Chapter 15
Echinoderms of the Canary Islands, Spain

José Carlos Hernández, Sabrina Clemente, Fernando Tuya, Angel Pérez-Ruzafa, Carlos Sangil, Leopoldo Moro-Abad and Juan José Bacallado-Aránega

J. C. Hernández (✉) · S. Clemente
Departamento de Biología Animal (Ciencias Marinas), Universidad
de La Laguna, Biodiversidad, Ecología Marina y Conservación,
c/Astrofísico Francisco Sánchez sn, La Laguna, 38206 , Tenerife, Canary Islands, Spain
e-mail: jocarher@ull.es

S. Clemente
e-mail: msclemen@ull.es

F. Tuya
Departamento de Biología, Universidad de Las Palmas de Gran Canaria,
Las Palmas de Gran Canaria, Campus Tafira s/n, Las Palmas de G.C.,
Canary Islands 35017, Spain

A. Pérez-Ruzafa
Departamento de Ecología e Hidrología, Universidad de Murcia, Murcia, Spain

C. Sangil
Departamento de Ecología e Hidrología, Universidad de La Laguna,
Biodiversidad, Ecología Marina y Conservación, c/Astrofísico Francisco Sánchez sn,
La Laguna, 38206 , Tenerife, Canary Islands, Spain

L. Moro-Abad
Servicio de Biodiversidad del Gobierno de Canarias, Santa Cruz de Tenerife,
Canary Islands, Spain

J. J. Bacallado-Aránega
Museo de Ciencias Naturales de Tenerife, c/Fuente Morales s/n, 38004,
Santa Cruz de Tenerife (Canarias), Canary Islands, Spain

15.1 Introduction

15.1.1 Geographical and Geological Context of the Canary Islands

The Canary Islands are located in the Northeast Atlantic, between 27°–29° N and 14°–18° W. The Archipelago consists of seven major islands, four smaller islets and numerous rocky outcrops (Table 15.1, Fig. 15.1). The islands are arranged longitudinally along 450 km. Fuerteventura Island is only 90 km from the African continent, La Palma is almost 400 km from it (Fernández-Palacios and Martín Esquivel 2001a). The islands have a land surface area of 7,490 km² and 1,501 km of coastline. The land surface and length of coastline vary in the different islands; Tenerife is the largest in area and length of coastline (2,034 km², 336 km), while El Hierro has the smallest surface (269 km²) and La Gomera the shortest length of coastline (97 km).

From a geological point of view, the Canary Islands belong to the group of "oceanic islands", they emerge from the ocean floor and have their own structures (insular edifice) completely independent of the continents. In fact, the Canary Islands, except for Lanzarote and Fuerteventura that share the same insular edifice, had independent origins from the others. The size of the islands'edifice is especially relevant since over 80 % of most islands is under water. On average, insular edifices rise from a depth of 3,500 m. The depth is greater than 4,000 m for La Palma and El Hierro (Carracedo 1988; Carracedo et al. 2001).

The origin of the islands dates back to about 20 million years, but there are also important variations in age between islands (Table 15.1). In fact, while in some islands the eruptive periods have ceased several million years ago, in others it has continued up to the present, as indicated by the large number of historical eruptions (<500–600 years old). A good example of this volcanic activity is the recent eruption off El Hierro Island that started in October 2011. The difference in the ages between islands has important implications for the substrate morphology and topography, both inland and underwater, since erosion and remodeling of insular edifices are higher in older islands (Carracedo et al. 2001).

The abyssal plain between the islands is dotted by a large number of submarine mountains and volcanoes. Most rise only a few hundred meters above the ocean floor, but there are two mountains, the "Banco de La Conception" located north of Lanzarote and the "Banco de Amanay" southwest of Fuerteventura, whose summit is less than 100 m deep. In the past, when sea level was lower, these mountains were above sea level and were true islands (Fernández-Palacios 2004). The current submarine volcanism is now considered more important than terrestrial activity, since recent seismic studies and dating of lava flows indicate the presence of active submarine volcanoes in the western region of the archipelago (Carracedo 2001).

Due to the volcanic nature of the islands, their edifices have a significant slope, thus the island platforms (shallow bottoms of gentle slope located between 0 and 100 m depth) are limited in area compared to the land surface (Mitchell 1998; Masson et al. 2002). The extension of the island platforms largely depends on the

Table 15.1 Geographic data of the Canarian Arquipelago, including islets (*). Source: Instituto Geográfico Nacional, Ministerio de Fomento (http://www.ign.es), Carracedo et al. (2001)

Island	Area (km2)	Coastal perimeter (km)	Age (mill. years)
Lanzarote*	885	237	15,5
Fuerteventura*	1.664	310	20,5
Gran Canaria	1.560	252	14,5
Tenerife	2.034	336	7,5
La Gomera	370	97	12
La Palma	708	162	1,5
El Hierro	269	107	0,8

geological age of the islands and on the physicochemical characteristics of erupted materials. The older islands (Fuerteventura, Lanzarote, Gran Canaria, La Gomera) have been exposed longer to the action of erosive agents (waves, wind, runoff) and therefore they have a wider platform than the younger islands (Tenerife, La Palma, El Hierro) (Mitchell et al. 2003). In the case of El Hierro, the youngest island, the edifice has hardly been remodeled and the insular platform is very small or non-existent (Fig. 15.1b). Within each island, the extent of the platforms may differ. They usually show greater development in the northern faces of the islands, which are areas more highly exposed to erosive agents (Mitchell et al. 2003).

Along with erosion and the creation of offshore platforms, other underwater structures and events have been recognized, such as rifts and massive landslides (Urgeles et al. 1999; Masson et al. 2002; Mitchell et al. 2002). Rifts are the growth axes of the islands that constitute their structural basis since they concentrate the greatest amount of volcanic activity. Landslides are sudden and intense events that generate large avalanches, caused by the gravitational effect due to the instability of the insular edifice or by volcanic eruptions. Landslides detected in the archipelago can extend into the ocean for over 100 km and constitute a volume of more than 100 km^3 (Watts and Masson 1995). These are not strange phenomena in oceanic islands, or in the Canary Islands, and they represent typical stages of consolidation and settlement processes of insular edifices (Gee et al. 2001a, 2001b; Mitchell et al. 2002).

The morphology of the coastline and the continental shelf is highly variable throughout the Canarian Archipelago and even in each island. However, several shapes or substrates are more frequent than others, in relation to the geologic age and its interaction with environmental factors (waves, currents, wind, etc.). The coastline on the older islands has been heavily modified. It is homogeneous in shape and hardly scalloped, representing the typical shape of a backward-stepping coast. Beaches of organic origin are abundant, but cliffs and cobble beaches are also frequent. Intertidal platforms, typically of small amplitude, show greater development in the eastern islands. In contrast, in younger western islands where the processes of coastal erosion coexist with volcanism, a more complex littoral, richer in shapes, is found. The coastline is fringed with numerous points and rock
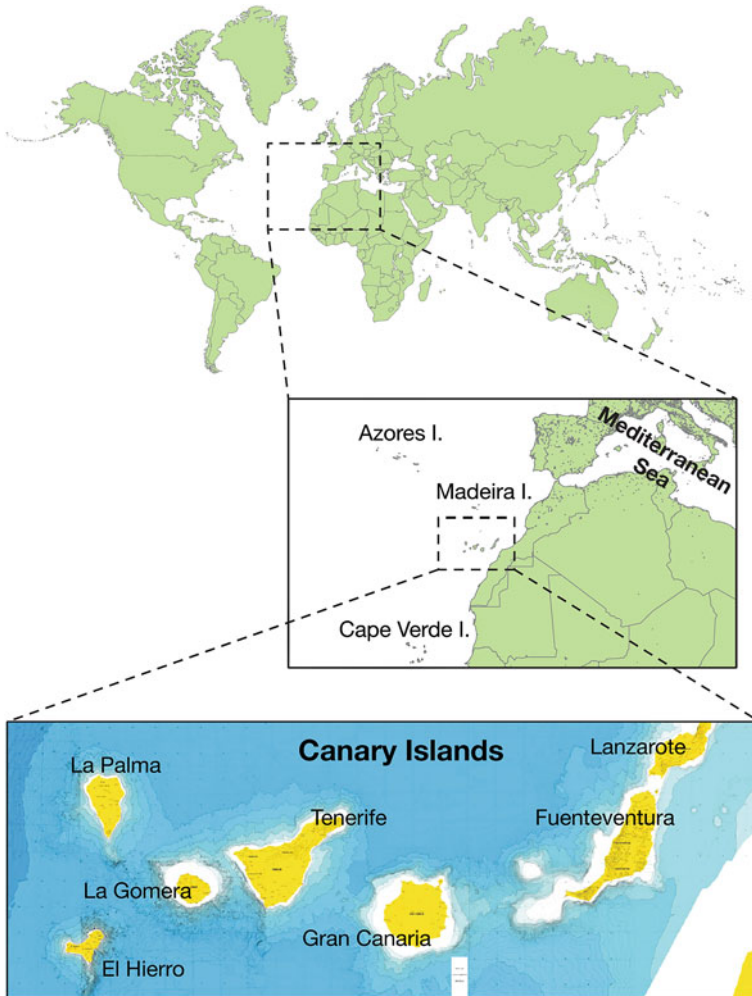
Fig. 15.1 Geographical position and bathimetric map of the Canarian Arquipelago. Island platforms between 0–100 m depth are in *white*. *Source* Estudio Hidrográfico y Oceanográfico de la Zona Económica Exclusiva de Canarias (ZEE-03), Ministerio de Defensa del Gobierno de España

ledges, as well as small shoals, but cliffs are the dominant forms. Beaches are scarce, smaller, and mostly of volcanic origin (Yanes 1990).

In the submerged platforms sandy bottoms dominate, a pattern that increases with depth because the sedimentation is favored by the reduction of hydrodynamics with depth. On the other hand, the percentage of surface occupied by sandy bottoms differs in each island. In older islands sedimentation seems to be favored by the low slope. The heterogeneity (roughness) of the bottoms is particularly high in younger islands, where the steeper slope of their bottoms along with the presence of submarine lava flows creates highly complex environments (Yanes 1990).

15.1.2 Oceanography

From an oceanographic point of view, the Canary Islands are a region of great interest due to the interaction of different phenomena: the upwelling off the African coast, the cold Canary Current, waves and trade winds. The combination of these phenomena creates a complex mosaic of environments throughout the archipelago, with peculiarities in the physical–chemical conditions of its waters. These processes cool the waters of the archipelago that would otherwise have higher temperatures in relation to the latitude (Brito et al. 1984; Aguilera et al. 1994; Fernández-Palacios and Martín-Esquivel 2001a; Fernández-Palacios et al. 2001b). The waters of the archipelago are situated on the eastern limit of the North Atlantic subtropical gyre, occupying an intermediate position between the rich cold upwelling waters of the northwest African coast and the warm and oligo-trophic waters of the open ocean, giving rise to the so-called Transitional Coastal Zone (Braun and Molina 1988; Barton et al. 1998; Barton and Arístegui 2004).

The surface seawater temperature ranges from minimum values of 17–19 °C in April-March to maximum values of around 23–25 °C in September–October. This surface temperature regime is slightly cooler than expected at the islands' latitude in the Atlantic Ocean. This is due to the cold Canary Current and the upwelling off the African coast (Braun and Molina 1988; Molina et al. 1996; Hernández-Guerra and Nykjaer 1997; Tejera et al. 2002; Marrero-Díaz et al. 2006).

