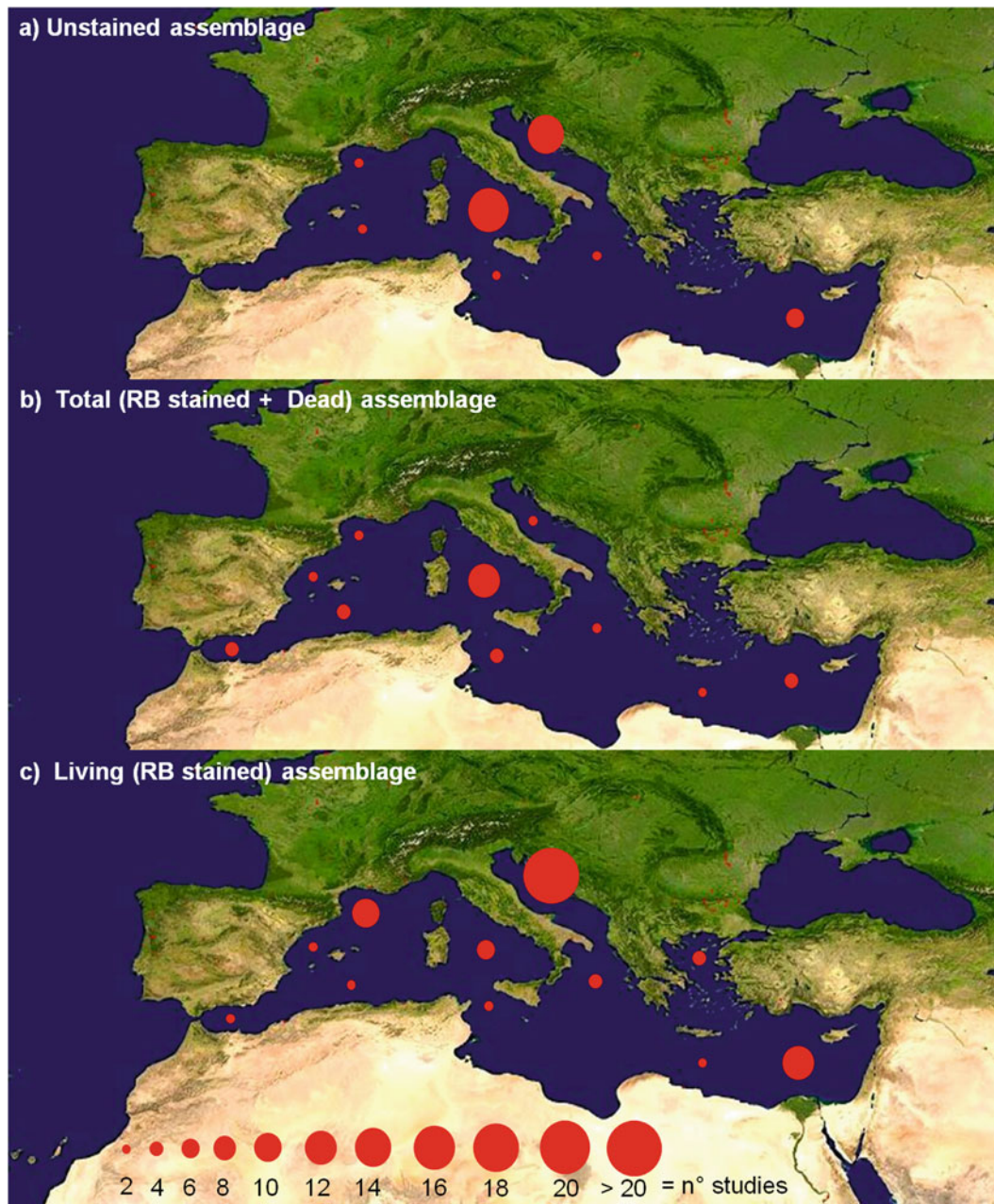


Fig. 13.3 Geographical distribution of total foraminiferal studies in the Mediterranean Sea divided for Unstained (a), Total (Rose Bengal stained + dead) (b) and living (Rose Bengal stained) assemblages (c).

