Chapter 29

Chile: Environmental Status and Future Perspectives

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29.1 GEOGRAPHY AND TOPOGRAPHY

The coast of mainland Chile extends from 18°S to about 56°S, is about 4200 km long (Fig. 29.1), and contains a highly heterogeneous coastal geomorphology, climate, and oceanographic features. Two main tectonic plates configure the large-scale geomorphology of the coastline, namely the oceanic "Nazca" plate and the continental plate of South America, and direct collision and subduction results in a very narrow continental shelf and a deep trench along the coast (see Fig. 29.1). These, in combination with geological hotspots, are also responsible for the creation of seamount chains (Cahill & Isacks, 1992).

The northern Chilean coastline between 18°S and 40°S is a continuous, relatively straight wave-exposed shore, while between 40°S and 56°S it is fragmented with long fjords and small archipelagos with extensive wave-protected zones. The eastward flowing West Wind Drift reaches the South American continent between 40°S and 45°S, resulting in a northward-flowing branch, the Humboldt Current System (HCS), and a southward-flowing branch, the Magellan Current (Strub, Mesías, Montecino, Rutllant, & Salinas, 1998) (see Fig. 29.1). The complex system of currents within the larger HCS determines diverse and productive coastal ecosystems and biogeographic zones along the mainland coast of Chile (Camus, 2001; Thiel et al., 2007).

29.2 GEOLOGICAL DESCRIPTION

From 18°S to 23°S the coast is mainly Jurassic and Cretaceous, with sedimentary intrusions (Araya-Vergara, 1981). The few small rivers (e.g., "El Loa" river) add sediments and freshwater to the coast especially during the rainy season in the Andes (December–January). Between 24°S and 33°S, the coast is primarily granitic with lower elevation and some extended terraces. Continuous rocky reefs are interrupted by sandy beaches, boulder fields, and estuaries, which tend to become more common toward the south (Santelices, 1991). The southern-central coast of Chile, from 33°S to 41°S, is mainly of Precambrian metamorphic shales with extended coastal terraces. This part is influenced by persistent river inflow. This coastline has diverse coastal habitats, grading, in general terms, from extended rocky platforms in the north to large sandy beaches and coastal wetlands which are more frequent to the south. To the south of Chiloé island (41°S), the coast has erosional tectonic patterns of fjords and a glaciated interior (Araya-Vergara, 1981). A large number of islands generate many wave-protected bays and fjords.

The continental shelf is relatively narrow in the north and expands toward the south. Deep canyons extend from the river basins, many of them associated with methane seeps between about 33°S and 36°S and there are also extensive fields of methane hydrates (Sellanes, Quiroga, & Neira, 2008). The Atacama Trench is very deep in the north (~7000 m) and becomes shallower to the south (Stuut, Kasten, Lamy, & Hebbeln, 2007).

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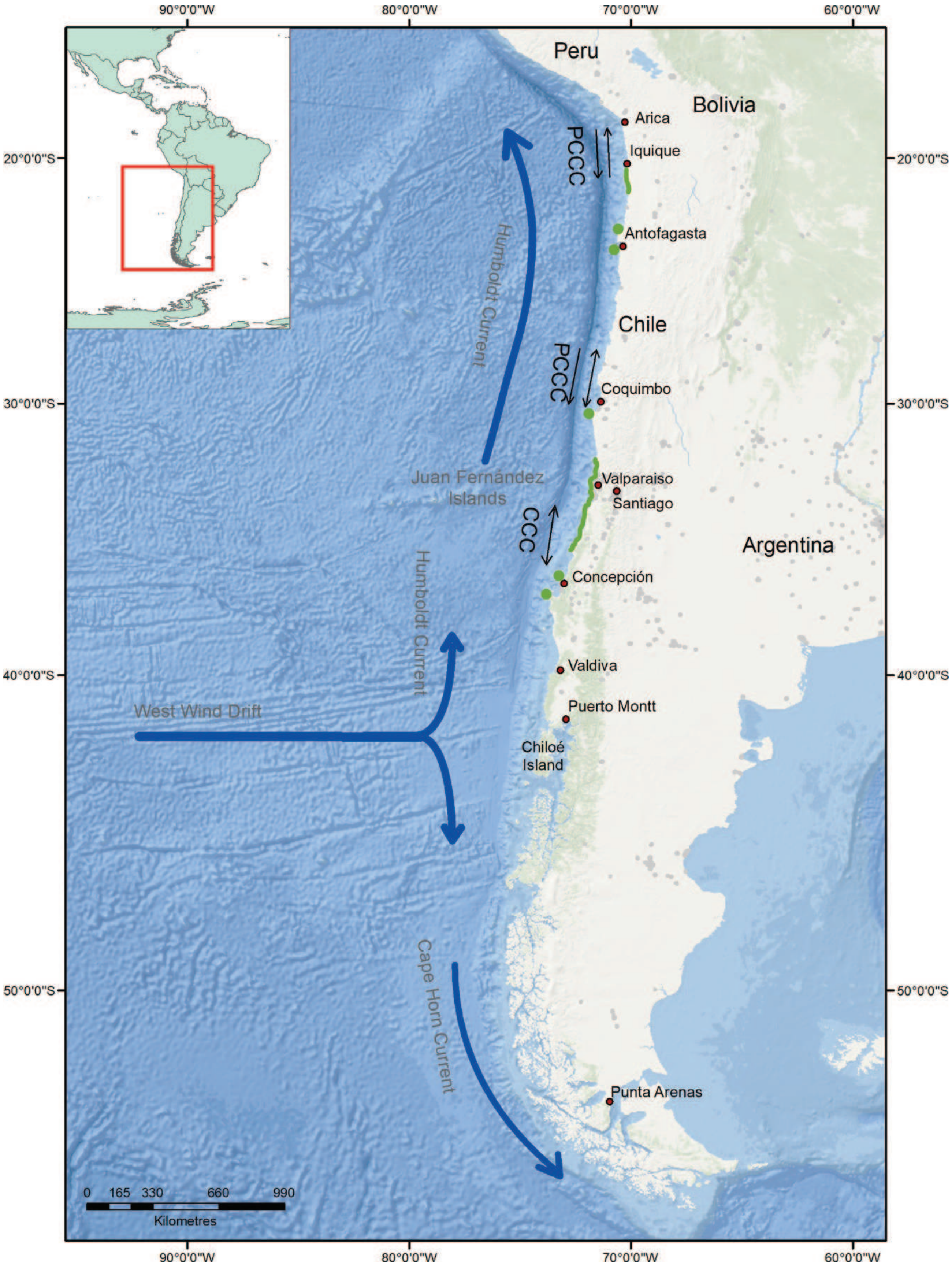

FIG. 29.1 Map of Chile, with principal currents and main geographic features of the Chilean continental coast.