The upwelling off the nearby African coast has its origin in the action of trade winds from the northeast over the northwestern coasts of Africa. This causes, following Ekman's theory (Ekman1905), the emergence of deep waters perpendicular to the direction of the winds and towards the archipelago. Upwelled seawater is colder, lower in salinity and richer in nutrients compared to surface water. The incidence of this phenomenon over the archipelago has an important spatial and temporal variation. The eastern islands, the closest to it up-welling, are more affected by this process. Its influence on central and western islands is less and mainly due to the incidence of the so-called upwelling filaments. Temporally, upwelling is more regular in those months when the trade winds are more intense and constant (May–August) (Braun and Molina 1988; Nykjaer and Van Camp 1994; Hernández-Guerra and Nykjaer 1997; Tejera et al. 2002; Barton and Arístegui 2004).

The cold Canary Current, which flows NNE–SSW, is a branch of the Gulf Current, a cyclonic system of currents that carries warm waters from the Caribbean Sea to the northeast Atlantic Ocean. As it crosses the Bay of Biscay, this current begins to cool, becoming a cold current when it reaches the Canaries. The average speed of this current is 0.1–0.2 ms^{-1}, but undergoes major seasonal changes reaching minimum values of 0.025 ms^{-1} in summer. Each island acts as a barrier during the flow of the current throughout the archipelago. This causes changes in speed and creates mesoscale phenomena such as cyclonic and anticyclonic eddies that produce sinking and upwelling events of small amounts of waters, and down-stream warm wakes in the south and southwest regions of some islands (Braun and Molina 1988; Arístegui et al. 1997; Tejera et al. 2002; Barton and Arístegui 2004).
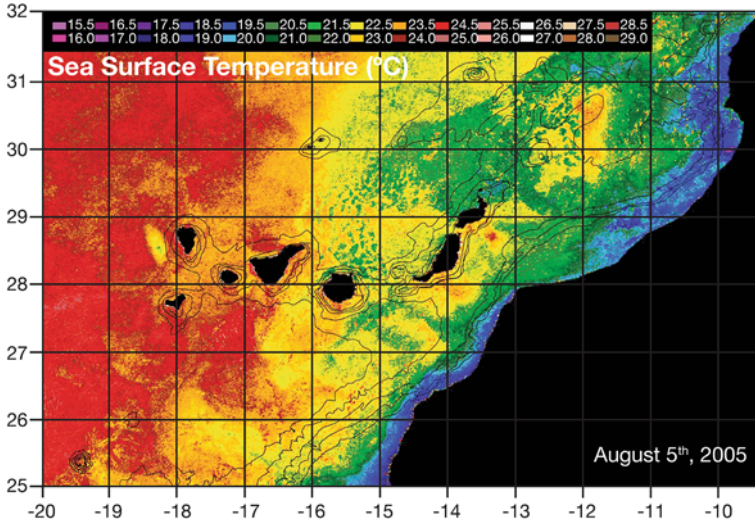
Fig. 15.2 Sea surface temperatura (SST) map of the Canarian Arquipelago and surrounding area. *Source* Dr. Antonio García Ramos, Departamento de Biología de la ULPGC

The different interactions of upwelling and, to a lesser extent, of the cold current of the Canary Islands along the archipelago creates a gradient in temperature (≈ 2 °C), salinity, nutrients and primary production between the eastern and western islands (Fig. 15.2). In this sense, the waters off the eastern islands have more affinity to the waters of the temperate regions, while those off the western islands are more similar to the waters of the tropics (Braun and Molina 1988; Barton et al. 1998; Davenport et al. 2002; Barton and Arístegui 2004).

The open nature of the coasts of the Canary Islands results in a great proportion of the littoral being exposed or semi-exposed to wave action. Bays and coves protected from the waves are much more localized along the islands and are a small part of the coast. The waves that affect the archipelago consist of two substantially different types: wind waves and swells. Wind waves are dominant over the swells. Wind waves, from the NNE and NE, have a mean speed of 18–22 kmh^{-1}. They are produced by the action of trade winds over the seawater surrounding the islands, creating waves that follow the direction and intensity of the winds. The mean annual height of these waves is 1.4 m, with a frequency of 9.5 s^{-1}. Swells from NNW and NW are produced by storms from remote areas of the North Atlantic. They create perturbations that travel along the ocean for distances of up to 3,500 km. This kind of wave movement shows a marked seasonal pattern, being more frequent from October to March. The mean annual height of waves is between 2 and 3 m, with a frequency of 18 s. The prevailing northern component in wave action at the Canary Islands makes the northern coasts of the islands more exposed than the southern coasts (Braun and Molina 1988; Pérez et al. 2003; Yanes et al. 2006).

The climatic regime of the islands is characterized by the predominance of trade winds from the northeast that affects the islands when they are under the influence of the Azores anticyclone. These winds have an average speed of 20–22 km h^{-1}. They are not constant throughout the year, undergoing major seasonal variations. In summer they reach their maximum frequency, occurring around 90–95 % of the days. In fall the Azores anticyclone gets weaker, producing periods of calm. However, it is in winter and spring when there are minimum levels of trade winds, with an incidence of less than 50 % of the days. During this period low pressures from the Atlantic Ocean are frequent, producing winds from the northwest, southwest or southeast, as well as warm and dry invasions of Saharan weather conditions towards the east and southeast (Marzol 1988).

The tidal regime of islands is semidiurnal as in the rest of the Atlantic region, with two high tides and two low tides each day. Usually two consecutive high tides and two low tides have the same amplitude, experiencing a change during the year. The maximum tidal amplitude occurs during the spring and fall equinoxes, reaching about 2.5 m, whereas minimum values are recorded during the summer and winter solstices, not exceeding 0.7 m of amplitude. During the rest of the year the average tidal amplitude usually ranges between 1.2 and 1.3 m, but local variations may occur due to the morphology of the coast, the depth, or to particular climatic conditions of winds and waves in favor or against tidal waves (Braun and Molina 1988; Yanes 1990).

15.1.3 General Characteristics of Communities and Ecosystems

The seabed of the Canary Islands is morphologically highly complex with a rich and diverse biota. The presence of certain biological populations and their structure are determined by the interplay of five factors: insularity, topography of the bottoms, great length of coastline, oceanographic conditions and geographical location. Since the Canary Islands originated from the seabed, isolated from other regions, its biota necessarily came from nearby continents or islands. One could expect to find in the islands the same patterns of communities and ecosystems structures as in nearby regions. However, despite the great dispersal ability of marine species, many species fail to cross ocean barriers. Therefore a biased representation of the biota appears in the archipelago. The volcanic nature of the islands determines the pronounced slope of the bottoms and the small extent of sublittoral platforms that abruptly terminates onto the islands' slopes. This implies that the extension on which benthic communities can develop is spatially very limited. However, the long coastline, along with the rich and diverse coastal morphology, allows the occurrence and development of numerous different habitats and ecosystems. On the other hand, the waters surrounding the islands are oligotrophic that limits production in the environment (Braun and Molina 1988).

From a biogeographic point of view, the geographical location of the archipelago has resulted in the coexistence of both temperate and tropical species (Brito

et al. 2001; Sansón et al. 2001; Brito and Ocaña 2004; Tuya and Haroun 2009). It has been noted that the main system of currents that affects the archipelago is the cold Canary Current, a descending branch of the Gulf Current that flows from the north of the Iberian Peninsula towards the southeast. On its way through the European Atlantic coast, it becomes progressively richer in propagule and larvae of different species. Some of these species successfully reach the islands and become established if conditions are favorable. Therefore, most of the species found in the Canary Islands have their origin in the Atlantic-Mediterranean region. To a lesser extent, American tropical and subtropical species have also colonized the Canary Islands through this current. In many cases, the islands constitute the only region in the eastern Atlantic Ocean where these species are found. Although there is no clear system of currents that connects the islands with the tropical southern African coast, some species from this region have colonized the Canaries. Probably southeast African weather conditions occasionally counteract the Canary Current, favoring the arrival of these species. Biota common to the Saharan coast (the region of mainland Africa nearest to the Canary Islands) are scarce, mainly because the oceanographic conditions generated by the upwelling of cold waters near the continent area are very different from the conditions of the Canaries (Aguilera et al. 1994).

This set of variables defines the characteristics displayed by coastal populations, communities and ecosystems. Because the structure, composition and functioning of ecosystems show characters in between those of temperate and tropical systems, they are considered subtropical. The richness, diversity, disparity and originality of the populations are very high and trophic relationships among species are complex in many cases. The size of populations is usually small, due to both the low productivity of the waters and the spatial restrictions of habitats. In this sense, it should be emphasized that all benthic ecosystems, with the exception of abyssal plain ecosystems, lack of continuity throughout the archipelago because they are confined to the insular edifices and seamounts. The surface occupied by benthic ecosystems depends directly on features inherent to the islands' edifices (e.g. coastal ecosystems between 0 and 100 m depth are larger on some islands than in others). In this sense, according to the different availability of habitats and to the oceanographic conditions at the islands, the population size of a species can be different in each of them. On the other hand, given that most species are linked to the bottoms, the non-continuity of ecosystems means that the only way of exchange between populations is by larval dispersal. Since few species (only some species of fish and probably also some cephalopods) have adults that are able to move between islands, genetic connectivity between the islands' populations in turn depends on factors such as the distance between islands, the speed and direction of currents, and characteristics of each species (e.g. dispersal ability of the larvae). The population size of each island is also directly related to different levels of human exploitation. The east to west oceanographic gradient across the archipelago is also responsible for the distribution of biota. In the western islands, with warmer waters, species with tropical affinities are more abundant, while species with temperate affinities are more abundant in the eastern islands of temperate waters (Brito et al. 2001; Sangil et al. 2007). Finally, the proximity of

the oceanic waters to the coast, and given that the Canary Islands are among one of the main routes of migratory species (e.g. tunids), the pelagic systems strongly interact with the benthic-littoral systems. Moreover, since great depths are occur near the coast, deep-water species that migrate to shallow areas during their diel rhythms and are temporarily integrated into coastal ecosystems (Aguilera et al. 1994). In this sense, it is also important to emphasize that some deep fauna occur in shallow caves along the coast (Sangil 2007).

15.2 Research

The following section provides a historical perspective on the development of studies on echinoderms in the Canarian Archipelago. We describe the shift in the scientific strategy for the study of this zoological group and as some data to quantity published material.

Although the echinoderm fauna of the Atlantic is well known, much of the research has focused mainly on Western North Atlantic coastal waters. The European Eastern Atlantic coasts have also been well studied (see Koehler 1921; Mortensen 1925, 1927; Høiseater 1990; Hansson 2001), while Macaronesian archipelagos (Azores, Madeira, Salvajes, Canary Islands and Cabo Verde) are less known. Some studies have been done on the coasts of the Azores and Portugal coasts (Barrois 1888; Nobre 1930, 1931, 1938; Chapman 1951; Marques 1983; Pereira 1997). De Jesus and Abreu (1998) studied Madeira although sampling was restricted to soft bottoms between 20 and 100 m depth. Recently, the echinoderm fauna of the shallow rocky bottoms (0–25 m depth) of the Macaronesian archipelagos has been surveyed in the context of the "Macaronesia 2000 Project" promoted by the Museo de la Naturaleza y el Hombre from Tenerife (Pérez-Ruzafa et al. 2002) and Cabo Verde (Pérez-Ruzafa et al. 1999, 2003a, Entrambasaguas 2008; Entrambasaguas et al. 2008).

Echinoderms are one of the groups of marine animals that have received considerable research effort in the Canaries. Because of its economic impact, research interest has primarily concerned, and sometimes even monopolized, by one species: the sea urchin *Diadema* aff. *antillarum*. This species have been recently described and named as *Diadema africana* (Rodríguez et al. in press.). It is worthwhile to note that researchers have used either *D. antillarum* or *D.* aff. *antillarum* to refer to the Eastern-Atlantic species. We recommend the use of *D. africana* when referring to eastern-Atlantic populations and have used this name throughout the text.

15.2.1 Pioneering Studies

The occurrence of echinoderms in the Canary Islands has been noted by a few authors (Greef in Theel 1886; Panning 1939) and by expeditions in these waters.