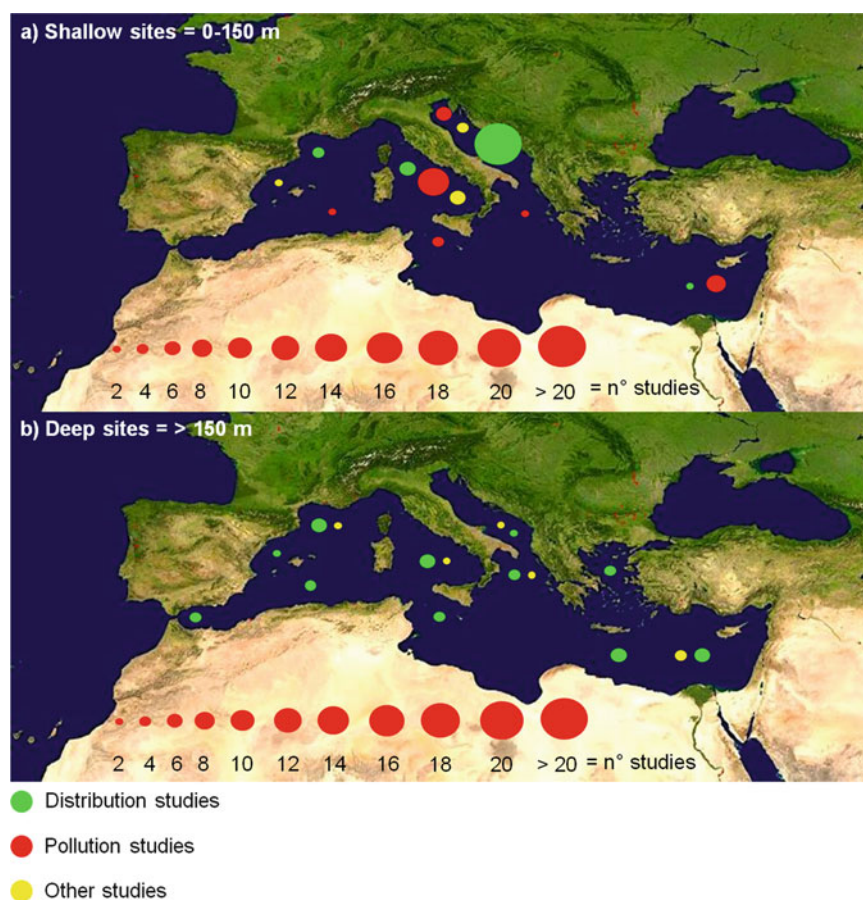
The red circle diameter is proportional to the number of studies on foraminifera. In the living assemblages, experimental studies where foraminifera are observed alive are included

methodologies (Balsamo et al. 2010, 2012; Frontalini and Coccioni 2011). This hampering the comparison of different studies and therefore the possibility to gather consistent data on biodiversity and abundance trends, or on the impact of a particular pollutant, or pollution in general, on the foraminifera. The problems are compounded by differences in staining and sampling methodologies, and the fact that an important part of the foraminiferal fauna is often neglected. In the following paragraph we will examine these two important issues (Table 13.1).

Problems in the Sampling Methodology

A variety of sampling gears has been used to collect material for the study of foraminifera (Murray 1991; Schönfeld 2012; Schönfeld et al. 2012). Earlier studies were based on samples obtained using grabs, gravity cores, or piston cores, which do not retain the surface sediment where living foraminifera are concentrated (Massiotta et al. 1976; Jorissen 1987; Parisi 1981) (Table 13.1). Even some recent investigations have

Fig. 13.4 Bathymetrical distribution of foraminiferal studies in (a) shallow sites (0–150 m) and (b) deep sites (>150 m). Studies typology (coloured circles) are shown: foraminiferal fauna distribution and ecology (green circles), pollution and biomonitoring (red circles) and other studies (yellow circles). The circle diameter is proportional to the number of studies on foraminifera. In the last category, we included papers on taxonomy, time series analyses, geochemistry and experimental laboratory



been based on samples taken using grabs, due to problems in sampling in harbour areas and the unavailability of a box corer or multi-corer. In some cases the first few centimetres of sediment are removed and in others, subsamples are taken using plexiglas tubes (Donnici et al. 1997; Bergamin et al. 2003, 2009; Cherchi et al. 2009; Coccioni et al. 2009; Frontalini et al. 2010; Aloulou et al. 2012; Caruso et al. 2011; Elshanawany et al. 2011) (Table 13.1). However, most modern studies have employed box cores (de Stigter 1996; Soetaert et al. 1991; Barmawidjaja et al. 1992; Jorissen et al. 1992; de Rijk et al. 1999, 2000; Jannink 2001; Serandrei Barbero et al. 2003; Ferraro et al. 2006; Di Leonardo et al. 2007; Hyams-Kaphzan et al. 2009) (Table 13.1) or hydraulically-damped multiple corers (Schmiedl et al. 2000; Fontanier et al. 2008; Mojtahid et al. 2009, 2010; Goineau et al. 2011, 2012).