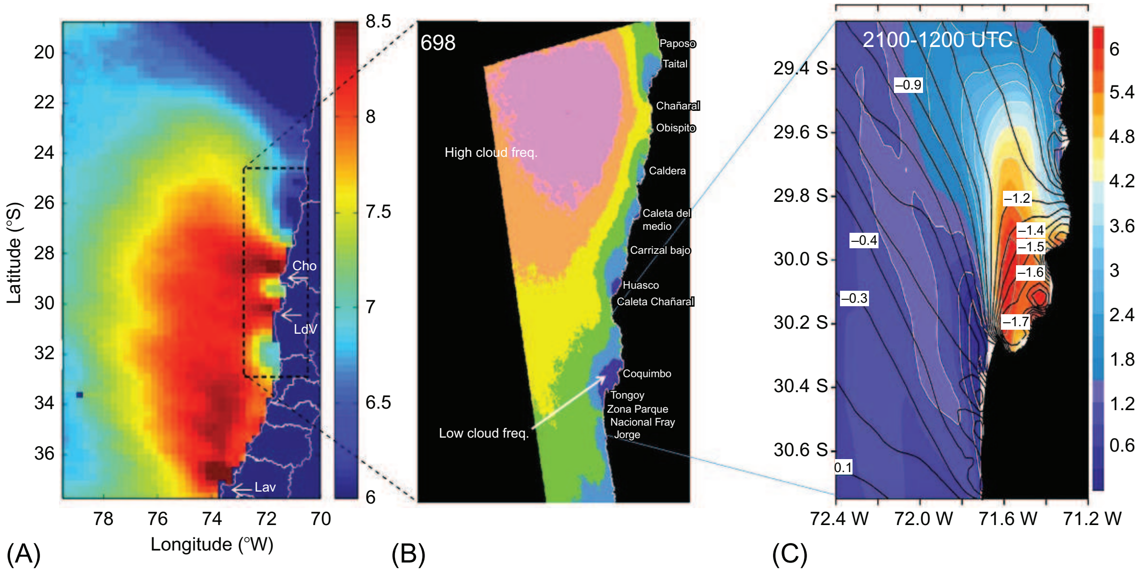

FIG. 29.2 (A) Austral spring-summer (SONDJF) average of surface wind speed derived from 4 years of QuikScat observations. Color scale at right in m s^{-1}. Note the nearshore coastal jet strengthening off Points Choros (Ch), Lengua de Vaca (LdV), and Lavapie (Lav). Adapted from Garreaud et al. (2011), their Figure 3b; (B) Austral spring (SON) climatology of low cloud frequency derived from visible GOES imagery. Adapted from Gonzalez et al. (2007), cited in Garreaud et al. (2011) their Figure 3c; (C) Simulated differences in surface pressure (hPa, contours) and 300-m temperature height air temperature (°C, color) between 17:00 LT and 08:00 LT (2100–1200 UTC) around Point Lengua de Vaca-Tongoy Bay (30.2°S). Adapted from Rahn et al. (2011), their Figure 14.

29.3 CLIMATE

Coastal upwelling ecosystems from north to south-central Chile (18°S–38°S) are driven by surface and subsurface ocean currents and localized coastal upwelling. The mean upwelling-active coastal strip, of around 50–100 km width is characterized by prevailing S–SW winds which, while variable in a wider range of time scales, strenghten from north to south. South of 27°S, quasi-weekly southerly (upwelling-favorable) wind events in austral spring/summer appear as coastal low-level jets centered around 150–200 km offshore with speeds exceeding 10–15 m s^{-1} (Garreaud & Muñoz, 2005; Muñoz & Garreaud, 2005) (Fig. 29.2A). The productivity of bays adjacent to capes and points (upwelling foci) benefits from enhanced solar radiation and cyclonic ocean circulation driven by the surface wind-stress curl during upwelling-favorable, cloud-free, wind events in connection with the quasi-weekly pace of coastal lows (Garreaud, Rutllant, & Fuenzalida, 2002; Garreaud & Rutllant, 2003; Rutllant, Masotti, Calderón, & Vega, 2004; Fig. 29.2B). During these wind events nutrient-rich and often oxygen-depleted subsurface waters reach the surface. This process culminates as soon as the center of the coastal low moves southwards, when mild NW winds bring oceanic waters to these bays stabilizing the water column, favoring phytoplankton blooms (e.g., Montecino, Paredes, et al., 2006; Montecino, Strub, et al., 2006).

The afternoon strengthening of the coastal southerlies occurs where cold-water advection, downwind from upwelling foci, contrasts with alongshore warm air advection from the heated land. This sharp contrast in air temperature has been documented over the Tongoy Bay area (Rahn, Garreaud, & Rutllant, 2011) (Fig. 29.2C) producing a local offshore surface pressure gradient that locally reinforces the coastal jet. An observed cooling trend along the coast (Falvey & Garreaud, 2009) has been related to enhanced upwelling (Garreaud & Falvey, 2009). Since strong southerlies result from a semi-geostrophic equilibrium between the alongshore pressure gradient and surface friction (Muñoz & Garreaud, 2005; Rahn & Garreaud, 2013), they are sensitive to southward expansion of the subtropical anticyclone in connection with anthropogenic global climate warming (e.g., Nguyen, Lucas, Evans, & Timbal, 2015). Rahn (2012) has reported somewhat stronger upwelling-favorable winds during the cold phase of the El Niño-Southern Oscillation (ENSO) cycle, the positive phase of the Antarctic Oscillation and when the subsident phase of the Madden-Julian intra-seasonal oscillation is around the central Equatorial Pacific. Over the past 150 years enhanced upwelling along the arid coast of northern Chile has been also related to a possible reduction in low-cloud cover (Vargas, Pantoja, Rutllant, Lange, & Ortlieb, 2007).