Expeditions visiting the archipelago at the end of the 19th century and the first half of the 20th include the Challenger, Travaillerur and Talisman, Princesse Alice, Michael Sars, The Java-Sud Africa Expedition. As an example, Barrois (1888) studied the echinoderm faunas of Azores and Madeira and made comparisons with faunas from Canary Islands and Cabo Verde. Mortensen (1943) provided one of the first references on echinoderms of the Canaries where he refers to the presence of long-spined black sea urchins during his visit to Las Palmas (Gran Canaria) at the beginning of 1930s. Reports from other foreign naturalists also emphasized, several decades ago, large densities of this sea urchin in the shallow rocky subtidal of the Canaries (Johnston 1969). This sea urchin (misidentified as *Centrostephanus longispinus*) was even pointed out as "guilty" of the lack of algae in the rocky subtidal through overgrazing (Johnston 1969).

15.2.2 1980s and 1990s-Establishing the Taxonomic Baselines and the First Bionomical, Biogeographical and Ethological Approaches

The first studies carried out by researchers from institutions on the Canary Islands to describe the species composition of the echinoderm fauna are from the early 1980s. A team from the University of La Laguna, led by J.J. Bacallado, implemented the research projects *Bentos I* and *Bentos II* (Bacallado et al. 1982). These works focused on the collection, identification and taxonomic description of the main animal groups of the marine bottoms of the Canary Islands, including echinoderms (Bacallado et al. 1984, 1985). As a result of these projects the original checklist was improved (Bacallado et al. 1988).

The *Bentos* project was the base for studies on holothurians (Pérez-Ruzafa 1984, 1984a, b; Pérez-Ruzafa et al. 1985a, b, 1992a, b; Pérez-Ruzafa and Marcos 1987), including their spatial distribution (Pérez-Ruzafa et al. 1984a), biogeographical relationships (Pérez-Ruzafa et al. 1984b; Pérez-Ruzafa and Marcos 1987) and behavior (Pérez-Ruzafa et al. 1987). A morphological description of spines for eight common species of echinoids was published by Moreno-Batet et al. (1980). Of particular relevance for echinoids, was the publication of a monograph on the main biological characteristics of *Diadema africana* (Bacallado et al. 1987). This work reinforced previous observations of this research group (Brito et al. 1984) on the important role this sea urchin seemed to play in the structure and organization of shallow rocky bottoms of the archipelago. Importantly, this environmental issue took on a social dimension with the publication of the book by Aguilera et al. (1994) about environmental sustainability of the Canaries. These documents constituted the baseline on which subsequent works were carried out, including taxonomic revisions and additions to all classes of echinoderms.

15.2.3 The "recent" Past-An Explosion of Studies on Echinoderm Ecology at the Start of the 21st Century

The end of the 20th is linked to an increase in studies on the ecology of echinoderms from the Canaries. Of special importance is the project *Macaronesia 2000* supported by the Museo de Ciencias Naturales de Tenerife and directed by J.J. Bacallado. This project was done between 1998 and 2006 and was a great advance for echinoderm studies in the Macaronesian islands (Azores, Madeira, Salvage Islands, Canary Islands and Cape Verde). We have to emphasize the importance of the doctoral thesis of L. Entrambasaguas (2009) and other works derived from this project (Pérez-Ruzafa et al. 1999, 2002, 2003a; Entrambasaguas et al. 2008).

These and previous studies on taxonomy had their final zenith with the completion and subsequent publication of the BIOTA book, which compiled all taxonomic citations published until 2003 for each group of marine animals from the Canarian Archipelago (Pérez-Ruzafa et al. 2003b). This document identified 91 species of echinoderms living in the waters of the Canary Islands (including two subspecies): 15 echinoid species, 18 asteroids, nine crinoids, 15 ophiuroids and 34 holothurian species (Sect. 15.3 and Appendix).

Without doubt, the sea urchin *D. africana* was the center of attention for studies on benthic ecology: high density of the sea urchin and the subsequent formation of "urchin barren grounds" (*blanquizales*—white bottoms with no erect macroalgal cover as a result of overgrazing) catapulted the species to the spotlight of benthic research in the Canary Islands. As a result, studies covered a suite of biological and ecological topics: colonization of artificial substrates and interactions of this sea urchin with other elements of the subtidal biota (Herrera 1998), patterns of circadian movements and feeding preferences (Tuya 2002), reproductive biology and genetic diversity (Garrido 2003), gametogenesis, larval development, settlement and recruitment patterns (Hernández 2006), predation as a mechanism that controls populations, including the role of marine protected areas (Clemente 2007), trophic ecology (Cabanillas 2009), and processes determining structure and organization of benthic communities (Ortega 2010). Two projects: "*Estudio de la biología y ecología del erizo Diadema antillarum y de las comunidades algales de sucesión en diferentes zonas de blanquizal del Archipiélago Canario*" and "*Canarias, Costa Viva*", as well as monitoring studies to evaluate the effectiveness of marine protected areas throughout the Canaries, have provided considerable data on the ecology of *D. africana* during 2001–2004. In particular, a large body of research has described the relationships between size and abundance patterns, and the connection between the abundance and size patterns of *D. africana* populations and algal and fish assemblages.

The end of the 20th century saw a drastic shift in the way science was evaluated in Spain: a consolidation of peer-reviewed international indexed journals (included in international databases where journals are ranked according to their scientific relevance) as the main output of scientific publication. Therefore, the publication of articles in peer-reviewed indexed journals on aspects related to the echinoderms
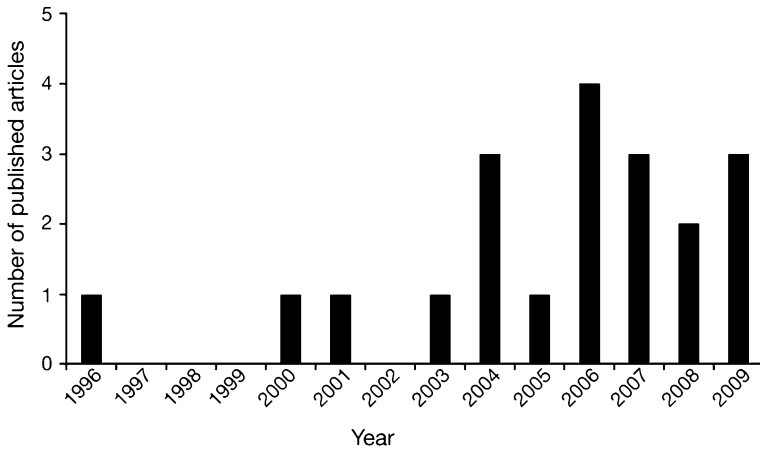
Fig. 15.3 Number of published articles in international, indexed, peer-reviewed journals on aspects related to the sea urchin *Diadema africana* in the Canaries

from the Canaries has increased considerably in the last years (Fig. 15.3). These works include some of the biological and ecological topics derived from the doctoral theses and the projects noted above. Here, we compile these studies on the biology and auto-ecology of *D. africana*, including reproductive biology (Garrido et al. 2000; Hernández et al. 2006a), feeding preferences (Tuya et al. 2001), nocturnal movements and "homing" behavior (Tuya et al. 2004a), seasonality of settlement patterns and its coupling with the oceanographic scenarios of the Canaries (Hernández et al. 2006b, 2010a), as well as technical topics related to the in situ tagging to monitor movement (Tuya et al. 2003; Clemente et al. 2007a) and predation (Clemente et al. 2007b). Another group of studies analyzed the spatial and temporal variability of populations (Tuya et al. 2006a; Hernández et al. 2008a), including the effect of a set of environmental factors (e.g. turbulence (Tuya et al. 2007), the topography of the reef and sedimentation (Clemente and Hernández 2008), respectively human-induced factors such as fishing effort (Hernández et al. 2008a) and the establishment of protection frameworks over the coast (Hernández et al. 2008b). A large body of research analyzed the way *D. africana* affects the composition, abundance and organization of algal assemblages (Tuya et al. 2004b, 2004c, 2005). Two studies analyzed how the populations of this echinoid interact with other parts of the animal biota, including the abundance, diversity and organization of macro-invertebrate assemblages (Tuya et al. 2006b; Ortega et al. 2009). Finally, recent investigations have focused on the way predation, mainly exerted by fishes, shape the abundance and size patterns of *D. africana* in marine protected areas (Clemente et al. 2009, 2010) and non-protected zones (Clemente et al. 2007b). Comparison of protected areas (marine reserves) and zones subject to prominent exploitation that have qualitative and quantitative distinct fish assemblages, in conjunction with previous observations (Tuya et al. 2004b; Hernández et al. 2008a), has been used to demonstrate the key role that

predation, chiefly induced by overexploited fish species, exert in the control of populations of *D. africana*. Consequently, overexploitation of sea urchin predators has been directly linked to large densities of *D. africana*, which causes the direct elimination of erect algal beds and results in the prevalence of rocky unvegetated bottoms in the rocky subtidal ("urchin barren grounds"). The disappearance of these algal beds limits benthic primary production, as well as the amount of food and shelter these algal habitats provide for associated invertebrates and fishes. This exacerbates, even more, the deterioration of marine biodiversity in the shallow subtidal waters of the Canarian Archipelago. Last, but not least, there is a positive relation between the increases in densities of *D. africana* and the recent increase in sea water temperature (Hernández et al. 2010a). This work is based on a historical compilation of sea water surface temperature data from 1948 to the present and a continuous collection of data on settlement, recruitment and densities from 2001 to 2008. The major conclusion is that the increase in sea water temperature, coupled with the prevalence of "urchin barren grounds", enhanced the survivorship of *D. africana* recruits. This work predicts an increase in the densities of this sea urchin as well as the extension of "urchin barren grounds" under the predicted scenario of raising temperatures. In conclusion, the rise in sea water temperature has been a relevant factor in conjunction with overfishing of sea urchin predators to enhance densities of the sea urchin.

The high level of social interest about the effect of high densities of *D. africana* has not only increased the publication of scientific manuscripts. Publications have disseminated the characteristics of the sea urchin to society in non-technical language (Brito et al. 2004; Tuya et al. 2004d; Hernández et al. 2009). These publications have tried to raise awareness on the necessity to implement conservation strategies to guarantee the sustainability and conservation of benthic communities in the Canary Islands since high densities of the sea urchins are directly connected with perturbed bottoms. Indeed, increasing interest on preserving the rocky subtidal reefs of the Canaries has been consolidated by the development of the project *Diademar* (Instituto Canario de Ciencias Marinas), which is exploring ways to commercially exploit the high densities of the sea urchin, mainly for human consumption of gonads, as a way of population control. In addition, the *Viceconsejería de Medio Ambiente* and the *Viceconsejería de Pesca* of the Canary Government and several insular administrations (*Cabildos*) have implemented a program to periodically eliminate this sea urchin in large experimental plots across the entire archipelago. The goal is to preserve algal beds (but see Sect. 15.5).

Other echinoderms have not received the same focus of attention within the scientific community. There are only a few studies on other species of sea urchins, such as the genetic diversity (Calderon et al. 2008) and a description of the juvenile phases of *Paracentrotus lividus* (Hernández et al. 2005), and the spatial distribution patterns of *P. lividus* and *Arbacia lixula* across depth gradients in the shallow subtidal (Tuya et al. 2007). Other works focused on some ecological aspects, such the relation between densities of *D. africana* and other species of echinoderms (Ortega et al. 2009), particularly the holothurians (Tuya et al. 2006b).

15.3 Diversity of Echinoderms and Distribution

The echinoderm fauna from the Canary Islands is presently composed of 127 species, nine of Crinoidea, 25 of Asteroidea, 42 of Ophiuroidea, 26 of Echinoidea and 28 of Holothuroidea. Of these, 71 species inhabit the littoral zone, at depths less than 50 m (one of Crinoidea, 16 of Asteroidea, 24 of Ophiuroidea, 13 of Echinoidea and 17 of Holothuroidea) (see Appendix and pictures on Figs. 15.4–8 for the most common species). This biodiversity is similar to that reported for the Mediterranean (147 species in total, 101 in shallow water) or the British Isles (119 and 71 respectively). It is higher than the reported in other archipelagos such as Cabo Verde (66 species in total and 42 in shallow waters) but this is due probably to differences in sampling effort.