There is also a considerable variety in the subsampling procedure. Sample from grabs or box corers are often limited to the first few centimetres of sediment (0–1, 0–2 cm up to 0–5 and 0–7 cm) in both distributional and pollution studies. Several authors studied only the top 2 cm of sediment (Albani et al. 1984; Barmawidjaja et al. 1992; Panieri 2005, 2006a, b; Bergin et al. 2006; Romano et al. 2008, 2009a, b; Bergamin et al. 2009; Carboni et al. 2009; Sabbatini et al. 2010;

Aloulou et al. 2012; Arieli et al. 2011) (Table 13.1). Others consider the first 3, 4, 5 or 7 cm of sediment (Frontalini et al. 2011) or even 20 cm (Ferraro et al. 2006, 2009) as one unit, thereby mixing the different levels without considering the living depth of individual species. Other authors, however, have addressed the important issue of the vertical distribution of foraminiferal species in the sediment. Generally, the first 2 cm are sub-sampled every 0.5 cm and levels below 2 cm are sub-sampled every cm. Only a few authors have examined sediment layers down to 10 cm depth (de Stigter 1996; Schmiedl et al. 2000; Jannink 2001; Fontanier et al. 2008; Hyams-Kaphzan et al. 2009). The studies of Hohenegger et al. (1993), Pancotti (2011), Pucci et al. (2009), Mojtahid et al. (2009, 2010) and Goineau et al. (2011, 2012) were limited to the first 5 cm.

Another important problem concerns sample replication, which provides statistically useful information on the small-scale density and biodiversity variability of faunal assemblages in terms of density and diversity. Although this is standard practice in metazoan meiofaunal and macrofaunal research, the use of replicated samples is still fairly rare in studies of foraminiferal distributions (Hohenegger et al. 1993; Duijnsteet et al. 2004; Fontanier et al. 2008; Lampadariou et al. 2009; Pancotti 2011;

Goineau et al. 2012), as well as in biomonitoring studies (Ferraro et al. 2006; Panieri 2006b; di Leonardo et al. 2007; Cherchi et al. 2009; Arieli et al. 2011). Sieve mesh size (Table 13.1) is another crucial variable that strongly influences assemblage composition. In the Mediterranean the following meshes have been used: 32, 38, 63, 90, 125, 150, 595 and 1,000 μm . A final point to consider is that in many geological-oriented studies, specimens are not identified to species level but grouped together as genera or morpho-group, making impossible to analyse the full extent of the assemblage diversity.

The Hard vs. Soft Shelled Foraminifera Issue

Few authors have included soft-shelled monothalamous species in their study of Mediterranean foraminifera: Soetaert et al. (1991) in the Gulf of Lions; Moodley et al. (1997), Pucci (2006), Pancotti (2011), Nardelli (2012) and Sabbatini et al. (2010, 2012) in the Adriatic Sea; Hatziyanni (1999), Lampadariou et al. (2009) in the Eastern Mediterranean Sea. Only Pucci (2006), Pancotti (2011), Nardelli (2012) and Sabbatini et al. (2010, 2012) have studied this rarely-studied component in terms of abundance and species diversity and in relation to the environmental setting (Fig. 13.5). Instead, some studies (Bizon and Bizon 1983; de Rijk et al. 2000; Fontanier et al. 2008) only report counts for selected species of soft-shelled monothalamous foraminifera. All other authors have confined their investigations to hard-shelled species and therefore have not encompassed the full range of foraminiferal biodiversity in the Mediterranean (Fig. 13.6). As reported in the previous paragraphs, early studies did not consider treatment with Rose Bengal and therefore yielded total assemblages, that is, a mixture of live and dead tests. Other studies instead considered foraminiferal specimens stained with Rose Bengal to distinguish between alive and dead organisms at the time of collection. In addition, most analyses are based on the dry picking of individuals, but in some cases, (Table 13.1; e.g., Jannink 2001; Duijnsteet et al. 2004; Panieri 2006a; Hyams-Kaphzan et al. 2009) the foraminifera were picked out from sample residues in water. This technique instead allows the evaluation of all the foraminifera, including the soft-shelled monothalamous forms with delicate organic or agglutinated walls that shrink and disappear when dried.