29.4 PHYSICAL OCEANOGRAPHY

The HCS is characterized mainly by a surface circulation toward the equator, a subsurface current toward the pole, and frequent events of coastal upwelling along the coast (Thiel et al., 2007). Two large upwelling regions can be defined: the northern zone between 18°S and 30°S and the central-southern one, between 30°S and 40°S (Escribano, Rosales, & Blanco, 2004; Strub et al., 1998). Where they meet at 30°S, upwelling-favorable winds and Ekman transport are the most intense. In the northern zone, upwelling occurs throughout the year, with a maximum between spring and summer (Monteiro, Dewitte, Scranton, Palmier, & van der Plas, 2011; Shaffer, Hormázabal, Pizarro, & Salinas, 1999), while in the southern part, there is a spring-summer upwelling regime and downwelling in winter. Generally, the most active upwelling centers occur near promontories such as Punta Choros (28.5°S), Punta Lengua de Vaca (30°S), Punta Curaumilla (33°S), Punta Topocalma (34°S), and Punta Lava Pie (37°S) (Figueroa & Moffat, 2000). A mechanism that modulates the upwelling is the Ekman pumping caused by the cyclonic wind-stress curl that is part of a defined band along the coast (Bakun & Nelson, 1991). Recently, this process has been reevaluated (Astudillo et al., 2017; Bravo, Ramos, Astudillo, Dewitte, & Goubanova, 2016), which allows for the improvement in the resolution of the meridional wind that decays toward the coast ("drop-off") in a coastal band of 50–100 km.

The coast is affected by ocean perturbations of equatorial origin. On the scale of 30–90 days, the variability in sea level and currents is mainly attributed to coastal trapped waves (Shaffer et al., 1999; Shaffer, Pizarro, Djurfeldt, Salinas, & Rutllant, 1997). However, part of the intraseasonal variability is forced by the local wind associated with equatorial atmospheric teleconnections (Hormazábal, Shaffer, & Pizarro, 2002). At lower frequencies, equatorial forcing is also important on a seasonal scale, especially in the semiannual time scales (Pizarro, Shaffer, Dewitte, & Ramos, 2002; Ramos, Pizarro, Bravo, & Dewitte, 2006) On an inter-annual scale, the variability of currents in the continental slope, thermocline depth and sea level are mainly due to remote forcing associated with ENSO (Pizarro, Clarke, & Van Gorder, 2001; Ramos, Dewitte, Pizarro, & Garric, 2008). (Escribano et al., 2004; Hormazábal, Shaffer, Letelier, & Ulloa, 2001). In addition, the coastal trapped waves, as they propagate southward, may interact with submarine canyons, producing a subsurface cooling of the ocean near the coast (Sobarzo et al., 2016).

Between 29°S and 39°S, there is a coastal transition zone extending from the coast to ~600–800 km offshore, which shows intense mesoscale activity with high values of eddy kinetic energy (Hormazábal, Shaffer, & Leth, 2004). Recent studies indicate the recurrent existence of superficial cyclonic and subsurface anticyclonic eddies (Morales et al., 2012). These are generated and detached from the core of the Peru-Chile subsurface current, moving in the form of subsurface "lenses" toward the west at an average speed of ~2 km d^{-1}. The oceanic influence of this type of eddies have been reported up to 900 km from the coast (30°S, 81°W) (Cornejo et al., 2016).

The discharge of freshwater from rivers is important, especially in the south, due to higher river runoff. Due to distinctive seasonality of river flows, the effects and dynamics of river plumes change throughout the year, influencing a wider coastal region during the winter (Saldías, Sobarzo, Largier, Moffat, & Letelier, 2012). In addition, the dynamics of river plumes can be controlled by the interaction of outflow inertia, buoyancy, Coriolis effect and wind forcing (Saldías et al., 2012). The effect of river dynamics on the transport and connectivity of organisms is a factor that should be considered in areas with high precipitation, especially since rivers also affect the local delivery of floating litter to nearby sandy beaches (Rech et al., 2014).

Finally, as a long-term trend, intensification of the southern wind along the coast is expected in the central-southern zone of Chile (Garreaud & Falvey, 2009), because of the intensification and displacement toward the pole of the South Pacific anticyclone (SPA) (Belmadani, Echevin, Codron, Takahashi, & Junquas, 2014). Schneider, Donoso, Garcés-Vargas, and Escribano (2017) showed that since 2007 there has been a cooling of the water column (Fig. 29.3) and an increase in the salinity of the upper layer of the continental shelf off Concepcion, mainly due to decrease in rainfalls. This is explained by the intensification of coastal upwelling mainly in winter as the result of the displacement of the SPA toward the south.

29.5 PELAGIC PRODUCTIVITY

The HCS is recognized as being highly productive, supporting one of the largest fisheries of the world, providing about 10% of the world fish catch (Montecino & Lange, 2009), due to the coastal upwelling that brings nutrient-rich subsurface waters to the surface and the ENSO (Thiel et al., 2007). These processes are also influenced by multi-scale perturbations (Montecino & Lange, 2009; Montecino, Strub, et al., 2006). In the HCS, three well-defined upwelling subsystems are recognized: (1) a productive seasonal upwelling system in central-southern Chile, (2) a lower productivity and rather extensive "upwelling shadow" in northern Chile and southern Peru, and (3) the highly productive year-round Peru upwelling system (Montecino & Lange, 2009).

Primary production (PP) was shown to experience great variability (Fig. 29.4) and coastal confinement of higher chlorophyll-a concentration (Chl-a) consistent with other eastern boundary currents (reviewed by Montecino, Pizarro, & Quiroz, 1998). Daily PP and Chl-a reported for different latitudes were as follows: 0.3–5.5 g C m^{-2} d^{-1} in Antofagasta (~23°S), 0.1–3.0 g C m^{-2} d^{-1} in Coquimbo (~29°S), 0.5–6.1 g C m^{-2} d^{-1} mean monthly values off Concepción (~36°S), and 0.1–1.4 mg C m^{-2} d^{-1} in fjords and channels (~42–56°S). More recently, PP studies were analyzed by Thiel et al. (2007) and Montecino and Lange (2009). With a mean of 0.8 g C m^{-2} d^{-1} from data obtained between 1998 and 2007, PP anomalies were positive and highest in the coastal southern area in spring, summer, and autumn (2.5, 8.8, and 3.7 g C m^{-2} d^{-1}) and negative and least in oceanic northern and southern areas, including data from exposed and protected areas in Quintay and Hualpén (33.19°S and 36.75°S, respectively).