The present status of the echinoderm fauna of the Archipelago needs a major revision, because many citations come from old works and indirect references, some species reported could be misidentifications. For example, *Holothuria* (*Lessonothuria*) *poli*, was reported for the Canary Islands by Ludwig (Greef, in Theel 1886), Herouard (Tortonese 1965) and for Palma by Tortonese (1965). We have never found the species in our sampling of the different islands. In the same way, the cluster composed of *Holothuria* (*Holothuria*) *stellati*, *Holothuria* (*Holothuria*) *tubulosa*, *Holothuria* (*Holothuria*) *mammata* and *Holothuria* (*Holothuria*) *dakarensis*, which have been cited for the archipelago, must be reduced to *Holothuria* (*Holothuria*) *mammata* after the taxonomic and genetic review of the group in Atlanto-Mediterranean waters by Borrero-Pérez et al. (2009). According to their results, *H. dakarensis* would be restricted to the Cape Verde Islands and the coast of West Africa, *H. mammata* to the Atlanto-Mediterranean area and *H. tubulosa* to the Mediterranean Sea. *Holothuria stellati* was considered a junior subjective synonym of *H. tubulosa*.

The small holothuroid *Holothuria* (*Holothuria*) *helleri* was reported by Pérez-Ruzafa (1984) and Pérez-Ruzafa et al. (1984a) from samples of coral branches at 102 m depth, but the validity of this species must be reviewed as it could be confused with juveniles of other *Holothuria* species.

Some confusion has existed with species with anfiatlantic distributions. Lessios et al. (2001) divided *Diadema antillarum* into Western and Eastern Atlantic clades from a molecular genetic analysis. This could also be the case for the small brooding holothuria *Neocnus incubans*, reported at the Canary Islands as its only locality of its distribution in the Atlantic Ocean (Pérez-Ruzafa et al. 1984a; Pérez-Ruzafa et al. 1984b).