Soft-shelled monothalamous foraminifera are often an important component of benthic fauna in both shallow and deep-water settings (Gooday 2002) and ignoring them would lead to underestimating the real variability of foraminiferal abundance and diversity. In the deep sediments of the Mediterranean Sea the soft-shelled monothalamous foraminifera account for up to almost 30 % of the entire assemblage both in the western and eastern basin (Pancotti 2011). In the

shallow northern Adriatic Sea, this component ranges from 20 to 60 % of the living (RB stained) assemblage (Sabbatini et al. 2010); it can reach even 80 % of relative abundance in shallow waters of the central Adriatic (Nardelli 2012).

Unfortunately, soft-shelled monothalamous foraminifera are time consuming to extract, and largely undescribed. Moreover, they have little fossilization potential and therefore they are often ignored because they are not useful in paleoecological and geological studies. Also in comparison to the many workers on foraminifera in general, there are few specialists on soft-shelled monothalamous foraminifera.

Nevertheless, there are some scattered, early records of soft-walled allogromiids from the Mediterranean Sea. Notable among these is the paper by Grüber (1884), who described several species from coastal waters of the Bay of Naples. These included *Craterina mollis*, later established as the type species of the genus *Allogromia* by Rhumbler (1904). Other examples are from Huxley (1910) who reports *Shepherdella taeniformis* from the Bay of Naples, and earlier Dujardin (1835) who described the gromiid *Gromia oviformis* (a close relative of the foraminifera) based on material from the NW Mediterranean coast and elsewhere. In more recent years, there have been few species-level studies of soft-shelled, monothalamous foraminifera from the Mediterranean. They include Nyholm's (1951) description of an allogromiid-like protist, *Marenda nematodes*, from the Catalan coast. He distinguished the new species from free-living nematodes, which it closely resembles, by its slow movements when irritated by the light of the microscope.

Comprehensive studies of "entire" foraminiferal assemblages (i.e. including both soft and hard-shelled forms) are a recent development (Pucci 2006; Sabbatini et al. 2010, 2012; Pancotti 2011; Nardelli 2012). Pucci (2006) studied the biodiversity of benthic foraminifera along a shallow transect from the Po outflow to the central Adriatic Sea. Based on the results obtained in the period between May and June 2004, the coast between Goro (near the mouth of the river Po) and Cattolica (Central Adriatic coast) was divided into three areas with different foraminiferal assemblages linked to physical-chemical parameters (chlorophyll, oxygen, temperature and turbidity) and specific grain sizes. Pucci (2006) also reported qualitative data on soft-shelled monothalamous taxa, indicating that they were rather uncommon (6 % of all the stained foraminifera in the samples). However, they were distributed across all 14 transects along the Adriatic area from Cattolica to Goro, and were most abundant in the northern transects in front of the Comacchio region. The relative abundance of soft-shelled monothalamous foraminifera reached 65 % at one station located near the coast at 5 m water depth off Comacchio. Most of the soft-shelled monothalamous species were undescribed and there was a relatively high abundance of small, thin wall specimens.