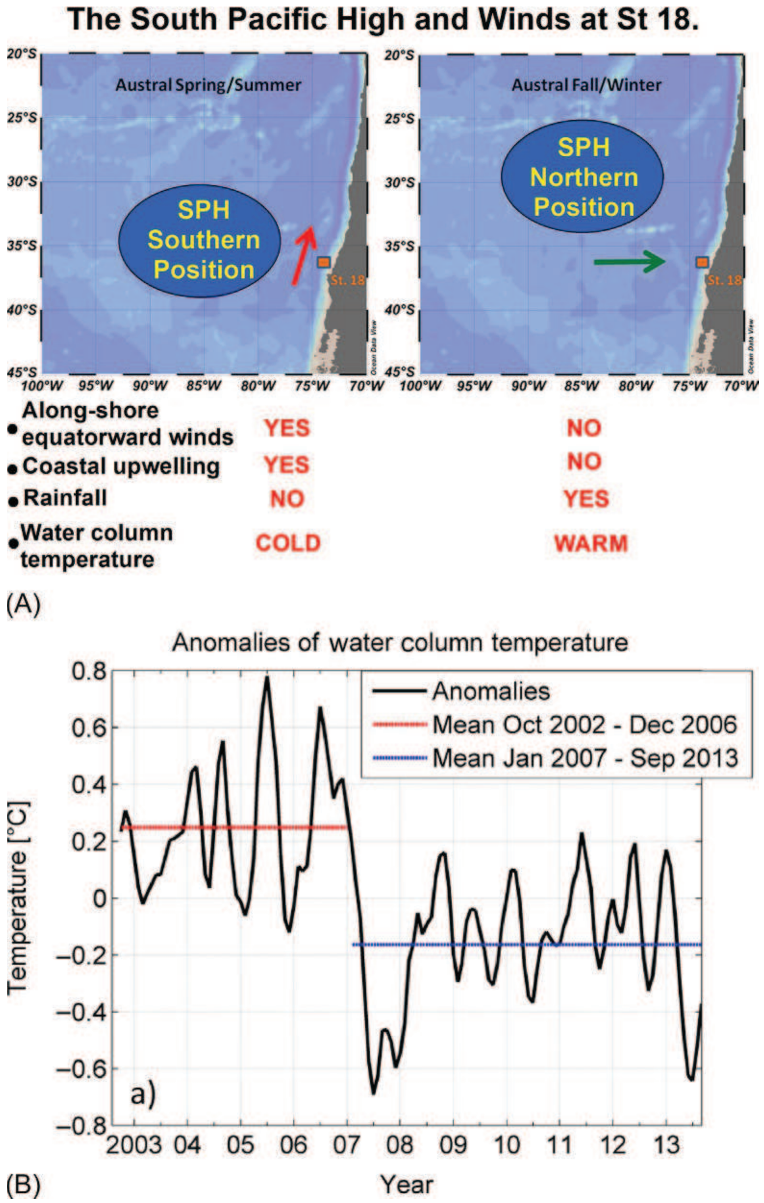

FIG. 29.3 (A) Seasonal position of the South Pacific anticyclone (SPA, also called South Pacific high), and (B) the changes in water column temperatures during the past decade caused by the southward movement of the SPA. *Modified after Schneider, W., Donoso, D., Garcés-Vargas, J., & Escribano, R. (2017). Water-column cooling and sea surface salinity increase in the upwelling region off central-south Chile driven by a poleward displacement of the South Pacific High.* Progress in Oceanography, 151, *38–48.*

Photosynthetic parameters P^{B}_{max} and Alpha (see Fig. 29.4), derived from the functional relationship between photosynthesis and irradiance experiments using a photosynthetron, showed that PP decreased with depth off Coquimbo whereas Alpha did not change (Montecino & Quiroz, 2000). At 30°S, PP did not vary between seasons (5.19 mg C mg Chl-a^{-1} h^{-1}), probably because of an adjustment of Chl-a under nutrient-deficient conditions (Henríquez et al., 2007; Montecino et al., 1998). Alpha is higher in autumn/winter compared with spring/summer, 0.068–0.031 (mg C mg Chl-a^{-1} h^{-1}) (mmol m^{-2} s^{-1}), attributed to phytoplankton photoacclimation (Fig. 29.4). Overall, PP can be affected by changes in acidification, winds, upwelling rates in the north, seasonality in central Chile, and temperature and freshwater runoff in the southern Patagonia and Magellan areas. Intensive aquaculture adds to the natural variability in nutrient availability. Recently, Aracena et al. (2015) indicated that meltwater from glaciers plays a crucial role in controlling fjord productivity. In the Patagonian fjords and channels, a nonproductive season might occur only during the three winter months (Montecino, Paredes, et al., 2006; Montecino & Pizarro, 2008; Montero, Daneri, Tapia, Iriarte, & Crawford, 2017). Little information is available about the spatial variability between the Chilean oceanic islands and continental Chile, but concentrations of Chl-a drastically