Shallow rocky bottoms are inhabited by few species. The more conspicuous are the sea stars *Ophidiaster ophidianus*, *Coscinasterias tenuispina* and *Marthasterias glacialis*, the holothuroid *Holothuria* (*Platyperona*) *sanctori*, and the sea urchins *Diadema africana*, *Arbacia lixula* and *Paracentrotus lividus*. The three sea urchins coexist at all depths down to 30 m, but some vertical zonation can be observed in their distribution (Tuya et al. 2007). *Paracentrotus lividus* is herbivorous and dominates in shallower areas, from 0 to 5 m depth, with algal cover and well
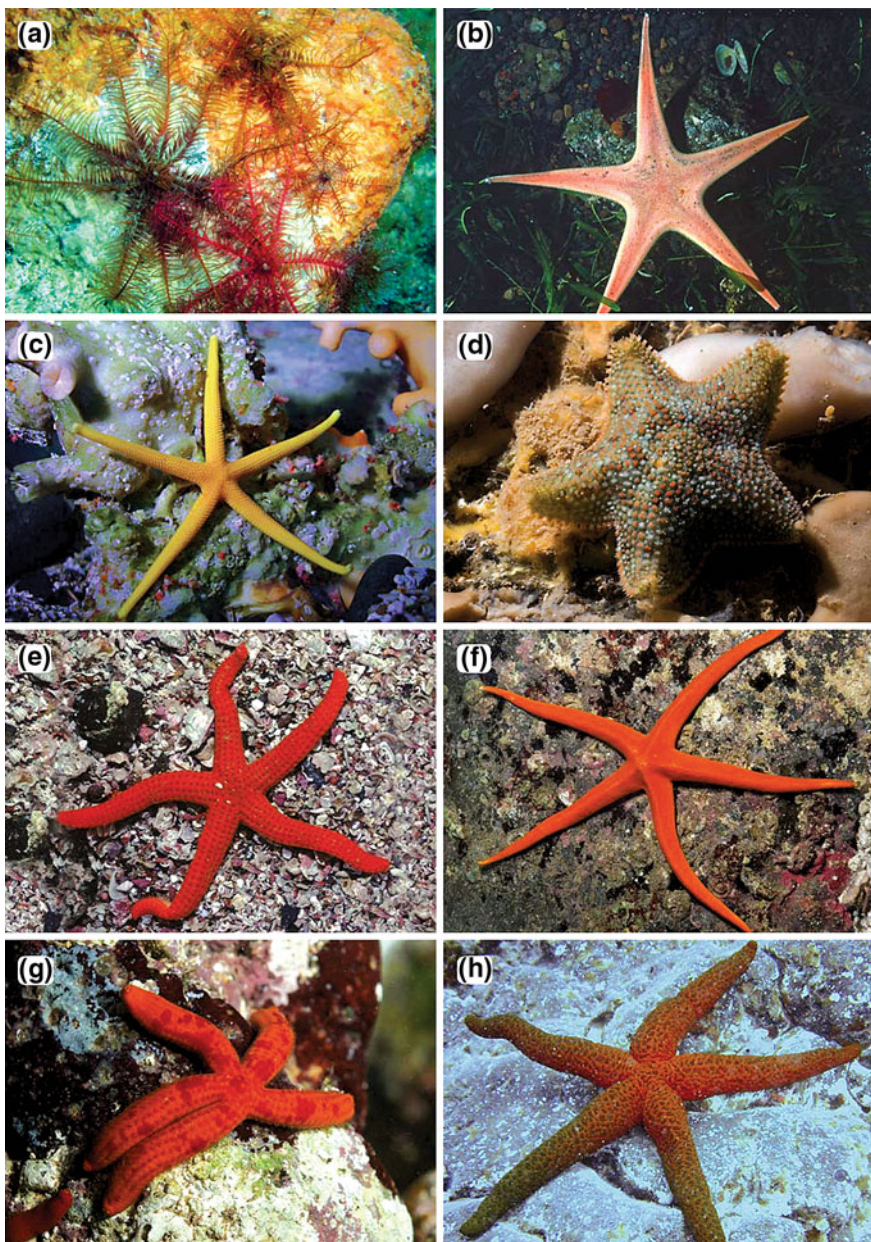
Fig. 15.4 **a** *Antedon bifida* (Pennant, 1777); **b** *Thethyaster subinermis* (Philippi, 1837) (Photo: J. Barquín); **c** *Chaetaster nodosus* Perrier, 1875; **d** *Asterina gibbosa* (Pennant, 1777); **e** *Hacelia attenuata* Gray, 1840; **f** *Narcissia canariensis* (d'Orbigny, 1839); **g** *Ophidiaster ophidianus* (Lamarck, 1816); **h** *Echinaster sepositus* (Retzius, 1783)
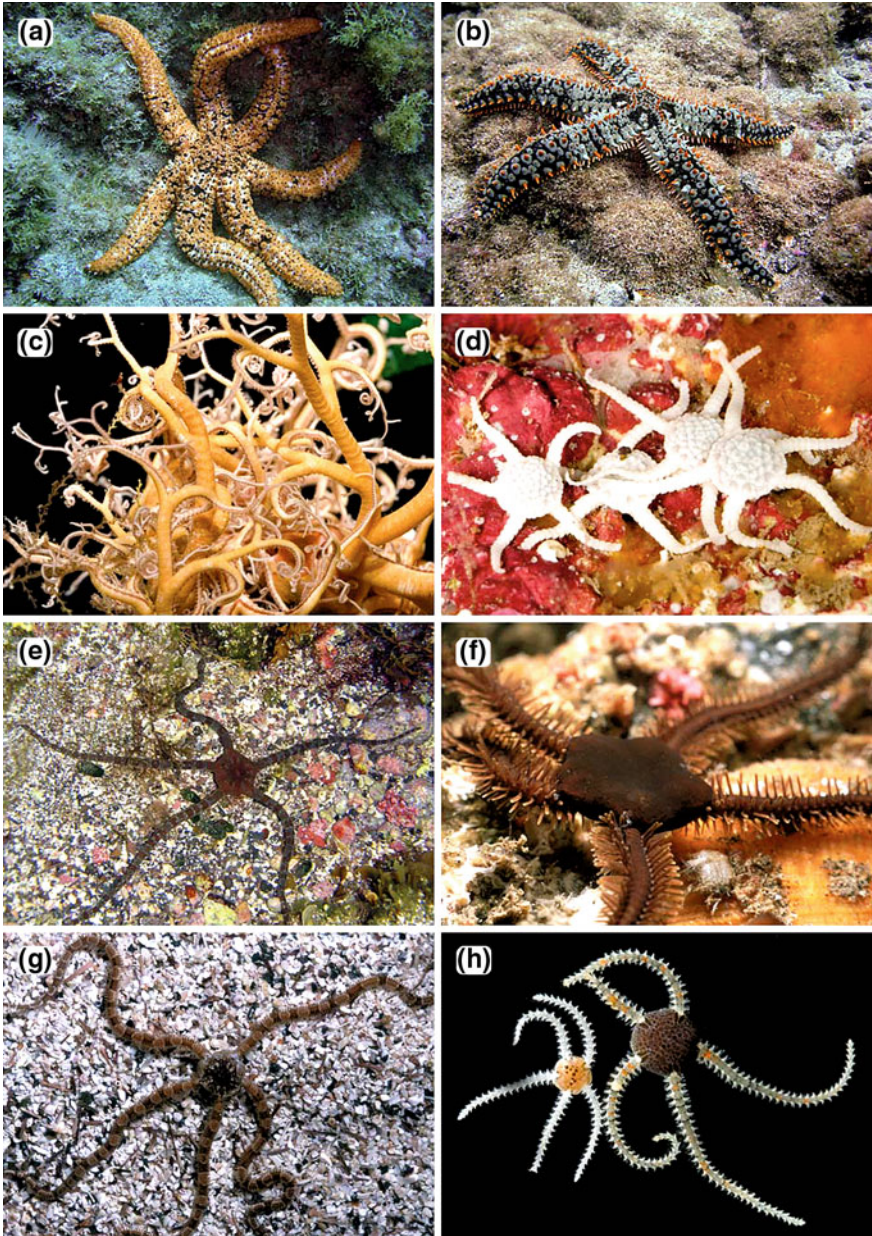
Fig. 15.5 **a** *Coscinasterias tenuispina* (Lamarck, 1816); **b** *Marthasterias glacialis* (Linnaeus, 1758); **c** *Astropartus mediterraneus* (Risso, 1826); **d** *Ophiolepis paucispina* (Say, 1825); **e** *Ophioderma longicaudum* (Retzius, 1789); **f** *Ophiocomina nigra* (Abildgaard, 1789); **g** *Ophiopsila aranea* Forbes, 1845; **h** *Amphipholis squamata* (delle Chiaje, 1829)
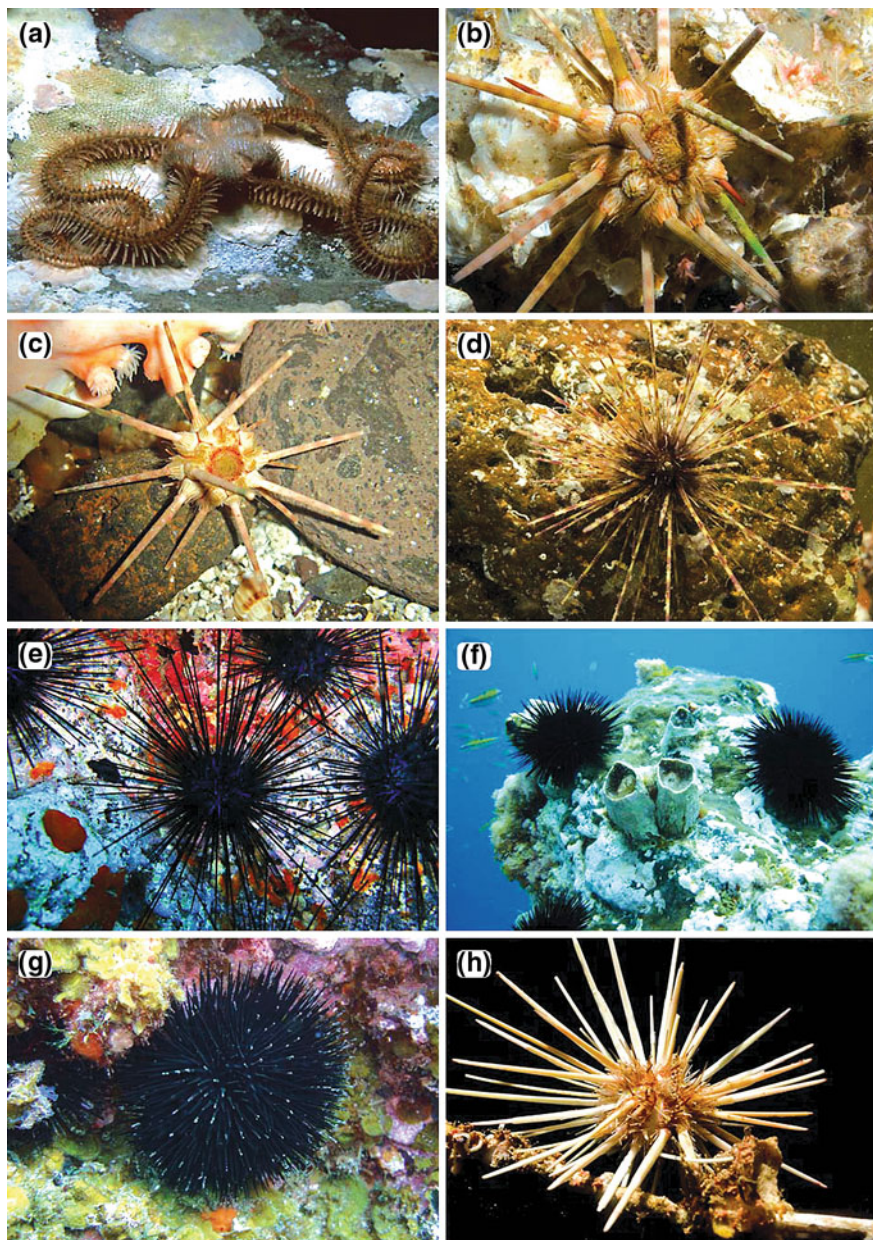
Fig. 15.6 **a** *Ophiothrix fragilis* (Abildgaard, 1789); **b–c** *Stylocidaris affinis* (Philippi, 1845); **d** *Centrostephaus longispinus* (Philippi, 1845); **e** *Diadema africana* (Rodríguez, Hernández, Clemente 2010); **f**, **g** *Arbacia lixula* (Linnaeus, 1758); **h** *Coelopleurus floridianus* Agassiz, 1872
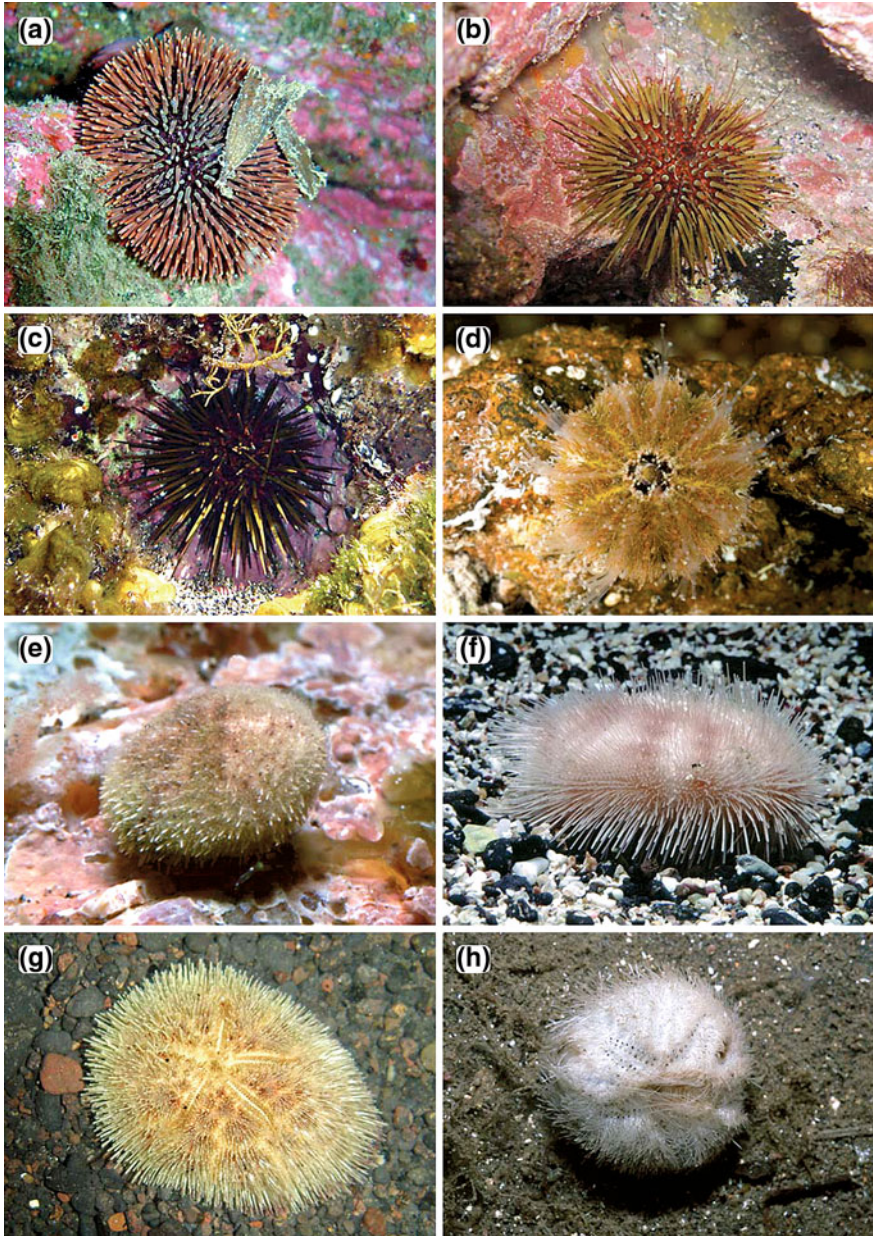
Fig. 15.7 **a** *Sphaerechinus granularis* (Lamarck, 1816); **b–c** *Paracentrotus lividus* (Lamarck, 1816); **d** *Genocidaris maculata* Agassiz, 1869; **e** *Echinocyamus pusillus* (Müller, 1776); **f, g** *Brissus unicolor* (Leske, 1778); **h** *Echinocardium cordatum* (Pennant, 1777)
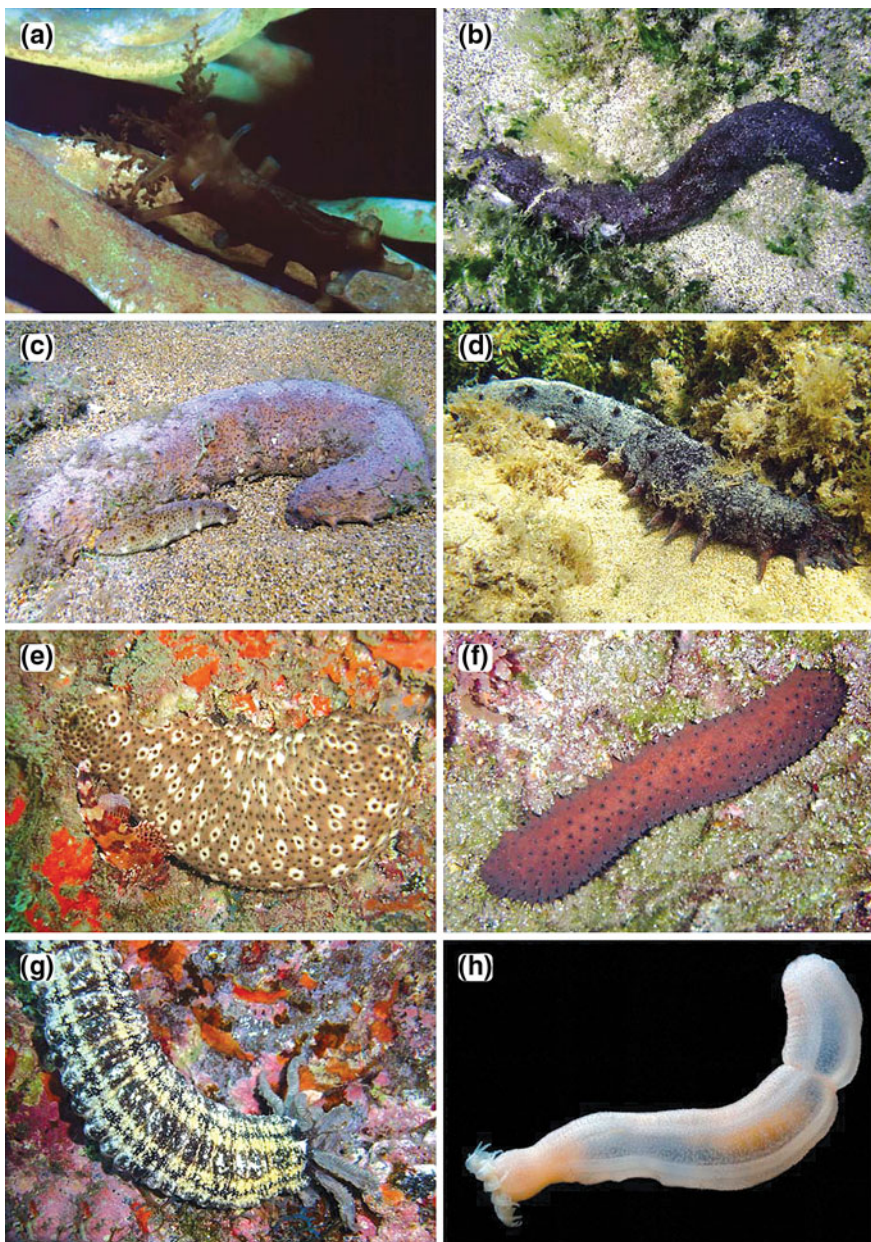
Fig. 15.8 **a** *Neocnus incubans* Cherbonnier, 1972; **b** *Holothuria mammata* Grube, 1840; **c**, **d** *Holothuria arguinensis* Koehler and Vaney, 1906; **e**, **f** *Holothuria sanctori* delle Chiaje, 1823; **g** *Euapta lappa* (Müller, 1850); **h** *Leptosynapta inhaerens* (Müller, 1776)

illuminated environments. *Arbacia lixula* is more abundant at slightly deeper waters (1–15 m) and in sciaphilous assemblages, probably having a slightly higher trophic level than *P. lividus*. Finally, *D. africana* is the most abundant species, reaching densities up to 240 ind. per 100 m^2 covering large extensions of unvegetated rock. It can reach depths up to 100 m. A less abundant species that can be confused with *Diadema* is another long-spined sea urchin *C. longispinus*. The sea star *Hacelia attenuata* can also be found on rocky and detritic bottoms.

On rocky substrata, but close to soft bottoms, the holothurians *H. (H.) mammata* and *Holothuria (Lessonothuria) arguinensis* are common. The daily feeding behavior of these species in Canary Islands has been described by Pérez-Ruzafa and Marcos (1987). *Holothuria (Vaneyothuria) lentiginosa lentiginosa* inhabits rocky and sandy bottoms deeper than 20 m. *Holothuria (Panningothuria) forskali* has been collected on rocky substrata at 348 m depth at Tenerife Island (Pérez-Ruzafa et al. 1987). This is the southernmost and greatest depth reported for the species.