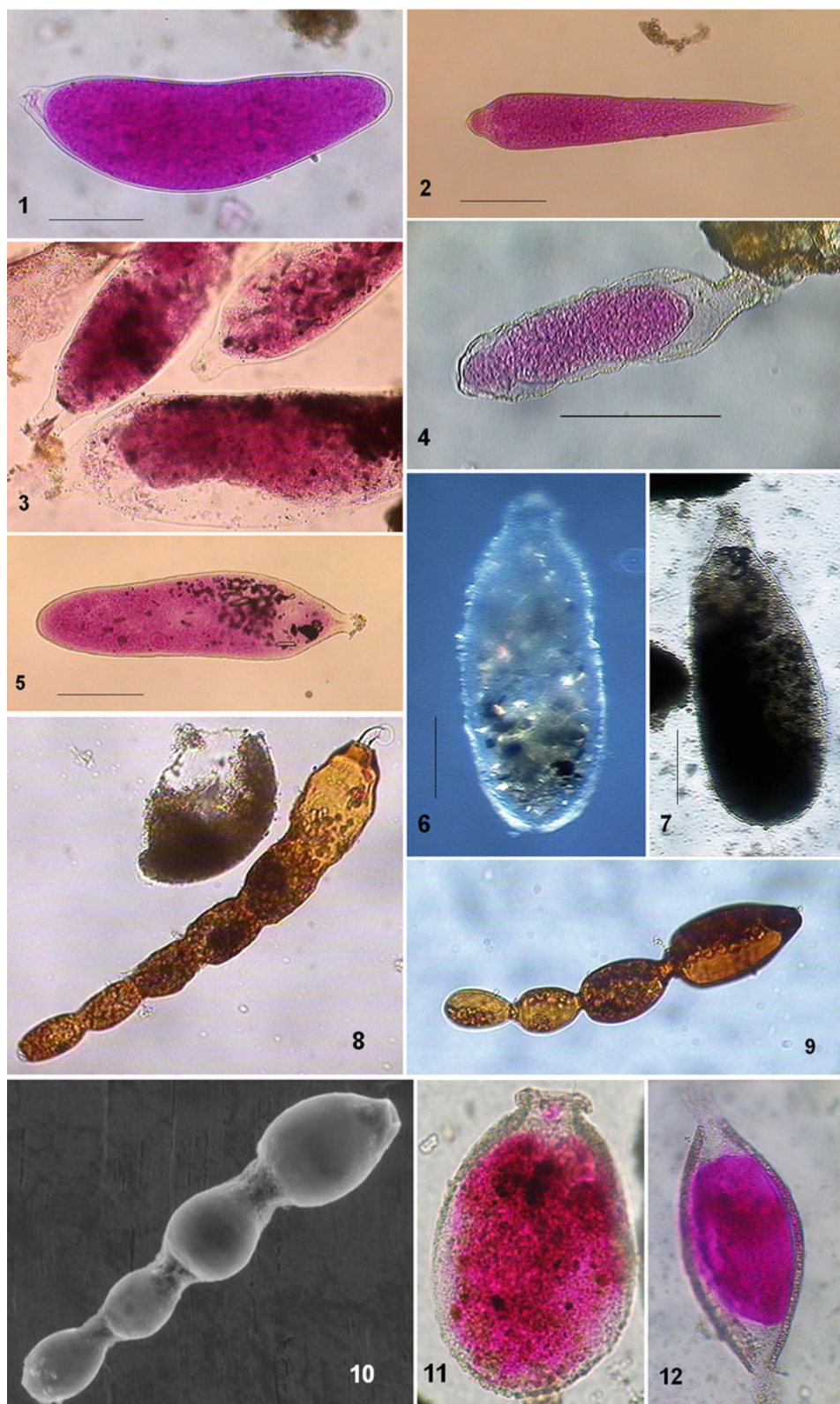


Fig. 13.5 Foraminifera from the Mediterranean Sea: monothalamous taxa with an organic test; unless otherwise stated, all are Rose Bengal stained specimen viewed under the optical microscope: **1.** *Goodayia* sp., magnification 400X. **2.** *Micrometula* sp., magnification 200X. **3.** *Gloiogullmia* sp., magnification 200X. **4.** *Vellaria* sp., magnification 400X. **5.** *Psammophaga*-like type 2, magnification 200X. **6.** *Psammophaga*-like type 1, live specimen, magnification 200X. **7.** *Psammophaga*-like type 1 (different specimen from 6), phase contrast image of a live specimen, magnification 200X. Specimens 1, 2, 3 and 5 are collected from the northern Adriatic Sea, water depth between 8 and 20 m, while

specimens 4, 6, 7 are from the central Adriatic Sea, water depth between 10 and 15 m. **8.** *Nodellum membranaceum*, magnification 200X. **9.** *Resigella* sp., magnification 400X. **10.** *Resigella* sp. (same specimen as in 9), Scanning Electron Micrograph, magnification 600X. **11.** *Saccamminid* sp.8, magnification 400X. **12.** *Vanhoeffenella gaussi*, magnification 400X. Specimens 8 and 9 were collected from the western Mediterranean Sea, water depth between ~2,500–2,600 m, specimen 10 is from the eastern Mediterranean Sea, water depth ~4,300 m and specimen 11 is from the central Mediterranean Sea, water depth ~3,900 m. Scale bar= 100 µm; if different, the scale is indicated in the figure