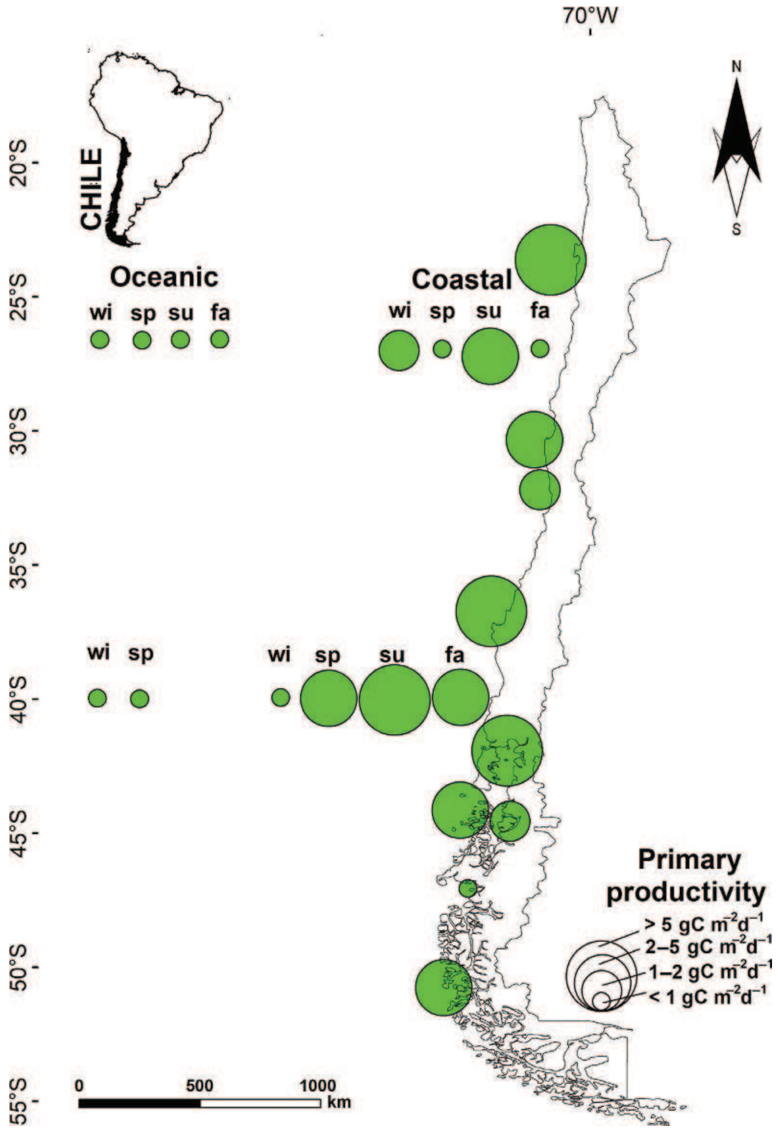

FIG. 29.4 Coastal and oceanic primary productivity (net/gross PP) in g C m^{-2} d^{-1} during different seasons from 1996 onwards. Photosynthetic parameters PBmax and Alpha mean values are also given for northern, central, and austral Chile (Iriarte, Pizarro, Troncoso, & Sobarzo, 2000; Montecino & Quiroz, 2000; Pizarro et al., 2006; Montecino, Astoreca, Alarcón, Retamal, & Pizarro, 2004; Montecino, Strub, et al., 2006; Montecino, Paredes, et al., 2006, Montecino & Pizarro, 2008, Montecino et al., 2013; Montero et al., 2017; Henríquez et al., 2007; Montecino & Pizarro, 2008; Jacob, Daneri, Quiñones, & Sobarzo, 2011).

decrease toward oceanic waters, where phytoplankton composition shifts toward smaller species (Von Dassow & Collado-Fabbri, 2014).

A review of the HCS by Montecino, Paredes, Ibáñez, and Landaeta (2013) refers to phytoplankton biomass (Chla-a) and also to algal blooms that can be considered as harmful algal blooms (HABs). A disproportionate increase in cell density could lead to hypoxia or anoxia, and diatom frustules can cause mechanical damage to the gills of fish, resulting in economic problems for marine farming and fisheries. Among the bloom-forming species in northern Chile are the dinoflagellates *Prorocentrum micans*, *Gymnodinium* spp. *Glenodinium* spp. and the ciliate *Mesodinium rubrum*. The latter is associated with upwelling processes, whereas dinoflagellate blooms in this region are related with ENSO. No information on PP is available in relation to HABs.

In southern Chile in 2016, HABs of the dinoflagellate *Alexandrium catenella* reached their northern extent at the offshore bifurcation of the HCS and the Cape Horn Currents west of Chiloé Island (43°S; 76°W). The average currents along the coast are weaker than those farther offshore in the HCS north of 42°S, due to the greater variability of currents within this zone. This appears also to be true inshore of the northern part of the Cape Horn Current between 46°S and 52°S (Strub et al., in preparation). Possibly this leads to higher retention of HABs in this area; however, currently no information on the short-term development of HABs or on PP studies exist for the Southern Chile Transition Zone.

Future research for understanding PP is challenging due to Chile's large latitudinal extent, with permanent upwelling in the northern coastal ecosystems and seasonal upwelling in the south, along with deep ocean and coastal systems that are periodically affected by ENSO disturbances. A priority objective is to monitor changes within each region by establishing an observing system with two or more permanent time series of PP measurements.

29.6 BENTHIC HABITATS

29.6.1 Rocky Shores

The intertidal and subtidal rocky shore habitat of Chile have been extensively studied, which has contributed information to manage coastal marine habitats and resources (e.g., Castilla, 1999; Fernandez et al., 2000; Gelcich et al., 2010). From northern to southern continental Chile, intertidal rocky shore habitats shift substantially in species composition and dominance following the environmental gradients along the coast (Santelices, 1991).

The dominant biota of the supratidal and intertidal zones from north to south are summarized in Table 29.1. Extending over such an ample latitudinal range, the changes are marked.