Pérez-Ruzafa (1984) made the first report of the small incubating holothurian *Neocnus incubans* in the Atlantic from the Canary Islands, it was always found on *Cystoseira* spp. on the upper infralittoral. The small, incubating ophiuroid, *Amphipholis squamata*, is common in photophilous algae.

The ophiuroid *Ophiothrix (Ophiothrix) fragilis*, *Ophiocomina nigra*, *Ophiomyxa pentagona* and *Ophioderma longicauda* are common under stones and in crevices. The nocturnal anfiatlantic apodid holothurian *Euapta lappa* is common in cryptic habitats and is particularly abundant in the western part of the archipelago where the waters are warmer. Other species of ophiuroids on rocky bottoms of the archipelago are *Ophioconis forbesi*, *Ophioderma appressum*, *Ophiocoma pumila*, *Ophiactis savignyi* and *Ophiactis virens*.

The sea stars *Luidia ciliaris* and *Astropecten aranciacus* and the sea urchin *Echinocardium cordatum* occur on sandy bottoms. The sea urchin *Brissus unicolor*, occurs on sandy bottoms under stones. The sea stars *Astropecten irregularis irregularis* and *Peltaster placenta*, the ophiuroids *Ophiura (Dictenophiura) carnea* and *Ophiura texturata*, the sea urchins *Genocidaris maculata*, *Schizaster canaliferus*, *Spatangus purpureus*, *Plagiobrissus costai* and the holothuroids H. (*H.*) *mammata* and *Thyone fusus* occur on sandy and muddy bottoms in shallow water and *Eostichopus regalis* and *Stichopus tremulus* in deeper water.

The sea urchin *Echinocyamus pusillus* and the ophiuroid *Ophiura grubei* are common on detritic bottoms. The ophiuroid *Ophiacantha setosa* can be found on gorgonians.

15.3.1 Biogeographic Relationships of the Echinoderm Fauna of the Canary Islands

The origin of the echinoderm fauna of the Canary Islands is mainly warm-temperate (28 %) and with a wide thermal distribution (26 %) (Fig. 15.9). The strictly
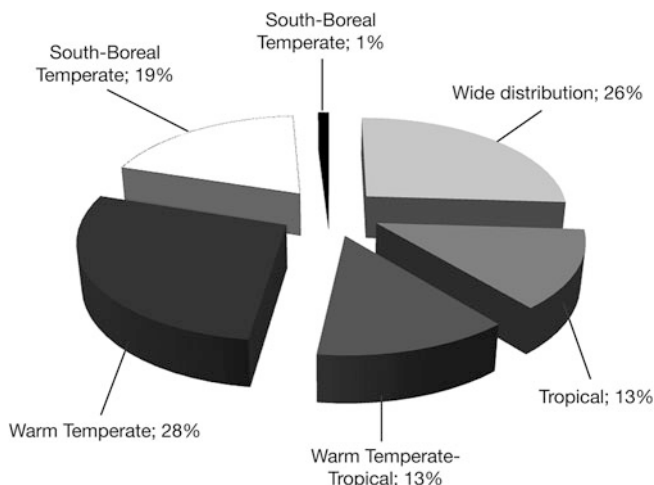
Fig. 15.9 Origin and affinities of the echinoderm fauna of the Canary Islands in relation with the thermal regions in the Atlantic described by Briggs (1996)

south boreal component is represented only by *Mesothuria connectens* reported for the archipelago by Mortensen (1927) from material collected by the Talisman expedition in 1975 at 2,518 m. However, the South-Boreal-Temperate component constitutes the 19 % of the species. It includes the shallow water species *Antedon bifida*, *Luidia ciliaris*, *Asterina gibbosa*, *Echinaster sepositus*, *Henricia sanguinolenta*, *Ophiocomina nigra*, *Echinocyamus pusillus*, *Aslia lefebrei*, *Pawsonia saxicola*, *Stichopus tremulus*, *Holothuria forskali* and *Leptosynapta inhaerens*, and the deep water species *Ophiomitrella clavigera*, *Amphilepis norvegica*, *Ophiactis abysicola*, *Araeosoma fenestratum* and *Araeosoma histrix*. The tropical (13 %) and tropical-warm temperate faunas (13 %) are well represented. Except for *Euapta lappa* which occurs at depths between 10 and 20 m and *Ophiolepis paucispina*, which reaches a maximum depth of 37 m, all strictly tropical species present at the archipelago occur in deep waters or over a wide range of depths. These include *Astropecten hermatophilus* (15−1,500 m), *Narcisia canariensis* (25–155 m), *Oreaster reticulatus* and *Astrophyton muricatum* (0–70), *Ophiomisidium pulchellum* (1,380–1,830 m), *Ophiocoma pumila* (0–368 m), *Ophionereis sexradia* (18–130), *Plesiodiadema antillarum* (651–3,111), *Diadema africana* (0–400), *Bathyplotes pourtalesi* (134–1,477 m) or *Psychropotes semperiana* (1,143–5,600 m). All of these, except *Astropecten hermatophilus*, *Narcisia canariensis* and *Ophionereis sexradia*.

The tropical-warm temperate component is represented mainly by Eastern Atlantic-Mediterranean species as *Astropecten aranciacus*, *Thethyaster subinermis*, *Chaetaster longipes*, *Peltaster placenta*, *Hacelia attenuata*, *Ophidiaster ophidianus*, *Ophiomyxa pentagona*, *Astropartus mediterraneus*, *Ophiacantha bidentata*, *Ophiacantha setosa*, *Ophiacantha valenciannensi*, *Ophiura* (*Dictenophiura*) *carnea*, *Ophiura grubei*, *Ophioderma longicaudum*, *Ophiopsila*
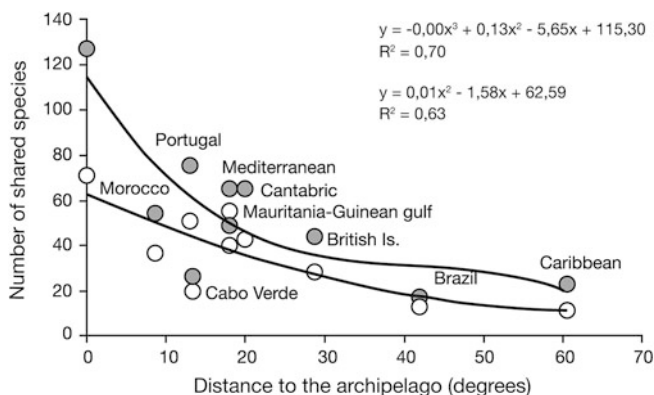
Fig. 15.10 Relationship between the number of shared species of the different biogeographic areas in the Atlantic and the Canary Islands and the distance to the archipelago. This relationship is negative emphasizing the importance of oceanic currents and connectivity to explain the composition of the fauna in oceanic islands. White circles: shallow water species (<50 m); Grey circles: all depths

guineensis, *Ophiactis virens*, *Ophiothrix maculata*, *Centrostephaus longispinus*, *Brissopsis atlantica mediterranea*, *Holothuria* (*Holothuria*) *dakarensis*, *Holothuria* (*Platyperona*) *sanctori*, *Holothuria* (*Vaneyothuria*) *lentiginosa lentiginosa* and *Molpadia musculus*. There are also some anfiatlantic species as *Coscinasterias tenuispina*, *Ophioderma appressum*, *Ophiactis savignyi*, *Arbacia lixula*, *Genocidaris maculata*, *Brissus unicolor*, *Benthodites lingua* and *Psychropotes depressa*.

There are few analyses on the distribution and biogeography of Atlantic echinoderms (Clark and Downey 1992). The relationships of the echinoderm fauna of the Canary Islands with other Atlantic faunas were analyzed for the class Holothuroidea (Pérez-Ruzafa et al. 1984b) and in the context of South-Western Mediterranean echinoderm fauna relationships (Pérez-Ruzafa and Marcos 1987).

The shallow water echinoderm fauna of Canary Islands is a consequence of its oceanography and location in the Atlantic. The number of species shared with other geographical areas is directly related to distance (Fig. 15.10). Therefore, of the 71 species inhabiting the archipelago above 50 m depth, the highest number corresponds to the Mediterranean (55 species), Portugal (50), the Cantabric (43) and Mauritania and Guinea Gulf region (40). The low number shared with Morocco (36) is probably due to the scarcity of works in this region. In fact, the number of species increases to 54 when deep water fauna is considered because most of the deep water expeditions which passed through the archipelago sampled in both areas.

The lower number of shallow water shared species is with the Caribbean (12), Brazil (13), and Cabo Verde Archipelago (20). In the case of the American coasts, this can be explained because of the distance. But in the case of Cabo Verde, the explanation has to do with the oceanographic currents system that precludes the flux of tropical species from south to north in the Eastern Atlantic.
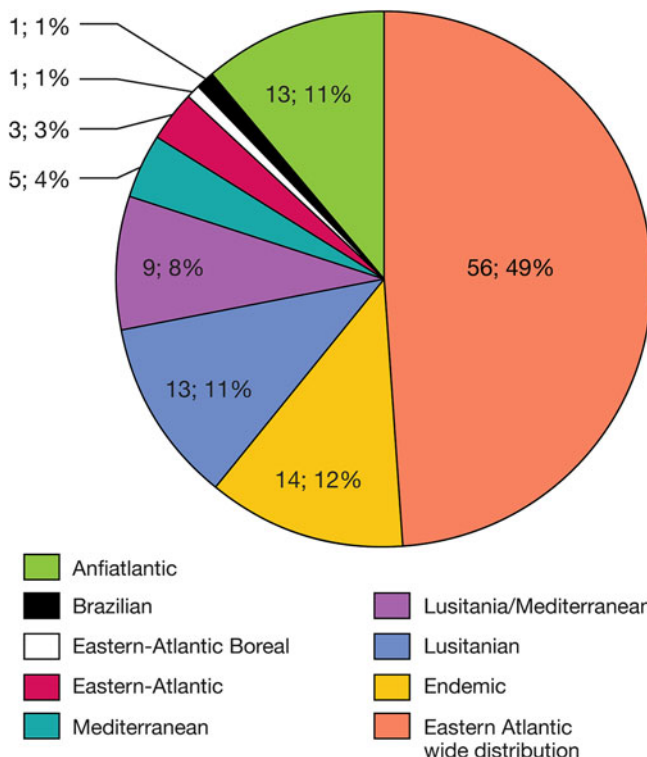
Fig. 15.11 Contribution to the echinoderm fauna of the Canary Islands of the different faunal groups according to the biogeographic regions and provinces described by Briggs (1996). Figures indicate the number of species shared and the percentage of the total

A 56 % of the species present in the archipelago has a wide distribution in the Eastern Atlantic area (Fig. 15.11). Furthermore, 27 species (23 %) are from the Lusitanian province (five from the Mediterranean, 13 from the Atlantic and nine which are present in both areas). Three species (*Astropecten hermatophilus*, *Narcisia canariensis*, *Ophionereis sexradia*) are shared exclusively with the tropical Eastern Atlantic region (from Cabo Verde Islands and the Cape Verde on the mainland to Angola (Briggs 1996). Only one species, the deep water holothurian *Mesothuria connectens*, is exclusively from the Eastern-Atlantic Boreal region. Finally, 13 species (13 %) are characteristic of the Caribbean-West Indian and Brazilian provinces in the Western Atlantic.