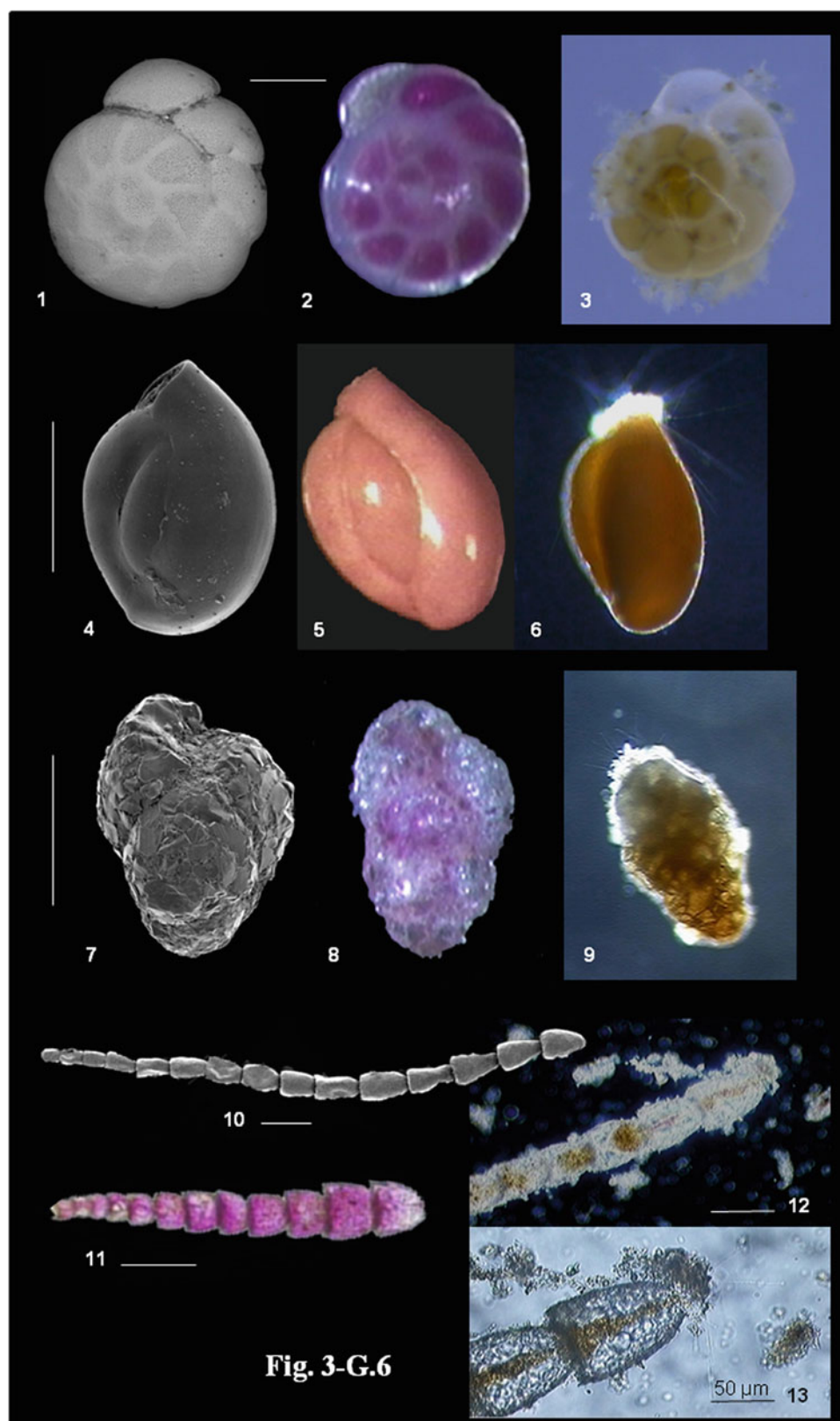


Fig. 13.6 Foraminifera from the Mediterranean Sea: hard-shelled polythalamous taxa with calcareous (perforated or imperforated) and agglutinated tests. Images are of dead (unstained) specimens photographed by Scanning Electron Microscopy, 'living' specimens stained with Rose Bengal and live specimens with pseudopods photographed