Kelp forests: from lower intertidal to shallow subtidal

TABLE 29.1 Most Representative Species of Different Functional Groups Present in Intertidal Habitats Along the Coast of Continental Chile (from North to South)

Functional Group	Intertidal Level	North (18°S–30°S)	Central (31°S–35°S)	South (36°S–42°S)
Ephemeral-opportunistic algae	High	*Ulva rigida, U. compressa, Pyropia* sp.	*Ulva rigida, U. compressa, Pyropia* sp., *Bangia* sp.	*Ulothrix flacca, Ulva compressa*
	Mid	*Ulva rigida, U. compressa, Centroceras clavulatum, Polysiphonia* sp. *Caulacanthus ustulatus*	*Ulva rigida, U. compressa, Petalonia fascia, Scytosiphon lomentaria. Centroceras clavulatum, Polysiphonia* sp. *Ceramium rubrum*	*Ulva rigida, U. compressa*
	Low			
	Mid	*Colpomenia sinuosa, C. trabeculata, Mazzaella denticulata, Glossophora kunthii*	*Mazzaella laminarioides, Gelidium chilense, G. lingulatum, G. rex, Dyctyota dicotoma*	*Mazzaella laminarioides, Gelidium chilense, G. pseudointrincatum, Mastocarpus latissimus*
	Low	*Gelidium chilense*	*G. lingulatum, G. rex*	*G. lingulatum, G. rex*
Kelps and Fucoids	Low	*Lessonia berteroana, (Lessonia berteroana and L. spicata present at 30°S), Macrocystis pyrifera*	*Lessonia spicata, Macrocystis pyrifera, Durvillaea antarctica*	*Lessonia spicata, Macrocystis pyrifera, Durvillaea antarctica*
Crustose non-calcareous (algae and lichens)	High	*Verrucaria* sp.	*Thelidium litoralis, Verrucaria* sp., *Hildenbrandia lecanelleri*	*Verrucaria* sp., *Hildenbrandia lecanelleri*
	Mid	*Hildenbrandia lecanelleri, Ralfsia* sp.	*Hildenbrandia lecanelleri, Ralfsia* sp.	*Hildenbrandia lecanelleri, Ralfsia* sp.
	Low		*Codium bernabei, Ulvella lens*	
Calcareous; encrusting and articulated				
	Low	*Mesophyllum* sp., *Lithophyllum* sp.	*Mesophyllum* sp., *Lithophyllum* sp., *Corallina officinalis*	*Mesophyllum* sp., *Lithophyllum* sp., *Corallina officinalis*

Continued

TABLE 29.1 Most Representative Species of Different Functional Groups Present in Intertidal Habitats Along the Coast of Continental Chile (from North to South)—cont'd

Functional Group	Intertidal Level	North (18°S–30°S)	Central (31°S–35°S)	South (36°S–42°S)
Filter feeders	High	*Jehlius cirratus*	*Jehlius cirratus*	*Jehlius cirratus*
	Mid	*Perumytilus purpuratus, Jehlius cirratus, Anemonia alicemartinae, Notochthamalus scabrosus, Patallus mollis, Phymactis papillosa*	*Jehlius cirratus, Notochthamalus scabrosus, Perumytilus purpuratus, Phymactis papillosa, Anemonia alicemartinae, Pyura chilensis*	*Perumytilus purpuratus, Jehlius cirratus, Notochthamalus scabrosus*
	Low	*Semimytilus algosus, Austromegabalanus psittacus*	*Semimytilus algosus, Balanus flosculus*	*Austromegabalanus psittacus*
Scavengers	High	*Leptograpsus variegatus, Orchestoidea tuberculata*	*Orchestoidea tuberculata*	*Orchestoidea tuberculata?*
Grazers	High	*Echinolittorina peruviana, Austrolittorina araucana, Lottia orbignyi, Siphonaria lessoni, Scurria viridula. Microlophus atacamensis, M. quadrivittatus*	*Echinolittorina peruviana, Austrolittorina araucana, Lottia orbignyi, Scurria zebrina, S. variabilis, S. araucana, Siphonaria lessoni. Microlophus quadrivittatus*	*Austrolittorina araucana, Lottia orbignyi, Scurria zebrina, S. variabilis, Siphonaria lessoni*
	Mid	*Chiton granosus, Scurria viridula, S. ceciliana, S. variabilis, Siphonaria lessoni*	*Chiton granosus, Scurria zebrina, S. ceciliana, S. variabilis, Siphonaria lessoni, Fissurella crassa*	*Chiton granosus, Scurria zebrina, S. ceciliana, S. variabilis, Siphonaria lessoni, Fissurella crassa*
	Low	*Enoplochiton niger, Tetrapygus niger, Loxechinus albus, Fissurella limbata, Chiton granosus, Tegla atra, Prisogaster niger*	*Tetrapygus niger, Loxechinus albus, Fissurella limbata, F. latimarginata, Chiton granosus, Tegula atra, Prisogaster niger*	*Fissurella picta, Chiton granosus. Nacella magellanica, N. deaurata*
Predators	High	*Leucophaeus modestus, Larus belcheri*	*Larus dominicanus, Haematopus ater*	*Larus dominicanus, Haematopus ater, Chroicocephalus maculipennis*
	Mid	*Haematopus ater, Leucophaeus modestus, Heliasther helianthus*	*Heliasther helianthus, Larus dominicanus, Haematopus ater, Concholepas concholepas*	*Larus dominicanus, Haematopus ater, Acanthina monodon*
	Low	*Meyenaster gelatinosus, Stichaster striatus, Heliasther helianthus, Luidia magellanica, Concholepas concholepas, Octopus mimus*	*Meyenaster gelatinosus, Stichaster striatus, Heliasther helianthus, Concholepas concholepas, Luidia magellanica*	*Meyenaster gelatinosus, Luidia magellanica, Stichaster striatus, Concholepas concholepas*

The lower intertidal level along the coast of Chile is characterized by the presence of the kelp species *Lessonia berteroana* which is distributed from 18°S to 30°S, where it is replaced by *Lessonia spicata*. Both are habitat-forming species that host diverse understory seaweeds (Santelices, Castilla, Cancino, & Schmiede, 1980) and invertebrates (Thiel & Vásquez, 2000). To the south of 30°S, the low-intertidal zone is also characterized by the presence of the fucoid alga *Durvillaea antarctica*, which extends to subantarctic coasts (Fraser, Thiel, Spencer, & Waters, 2010). All these algae are subject to intense harvesting by subsistence fisherman, and the reduction in their abundances is causing dramatic changes to intertidal and subtidal ecosystem structure (Krumhansl et al., 2016; Vásquez, Piaget, & Vega, 2012).

Among the most important consumers in kelp forests are the sea urchins *Tetrapygus niger* and *Loxechinus albus*, which feed directly on kelps and other foliose algae (Vásquez & Donoso, 2013). Although both species can destroy kelp beds on a local scale, *T. niger* is primarily responsible for the generation and maintenance of barren areas typically observed in northern Chile (Vásquez & Buschmann, 1997). The molluscan grazer *Enoplochiton niger* is also an important grazer in northern Chile where it can inhibit kelp recruitment at low intertidal levels (Aguilera, Valdivia, & Broitman, 2015).