Only 13 species have been reported exclusively from the Canarian Archipelago waters: the sea stars *Lonchotaster tartareus*, *Thoracaster cylindratos*, *Colpaster scutigera*, *Freyastera tuberculata*, the ophiuroids *Ophiomusium serranum*, *Ophiomusium vallidum*, *Ophiozonella molesta*, *Ophiura inermis*, *Amphiura grandis*, the sea urchins *Cidaris blakei*, *Salenocidaris rarispina*, *Aceste bellidifera* and the holothurian *Peniagone ferruginea*. All are deep water species occurring at more
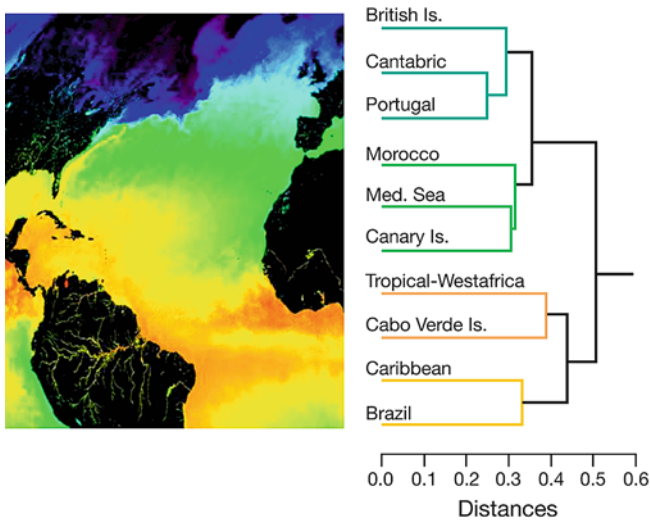
Fig. 15.12 Cluster tree representing the affinities of the echinoderm faunas between different geographic regions in the Atlantic. Distances were constructed with the Jaccard index for presence-absence data. Note the close relationship between distances and differences in mean annual surface water temperatures as showed by the satellite image at left

than 900 m depth. *Diadema africana* has been described for Madeira, Canary Islands and Cape Verde, but as this species had been reported until now as *Diadema antillarum* or *Diadema* aff. *antillarum*, a review of the distribution of the species in the Eastern Atlantic must be done.

The application of the Jaccard index to the echinoderm fauna of these mentioned regions (including shallow and deep sea faunas) produces two main groups (Fig. 15.12). The first includes British Islands, Cantabric Sea and Portugal coasts and the Atlantic coast of Morocco, the Mediterranean and the Canary Islands. The second group links the Caribbean and Brazil on one hand with Cabo Verde and the Mauritanian and Guinean Gulf on the other. These groups represent the four major thermal regions in the Atlantic surface waters: South Boreal, Cold-temperate, Warm-temperate and Tropical (Briggs 1996). The tropical zone is delimited by the 20 °C isotherm for the coldest month.

15.4 Echinoderm Ecology: Implications for Conservation

Echinoids are by far the most abundant group of echinoderms of shallow waters of the Eastern Atlantic Archipelagos. Few detailed ecological studies have focused on other taxa in this region. Comparisons of spatial distribution of sea urchins *A. lixula*, *P. lividus* and *D. africana* show a consistent depth-dependent partitioning pattern on rocky reefs, in which the latter is the competitive dominant species both

at the Canary Islands (Tuya et al. 2007) and Madeira Island (Alves et al. 2001). This depth gradient in the vertical distribution of the three sea urchin species has been related to their distinct morphological characteristics, and consequently, their different resistance to natural hydrodynamic forces (Tuya et al. 2007). *Arbacia lixula* and *P. lividus* seem to be morphologically adapted to minimize the chances of being dislodged by high water motion at the intertidal and first few meters of the subtidal and coexist in relatively high densities only in the shallowest depths (<5 m). Densities of *D. africana*, less adapted to support intense water movement, increase with depth. The result is a general pattern in the vertical distribution of these sea urchins in the warm-temperate rocky reefs of the eastern Atlantic Ocean (Alves et al. 2001, Tuya et al. 2007), in which wave exposure and island slope that affects wave energy are major environmental factors determining densities of these key herbivorous sea urchins (Hernández et al. 2008a). Moreover, protected coasts have calmer waters that promote retention of urchin larvae (Hernández 2006). Larvae at exposed sites larvae tend to be carried away. The result is that areas with higher hydrodynamics show greater urchin density in a deep band (15–20 m) just below the algal stand, whereas along sheltered coasts algal beds the urchins occur only at the first meters depth where more food is available (Hernández et al. 2008a).

Because of the biological and ecological features, such as size, motility, feeding preferences or longevity, several urchin species play a key role, even more important than other herbivores, in controlling epibenthic communities and in turn of the overall structure of coastal communities (Lawrence and Sammarco 1982). The main consequence of this overall phenomenon of intense grazing activity is a shift from large areas of rocky reefs covered by complex erect macroalgal beds to overgrazed substrates ('urchin barrens' or 'barren grounds') dominated by encrusting algae and some sessile invertebrates.

The influence of echinoids grazing activity on rocky reefs communities of the eastern Atlantic oceanic islands, particularly in the Canary Islands, have been well studied (Alves et al. 2001, Tuya et al. 2004c; Hernández et al. 2008b). These are relatively small barren grounds produced by *P. lividus* in tidepools, and by *A. lixula* on shallow bottoms and around artificial jetties (JC Hernández pers. obs.). However, barren grounds resulting from the intense grazing activity of *D. africana* are more extensive and commonly spread throughout the entire region (Aguilera et al. 1994; Brito et al. 2004; Tuya et al. 2004c), reaching up to 50 m depth and covering about 75 % of the total littoral rocky bottoms of the Canary Islands (Barquín et al. 2004). Densities of this species can reach more than 12 ind m^{-2}, with severe consequences (Brito et al. 1984, 2004; Alves et al. 2001; Tuya et al. 2004b; Hernández 2006). Field monitoring and experimental manipulations of urchin densities have shown its major effects on algal communities (Hernández et al. 2008a). At moderate densities, sea urchin grazing can stimulate plant production and promote species diversity. Because of this sea urchins should be considered an integral part of ecosystem dynamics (Sammarco 1982; Valentine et al. 1997). However, densities of as few as 4 urchins m^{-2} can remove up to 70–80 % of algal cover (Hernández et al. 2008a) and dramatically reduce

macroalgal diversity, resulting in the formation of impoverished sea urchin-dominated areas denuded of all but encrusting algae (Lawrence 1975; Sangil et al. 2006a, 2006b). Compared to typical urchin barrens elsewhere in the world (Chapman 1981; Pearse and Hines 1987; Valentine and Johnson 2005; Guidetti and Dulcic 2007), barrens generated by *D. africana* in the eastern Atlantic appear to be maintained by relatively low numbers of sea urchins (starting at 2 ind m^{-2}). Probably, the oligotrophic condition of waters surrounding the archipelago provides limited nutrient resources that are not sufficient to maintain extremely high urchin densities. However, species movement and food consumption rates, which involve grazing large areas of rocky substrate at night (Tuya et al. 2004a), allow comparatively lower urchin densities to maintain a barren habitat denuded of most erect macroalgae biomass.

Loss of macroalgal beds due to *D. africana* grazing activity produces not only lower species diversity (Herrera 1998; Garrido 2003) but also a lack of habitat suitable for fish feeding and reproduction (Brito et al. 2004; Tuya et al. 2005; Clemente 2007). Macroalgae constitute a major energy source that maintains the food web, and are the main biological engineers on rocky reefs of the Canary Islands, which lie between tropical and temperate waters and has no coral reefs. Consequently, algal cover provides the habitat that supports the whole system. It constitutes a well-known indicator of benthic conservation status (Hernández et al. 2008b). Another good example of a third-order change that occurs as a consequence of the development of urchin barrens is the distribution and abundances of large holothurians, linked to specific type of habitats across shallow-waters of the eastern Atlantic (Tuya et al. 2006b). This fact could be related to variations in the availability of particulate organic matter across habitats. Benthic grazers, such as sea urchins, can transform up to 70 % of the consumed algae to detrital fecal matter (Vadas 1977; Koike et al. 1987; Frantzis and Gremare 1992; Lison de Loma et al. 2000; Mills et al. 2000; Mamelona and Pelletier 2005). High densities of *D. africana* on barren grounds likely produce large amounts of fecal pellets, as a source of fresh particulate organic matter (Lawrence 1975; Wotton 1994; Lawrence and Klinger 2001; Levinton et al. 2002; Mamelona and Pelletier 2005). Consequently, holothurians were significantly more abundant in *D. africana* barrens compared with vegetated habitats, a pattern that was strongest for the numerically dominant species, *Holothuria sanctorii* (Tuya et al. 2006b).

As a major herbivore, *D. africana* is recognized as having a key ecological role that threatens the resilience of marine systems in the eastern Atlantic, with the subsequent establishment of undesired conservation states (Hernández et al. 2008a). The reported increasing frequency of overgrazing events, concomitant with loss of associated ecosystem goods and services, generates a serious environmental problem that constitutes a key threat to coastal marine ecosystems and local communities of the islands. Hence, the necessity of managing the populations of *D. africana* to prevent overgrazing management has become apparent, especially in areas of the Canary Islands where algae-associated services (such as fishing stocks) are important for livelihood sustenance. Algal stands are very restricted in space in the Canary Islands and have shown a temporal regression

related to the demographic explosion of the sea urchin during recent years (Clemente 2007; Hernández et al. 2008a). High percentage cover is usually attained only in shallow water stands at exposed sites where hydrodynamics prevent urchin activity (Alves et al. 2001; Tuya and Haroun 2006), at certain marine protected areas (Clemente 2007; Hernández et al. 2008a), or at barely perturbed areas associated with a delayed anthropogenic development such as isolated and less populated islands (Clemente et al. 2009).

Many factors are thought to be involved in the recent expansion of *D. africana* populations and regression of algal beds at the eastern Atlantic Archipelagos. We can indicate an array of environmental factors that promote high urchin densities, such as substrate topography and diversity and certain oceanographic events that can influence sea urchin settlement, recruitment and survival (Hernández et al. 2008a). In addition, several anthropogenic factors, such as the number of islanders and tourists per coastal perimeter, the number of operational fishing boats and the overfishing of the sea urchins' natural predators have been associated with increased urchin abundances (Hernández et al. 2008a; Clemente et al. 2009).

Diadema africana is a termophilus species, which probably constitutes a competitive advantage for its proliferation at the sublittoral latitude of the Canary Islands in contrast to sea urchins of temperate affinities such as *P. lividus*. This has been especially relevant in the last decades, when a trend of progressive sea water warming has occurred in the region as a consequence of global climate change processes (Brito 2008). In fact, a long-term study has detected a clear relationship between sea surface temperature and *D. africana* settlement (Hernández et al. 2010a). Urchin settlement was higher during warmer years. Temperatures above 24 °C produced major settlement pulses and higher post-settlement survival rates in barren areas. However, some variability across habitats indicates resilience of the systems. While sea water temperature is a major factor influencing *D. africana* density in urchin barrens because it enhances post-settlement survival, specific factors in healthy macroalgal beds constrain settlement, increases post-settlement mortality and controls sea urchin populations (Hernández et al. 2010a). The study shows that warmer summer temperatures (temperatures at settlement) have been more frequent since the early 1980′s with a parallel increase in urchin population densities (Hernández et al. 2008a). Assuming climate change predictions (IPCC 2007) for the future are correct, the strong positive relationship between thermal history and post-settlement survival of this ecologically important species suggests that barren grounds will become more extensive in the future as seawater temperatures warm in relation to anthropogenic activities. Nonetheless, mass mortality events, as found for *P. lividus* in 2003 (Girard et al. in press), could became more frequent due to warmer waters. In this sense, we would like to point out that researchers have observed mortality events of *D. africana* in Madeira and Gran Canaria islands in 2010 (F. Alves, M. Kaufman and F. Espino pers. com., respectively). However, it is too soon to know the cause of this recent phenomenon that, initially, seems to be very spatially restricted. In both cases, urchins were infected by the bald sea urchin disease, and possibly originated by the bacteria *Vibrio alginolitycus* (Hernández et al. 2010b).