under a light microscope with either reflected or transmitted light. All specimens are from the central Adriatic Sea, water depth 10–15 m. **1–3.** *Ammonia parkinsoniana* (calcareous species with perforated test), three individuals of this species are illustrated; **1.** Scanning Electron Micrograph. **2.** Rose Bengal stained specimen, reflected light.

Sabbatini et al. (2010) investigated the foraminiferal faunas, including the soft-shelled monothalamous component, along a shallow bathymetric transect in the Gulf of Trieste. The distribution of foraminiferal species was a function of differences in water depth, granulometry and distance from fresh water sources and other chemical and physical parameters (temperature, salinity and dissolved oxygen). The absolute and relative abundance of soft-shelled monothalamous foraminifera decreased with distance from the coast (and the nutrient source, the Isonzo River). All the soft-shelled monothalamous taxa found were new for the North Adriatic waters, undescribed at the species level and, in most cases, even at the genus level. Similar taxa are also abundant in deep waters. A regional-scale study extending from the western to the eastern part of the deep Mediterranean basin (Pancotti 2011) revealed that soft-shelled monothalamous foraminifera, the vast majority of them undescribed, represent at least 50 % of the assemblage at depths >1,500 m.

Benthic foraminifera make an important contribution to meiofaunal biomass. In some areas (the Algerian-Provençal and the Levantine basins), their biomass is comparable to that of the metazoan meiofauna. Sabbatini et al. (2012) analysed relationships between foraminiferal communities and trophic status in coastal sediments, revealing that temporal (seasonal) variability in the quantity and composition of the food sources is responsible of the variability of foraminiferal assemblages. These authors also suggested that soft-shelled monothalamous foraminifera (allogromiids *sensu lato*) respond to the nutritional quality of sedimentary organic matter rather than to its quantity. Nardelli (2012) described the occurrence of soft-shelled monothalamous foraminifera in a shallow water hydrocarbon seepage from the central Adriatic Sea; the soft-shelled component is particularly dominant (80 % of the entire foraminiferal assemblages) at the proximal station of the hydrocarbon seep influenced by the presence of high concentration of volatile aliphatic compounds.

The studies reviewed above emphasize the importance of soft-shelled monothalamous foraminifera and their potential in biomonitoring studies even if they cannot provide information on past ecosystems because they do not fossilize. The soft-shelled taxa must be taken into account in order to achieve a comprehensive taxonomic and ecological overview of foraminiferal assemblages. Their study can add information of importance in biomonitoring studies, particularly in shallow-water ecosystems where they can account for >50 % of living

foraminifera. Moreover, ecological studies of some key “allogromiid” species in coastal environments could lead to the recognition of sensitive or tolerant species with the potential to be used as bioindicators in the same way as hard-shelled foraminifera.

The Last Frontier in the Study of Foraminifera

The last frontier in the study of benthic foraminifera is the experimental approach. Laboratory experiments make it possible to evaluate foraminiferal responses to changes in one or more chemical-physical parameters under controlled conditions, either at the level of the whole fauna (in micro- or mesocosms) or of one or a few selected species (in culture). The results obtained in the laboratory could represent a model, albeit simplified, of ecosystem functioning, and can be tested *in situ*. Duijnste (2001) conducted laboratory experiments to explore how marine snow events (causing anoxia) influenced foraminiferal growth, reproduction and survival. Comparison of community structure in stressed situations and less stressed conditions can provide information on how the different species will respond to oxygen stress. This is very important, because oxygen availability is often considered to be the most important variable determining the structure of benthic communities in environments with high nutrient loads, as in the Adriatic Sea. Ernst (2002) examined this issue further in microcosm experiments aimed at assessing the separate effect of the oxygen concentration and organic flux on benthic foraminiferal assemblages.