Kelp-dominated subtidal habitats are characterized mainly by forests of *Lessonia trabeculata* and *Macrocystis pyrifera* (Fig. 29.5) (Macaya & Zuccarello, 2010). Consumer species are diverse, and characterized by fish, sea urchins, and turban

FIG. 29.5 Subtidal kelp forest of *L. trabeculata* with diverse associated species. Image courtesy of Alejandro Perez-Matus.

snails like *Tegula atra* (Vásquez & Buschmann, 1997). Omnivorous fish species also exert important grazing control (Pérez-Matus, Pledger, Díaz, Ferry, & Vásquez, 2012) (see Table 29.1), which seem to have strong direct effects on invertebrate assemblages (e.g., shrimps, bivalves, polychaetes, gastropods, amphipods, etc.) (Pérez-Matus et al., 2012). Other important species are echinoderms, which share food resources with fish species (Pérez-Matus et al., 2012; Vásquez & Donoso, 2013), and therefore can alter the habitat available to fish species in kelp forests (Pérez-Matus, Ferry-Graham, Cea, & Vásquez, 2007).

Due to the intense harvesting of kelps and consumer species (Godoy, Gelcich, Castilla, Lima, & Smith, 2016; Krumhansl et al., 2016; Vásquez et al., 2012), dramatic changes in rocky shore community structure are being reported in unprotected versus protected areas (e.g., Ory, Dudgeon, Dumont, Miranda, & Thiel, 2012; Pérez-Matus, Carrasco, Gelcich, Fernández, & Wieters, 2017; Fig. 29.6). An important part of the continental coast of northern Chile is being occupied by artisanal fishermen who build small and semipermanent fishing camps used for living and processing harvested kelps (MAA, personal observations). In addition, many rocky platforms are being reclaimed for port construction for mining industries and for tourism activities. Thus, there is increasing vulnerability of the rocky coastline to potential copper mine tailings (e.g., Fariña & Castilla, 2001), and litter (Thiel et al., 2011), as well as modification of the coastline.

29.6.2 Sandy Beaches

While the macrofauna community structure cannot be directly related to beach morphodynamics (Jaramillo, 2001), different processes related to wave disturbance patterns influence ecological processes on sandy beaches that harbor much abundant macrofaunal communities (up to 600,000 individuals m^{-1}, Jaramillo, 2001). Scavengers such as tenebrionid beetles, talitrid amphipods (*Orchestoidea tuberculata*), and tylid isopods (e.g., *Tylos spinulosus*) inhabit the upper beach zone (Kennedy, Naylor, & Jaramillo, 2000). Brachyuran crabs *Ocypode gaudichaudii* are common along the drift line in northern