Regulation of sea urchin populations also depends on certain trophic interactions. Experimental studies have identified key fish species that successfully prey upon *D. africana* and have the potential to control their populations (Clemente 2007; Clemente et al. 2011). This has important implications for coastal management. By controlling herbivore densities, and thus the amount of intact macroalgal cover, predatory fish indirectly aid in preserving ecosystems service or capacity to provide locally important fishing resources and coastal productivity in sublittoral rocky reefs. The predatory fish observed are mainly species very susceptible to fishing (Clemente 2007). Consequently increased fishing activities have been associated with lower numbers of these predatory species and higher urchin densities in the Canary Islands (Clemente et al. 2009; 2011) and elsewhere (Sala et al. 1998; Guidetti 2006; Guidetti and Dulčić 2007). Additionally, fishing decreases the mean size of fish. This adds to the loss of species capable of consuming large sea urchins and resulting in a smaller escape by size from predation that favour their proliferation. The removal of fish predators by severe overfishing in most areas of the Canarian Archipelago have led to an urchin population outbreak driven only by settlement and recruitment in the absence of any kind of predatory or top-down control (Hernández 2006; Clemente 2007). This ecological disequilibrium, mediated by trophic cascade processes, has major consequences for the structure and function of the entire benthic community.

Because top-down effects on *D. africana* at the eastern Atlantic archipelagos depend on specific predatory species and their abundances within the food web, preserving the diversity of fish predators must be a priority of conservation efforts (Clemente et al. 2010). However, at this time this scientific knowledge has not been fully taken into consideration by policy makers and no protection measures have been directly applied to key predators of the sea urchin. There is only one kind of effective management tool in force that can indirectly contribute to the control of sea urchin populations. This is marine protected areas in which fishing restriction measures are implemented to allow fishing stocks to recover (Hernández et al. 2008a). As elsewhere around the world (Sala et al. 1998; Babcock et al. 1999; McClanahan et al. 1999; Guidetti 2006), studies in the Canary Islands have stressed the value of marine protected areas as a tool for ecosystem restoration; not only for fishes and fishing resources that increases predation on urchins and indirectly aids regeneration of benthic communities (Hernández et al. 2008a; Clemente et al. 2009). In fact, the three marine protected areas within the Canary support higher densities of fish predators and higher levels of predation intensity on *D. africana* compared to equivalent non-protected locations (Clemente 2007; Clemente et al. 2011).

Regardless of the complexity of factors involved in regulation of overpopulations of *D. africana* may be achieved by aiding the recovery of the predatory fish community with appropriate fishing bans and protection measures. Current knowledge about the species' population dynamics has critical implications for the conservation of rocky reef ecosystems in the eastern Atlantic Islands. They add to a growing body of research suggesting that the incidence of barrens and their associated impacts are related to human disturbance (Steneck 1998; Jackson et al.

2001). However, active management actions directed to control urchin population have been limited to developing a strategy of manually removing sea urchin by scuba divers, providing evidence that erect macroalgae have the potential to recolonize encrusting macroalgae barrens (Brito et al. 2004), but of doubtful outcome in the long-term. Combined perturbations caused by overfishing and progressive sea water warming are likely to result in an environment increasingly favourable to the sea urchin, which seems difficult to control with such small-scale actions. Conservation policies need to focus efforts on specifically protecting healthy macroalgal bed habitats and the predatory fishes within them, because they are predicted to increase post-settlement mortality of *D. africana*. Such actions could improve ecosystem function by retaining the equilibrium between sea urchins and macroalgae.

15.5 Aquaculture and Fisheries

Pre-hispanic human settlement in the Canary Islands, commonly known as Guanches (Majos-Lanzarote and Fuerteventura; Canarii-Gran Canaria; Guanches-Tenerife; Benahoritas-La Palma; Bimbaches-El Hierro) usually consumed sea urchins. Indications of pre-hispanic human consumption have been discovered in various shells accumulations locations in the islands. However sea urchin species have been identified only at the "Guinea deposit" in Frontera-El Hierro (Martín Oval et al. 1985). The species most consumed was *P. lividus*, probably because of its abundance in intertidal rocky areas. Nowadays, this sea urchin is still consumed by the islanders. However it remains only in particular coastal areas as a tradition and no commercial exploitation exists. Presently, and probably then, this sea urchin is also used as fish bait for fishing traps or to attract fishes to hook lines. In some coastal locations this is the only known use. Today, other sea urchin species, such as *Arbacia lixula*, *Diadema africana* and *Sphaerechinus granularis*, are also used as bait. *Arbacia lixula* and *D. africana* are collected by snorkeling while *S. granularis*, due its deeper distribution, is a bycatch of trammel nets. The number of urchins used for this purpose is not known and is very difficult to monitor due to the diversity of discharging places, many of them located at inaccessible sites.

Paracentrotus lividus is commercially exploited in several European countries such as Ireland, France, Portugal, Italy, Greece and Spain. In the Spanish Peninsula, it is mainly exploited in the northwest (Galicia), north (Cantabria, Asturias y Pais Vasco), northeast (Cataluña), and in the south (Andalucía). Although, it is locally consumed in all these Spanish Comunidades, France is the main consumer of sea urchins in Europe and the second consumer in the world after Japan (Grosjean 2001). At the present, some of the most important fisheries in Europe like the ones in Ireland and Brittany have collapsed (Le Direach 1987; Andrew et al. 2002). In Spain, fishing activities regulations depend on the "Comunidad Autónoma". While Galicia has a well developed sustainable fishing activity (Catoira-Gòmez 1992), others like Asturias, Cantabria and Andalucía have a

growing semi-professional activity. However, the general overfishing situation of the traditional resources could favour an increase of sea urchin fisheries in the near future (Thorpe et al. 2000). At this time accurate stock studies are needed to promote appropriate regulations for a sustainable fishing activity and prevent the collapse of this resource.

Human fishing activity effects on *P. lividus* populations, although it has not been studied in the Canary Islands, are evident in many intertidal habitats of the islands compared to remote or marine protected areas locations. In these areas, of human use, *P. lividus* is scarce and is restricted to inaccessible deep cavities in the basaltic volcanic rock. In the Canary Islands, fishing activities in the intertidal are regulated. Only Sport Fishing Licence holders can fish for shellfish during weekends and holidays. No number or close season regulations exist. In our opinion, this is an insufficient measure to regulate shellfish fishing activities that favors overfishing in many intertidal benches. This situation has focused the attention of managers who have recently funded a National Project to optimize and promote *P. lividus* culture in Galicia and in the Canary Islands. This project aims to improve the technical and biological aspect of larval culture and to develop culture systems at different locations along the Spanish coast to provide juveniles for farms or repopulation. This project was supported by the *Ministerio de Medio Ambiente y Medio Rural y Marino through the Junta Asesora de Cultivos Marinos* (JACUMAR). It has contributed to the improvement of spawning and fertilization, larval culture and metamorphosis-settlement.

In addition to human collection, other factors such as temperature and competition also modify the abundance of *P. lividus*. The Canary Islands are the southern-most limit of this temperate species. It is more abundant off the eastern, colder islands. Although, there are no specific studies that assess the temporal abundance of this sea urchin, we have noticed that anomalous warm summers like occurred in 2003 were associated with localized mass mortalities at several intertidal and subtidal locations in Tenerife (Girard et al. in press). The sea water warming trend in the Canarian Arquipelago (Hernández et al. 2010a) will probably increase the frequency of these mortality events in the future, which would decrease the intertidal populations. Bathymetric segregation of *P. lividus* occurs in the littoral area. It is more abundant in shallow waters between 1–5 m (Tuya et al. 2007). This bathymetric segregation is mainly caused by competition with the grazing of the abundant *D. africana* which has greatly reduced food resources and has limited *P. lividus* distribution to shallow macroalgae stands refuges. Otherwise it could reach deeper waters as in the Mediterranean Sea. In summary, the depletion of macroalgae stands by *D. africana*, sea water warming and human collection is modifying the potential distribution of *P. lividus* in the archipelago.

In recent years, due to the outbreak of *D. africana*, local management agencies have become interested in the development of a commercial sea urchin fishery. At the same time, these agencies are proposing reducing activity of *D. africana* at some sites to gain in the conservation status of rocky bottoms of the Canary Islands. However, both strategies have the potential to restore local unproductive barren grounds to algal stands (Brito et al. 2004). These strategies should be

combined with other conservation measures such as the exclusion of urchin predators from fishing and protection of algal stand ecosystems. Combining these strategies would ensure that the ecosystem would keep the balance between urchins and algae. Urchin removals alone are inadequate (but see Sect. 15.4). In general, the management of urchin outbreak cases around the world has consisted in urchin removal. However better results have been always obtained when this is done inside a marine protected area (Tegner and Dayton 1977; McClanahan et al. 1996). This kind of management measures has been proposed for the Canary Islands several times (Clemente 2007; Hernández et al. 2008a; Clemente et al. 2009; Clemente et al. 2011).

These combined actions would potentially decrease the frequency and duration of urchin overgrazing but limited knowledge of direct and indirect effects of these ecosystem scale actions makes it difficult to assess the applicability and sustainability of this method. Therefore we call for governmental responsibility and rigor when planning this kind of action. Uncontrolled removal of urchins during the planned fishery could cause urchin populations to "crash" with potential ecological and economic side effects. The recent "boom and bust" trend of sea urchin fisheries around the word (USA, Mexico, Canada) (Andrew et al. 2002; Uthicke et al. 2009), most of them considered nowadays as overexploited, indicates the need for more information on basic population parameters of species when implementing removal actions (Russell 2000). Rigorously evaluating population demographics has, in the case of the species *D. africana*, both ecological and economic significance, especially now that it is beginning to be commercially harvested. We encourage seeking sustainable solutions to the increasing populations of the sea urchin *D. africana*, trying to contribute to the correct management and conservation of the fragile marine resources of the Canary Islands. However, we have to develop standards for the commercial exploitation of this species of what we lack today.

15.6 Recomendations

We have divided our recommendations into three major sections: biodiversity, ecology and fisheries. These constitute the main research lines that currently drive research on echinoderms in the Canarian Institutions (universities and research institutes). Moreover, in each section we have pointed out research gaps that should be considered for future studies in the archipelago.Biodiversity

– Accurate information about spatial distribution of echinoderm fauna is needed to precisely identify species habitats and depths ranges.
– Genetics studies of some taxonomic groups are needed to clarify biogeographical patterns and taxonomic identification problems (e.g. *Arbaciella elegans* is thought to be small *Arbacia lixula*).

– Field explorations should be extened to deeper habitats such as rhodoliths and deep coral communities. These have been poorly studied and probably contain a rich echinoderm fauna.

Ecology

– Population dynamics of key sea urchin species should be monitored, including their influence in triggering transition phases between algal stands and unproductive urchin barren grounds.
– The effectiveness of marine protected areas as tool to prevent and revert urchin barren situations should be studied.
– The effects of sea water warming and acidification on the calcification processes in larvae and adults of echinoderms and its relevance on population dynamics should be analyzed. The influence of environmental parameters is of special importance for species of echinoderms that modify the habitat and whose activity can greatly affect the whole system.
– The magnitude of the recent mortality events of *D. africana* in Maderia and the Canary Islands, and any related potential ecosystem wide effects should be determined.

Fisheries and aquaculture

– Tagging-recapture studies should be done to determine age, growth rate and natural mortality of sea urchins. These studies, combined with other population surveys, will provide baseline data to develop an adequate strategy of coastal management for the planned fishery of *D. africana*.
– Experimental reduction of sea urchin densities inside Marine Protected Areas that are still affected by dense urchin barren grounds should be done to identify effective strategies that could promote ecosystem transitions toward productive macroalgal stands. The potential reconstruction of the trophic structure at marine protected areas, where fishing activities have ceased during several years, may favour the control of newly settled urchins after reduction in density.
– Techniques need to be developed for production of juvenile sea urchin and sea cucumbers through laboratory cultures for aquacture or repopulation.

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