In the Adriatic Sea, Pucci et al. (2009) conducted mesocosm experiment to evaluate the survival of benthic foraminifera under hypoxic conditions, a potential source of stress, especially in eutrophic and shallow environments subjected to pollution from industrial activity. In anoxic sediments, the upward migration of foraminiferal species could be caused by decreasing oxygen concentrations in deeper sediment layers but also by changes in the distribution and availability of trophic resources at different sediment levels. In this context, Heinz et al. (2001) described the response of benthic foraminifera from the Gulf of Taranto (Ionian Sea) and Gulf of Lions (Ligurian-Provençal sub-basin) to simulate phytoplankton pulses under laboratory conditions.

Fig. 13.6 (continued) 3. Live specimen, transmitted light. 4–6. *Triloculina rotunda* (calcareous species with imperforated test), three individuals are illustrated; 4. Scanning Electron Micrograph. 5. Rose Bengal stained specimen, reflected light. 6. Live specimen with pseudopods, phase contrast, length 470 µm, magnification 100X. 7–9. *Eggerella scabra* (species with agglutinated test), three individuals are illustrated; 7. Scanning Electron Micrograph. 8. Rose Bengal stained

specimen, reflected light. 9. Live specimen with pseudopods, phase contrast, magnification 100X. 10–13. *Leptohalysis scottii* (species with agglutinated test); 10. Scanning Electron Micrograph. 11. Rose Bengal stained specimen, transmitted light. 12. Phase contrast image of live specimen. 13. Phase contrast image of live specimen; detail of the aperture and pseudopods (same specimen described in 12). Scale bar = 100 µm; if different, the scale is indicated in the figure

The use of benthic foraminiferal assemblages for the assessment of the quality of marine ecosystems has grown recently because of the high potential and of these organisms as monitoring tools (Schönfeld 2012; Schönfeld et al. 2012). Foraminifera respond rapidly to environmental changes, are relatively easy and cheap to sample and have an excellent fossil record, which can provide some information about the pre-impact conditions of the environment under scrutiny. However, many aspects of their biology remain far from clear, yet. Unlike other taxa already used for biomonitoring and ecotoxicological purposes, little is known in detail about how different kinds of impact affect their ecology and biology, including growth, death and reproduction rates, mechanisms of defence, intra- and inter-specific relationships. Moreover, the effects of chemical pollution on the biomineralization processes of calcareous species are poorly understood. To explore some of these issues through experimental studies, Nardelli (2012) performed a series of experiments on a miliolid species (*Triloculina rotunda*) aiming to investigate the effects of zinc contamination on its growth, survival, reproduction and cellular ultrastructure. The experimental species proved to be highly tolerant to zinc, in terms of survival (<50 % of deaths until 10 mg/l of zinc). This is probably due to its ability of this species to bioaccumulate the metal, as evidenced by ultrastructural observations at transmission microscopy (TEM). On the other hand, effects on growth rates (stop or delay of growth) were already observed at a zinc concentration of 0.1 mg/l and they seem to influence metal incorporations rates into the shell. In fact at the zinc concentration of 0.1 mg/l corresponded to a decrease of zinc incorporation rates into calcite, possibly as a consequence of cellular disease. The study also demonstrated that zinc, by itself, is not able to cause test deformations, as previously hypothesized by several authors (e.g. Sharifi et al. 1991; Samir and El-Din 2001; Romano et al. 2008; Madkour and Ali 2009). The work of Nardelli (2012), in which the cytology, biogeochemistry, and ecology of foraminiferal species were examined under controlled conditions, offers a promising approach to improving our knowledge of aspects of foraminiferal biology that are beyond the scope of environmental studies. Unfortunately, a considerable research effort is still required to further develop the culturing protocols necessary to improve this kind of experiments.

Concluding Remarks

The aim of this chapter has been to introduce the main issues in the study of foraminifera in the Mediterranean Sea and the state-of-the-art developments in the study of these organisms. The study of these protists has huge potential implications and benefits. They are good indicators of global change and are also promising indicators of the environmental health of

marine ecosystems. Nevertheless, much remains to be learnt about foraminiferal ecology. We stress here that the study of the ecology of foraminifera has been often hampered to date by inconsistent methodologies which have yielded an equally inconsistent body of data that cannot be easily integrated to produce an overall synthesis of community parameters. In the future, researchers will need to focus on specific topics and apply similar methodologies to improve our understanding of the role of foraminifera in the functioning of both present and past Mediterranean Sea ecosystems.

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