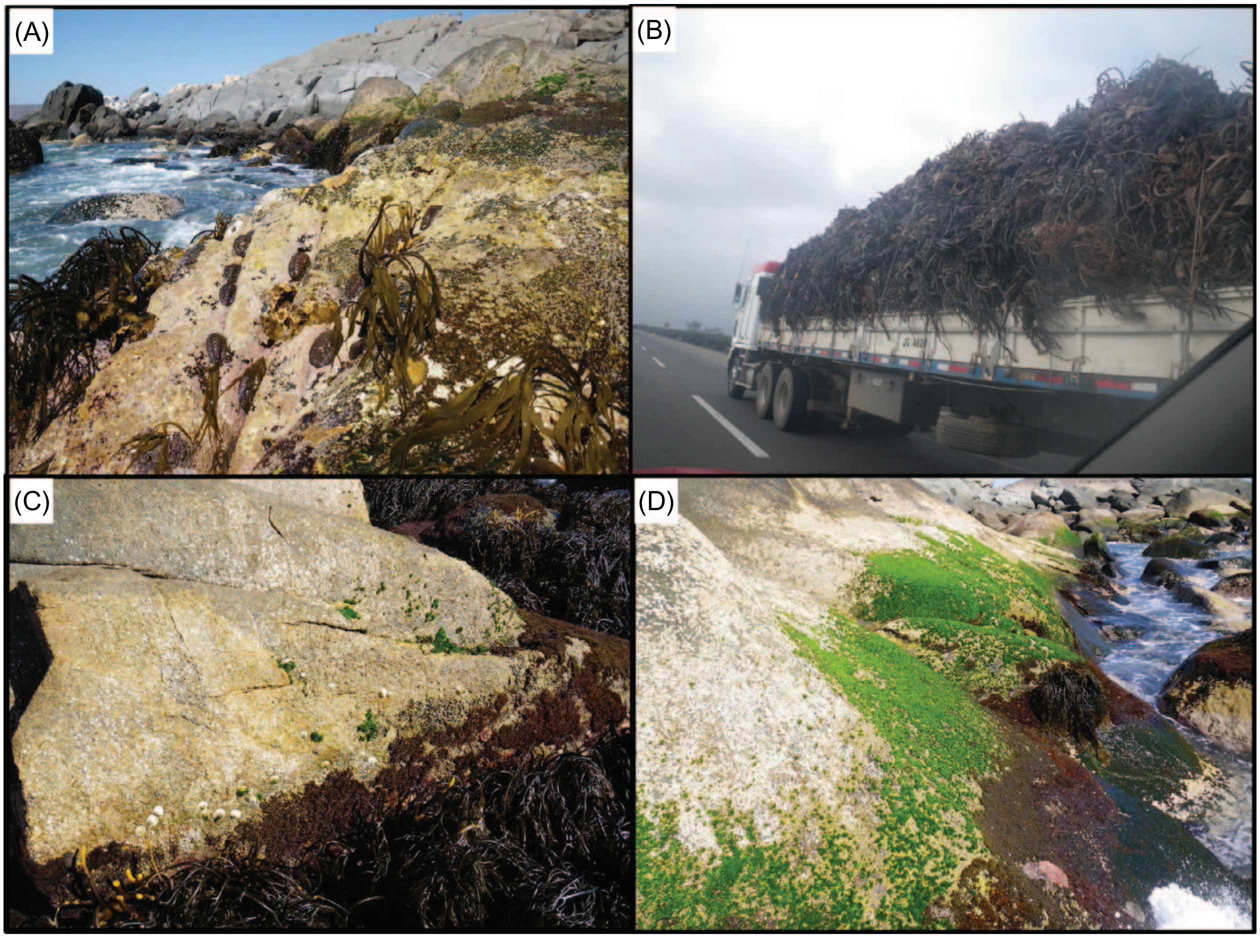

FIG. 29.6 Harvesting of *L. berteroana* and changes in community structure. (A) Recently harvested rocky shore with only small *L. berteroana* left intact, and the chiton *Enoplochiton niger* (not consumed) sheltering inside crevices. (B) Truck loaded with harvested *Lessonia* spp. (both *L. berteroana* and *L. spicata*) and *D. antarctica.* (C) High to low intertidal level showing the dense and intact belt of *L. berteroana* at Guanaqueros (~29°S), and (D) previously harvested area (> 12 months) with dominance of green ephemeral algae (e.g., ulvoids) and bare spaces in mid- and low-intertidal levels, respectively.

Chile, followed at lower levels by the hippid crab *Emerita analoga*, the isopods *Excirolana braziliensis* and *Excirolana hirsuticauda*, polychaetes like *Polydora* sp. and *Scolelepis* sp., and the surf clam *Mesodesma donacium*. Abundance of these species varies along the coast of Chile depending on sand grain size, wave disturbance, and/or ecological interactions (e.g., competition) among species (e.g., Jaramillo, 2001).

Copper mine tailing disposal in northern Chile (~26°S) has caused dramatic impacts and changes on sandy beach habitats (Lee & Correa, 2005; Lee, Correa, & Castilla, 2001). Persistent pollutants change the redox potential of sediments so it supports only few species (e.g., turbellarian worms).

29.6.3 Coastal Wetlands

More than 400 coastal wetlands have been reported from 18°S to 41°S, with a total area of almost 40,000 ha (Estades, Vukasovic, & Aguirre, 2012; Marquet, Abades, & Barría, 2012). However, about 60% of these have an estimated area < 10 ha and many of them are > 35 km distant from the nearest neighboring wetland. For birds, these spatial patterns of habitat distribution are highly fragmented, especially in more separated wetlands in northern Chile. More than 125 species of birds and 230 species of macrophytes have been identified in coastal wetlands (Estades et al., 2012; Ramírez & Álvarez, 2012) and in the desert region of northern Chile, making these coastal habitats zones of high species richness important hotspots of biodiversity. Even though some local wetlands are listed under the “Ramsar” convention and local strategies have been proposed for their management and conservation (CONAMA-CONAF, 2005), many coastal wetlands are threatened by intense urbanization and pollution.

29.7 COASTAL BIODIVERSITY AND BIOGEOGRAPHY

The coastline of Chile encompasses three broad biogeographic provinces: the Peruvian province extending from 5°S in Peru to 30°S, an intermediate transitional area that extends from 30°S to 42°S, and the Magellan province ranging from 42°S to 54°S (Camus, 2001). Patterns of biodiversity range from subtropical to subantarctic biota (Fernandez et al., 2000). The diversity and structure of these benthic communities are determined by interactions between broad-scale processes, such as vicariant speciation related to habitat fragmentation, mesoscale oceanographic processes influencing larval dispersal, and strong local selective controls such as predation and herbivory.

The Peruvian biogeographic province extends over a vast stretch of coastline, from Piura (5°S) to Coquimbo (~30°S). This sector experiences year-round upwelling, which contributes to the maintenance of the biogeographic break around Coquimbo (Haye et al., 2014; Tapia, Largier, Castillo, Wieters, & Navarrete, 2014), together changing the community structure of rocky shore intertidal communities around this latitude (Navarrete, Wieters, Broitman, & Castilla, 2005; Valdivia, Aguilera, Navarrete, & Broitman, 2015; Valdivia, Manzur, & Broitman, 2013). The Peruvian benthic assemblage is considerably less diverse than the poleward provinces (e.g., Rivadeneira, Thiel, González, & Haye, 2011), and is dominated by calcified crustose algae (e.g., *Lithophyllum* spp.), while the kelp belt in the low-intertidal zone extends northwards up to ~20°S (Broitman et al., 2011; Broitman, Navarrete, Smith, & Gaines, 2001; Tellier, Meynard, Correa, Faugeron, & Valero, 2009). However, the diversity of benthic fishes is dominated by subtropical elements and is higher than in the poleward provinces. This peaks around central Chile where several endemic species overlap with subtropical and subantarctic species (Navarrete, Lagos, & Ojeda, 2014). Perturbations associated with El Niño likely cause extirpation of the intertidal kelp stands of *L. berteroana* during strong EN events (Camus, 2001; Guillemin et al., 2016; Montecinos et al., 2012; Tellier et al., 2009).

An outstanding feature around northern Chile in Antofagasta bay is the invasion and habitat monopolization by the Australasian tunicate *Pyura praeputialis*, which has displaced most sessile species from the low- and mid-intertidal zone. After decades of habitat domination, human impacts are now removing the once-dominant tunicate over large sections of the bay, which is being recolonized by the former dominant species, highlighting the keystone effects of humans on rocky intertidal habitats (Manríquez, Castilla, Ortiz, & Jara, 2016). A similar case is observed for *Lessonia* spp. in northern-central Chile where intense human exploitation seems to severely curtail population abundance (Vásquez et al., 2012).

A broad transitional region extends from 30°S to 42°S, from Coquimbo to Chiloé; in this region the subtropical or Peruvian elements mix and are mostly replaced by subantarctic biota (Brattström & Johanssen, 1983). Interestingly, this zone is also where abundant populations of floating kelps are found (Fig. 29.7) (Hinojosa, Pizarro, Ramos, & Thiel, 2010; López, Macaya, Tala, Tellier, & Thiel, 2017). Around Chiloé, the poleward flowing branch of the West Wind Drift, favorable to downwelling circulation, is replaced by the equatorward-flowing HCS, where upwelling- conditions prevail (Strub et al., 1998). In this way, the clear division in biotas between the subantarctic and the temperate provinces is maintained by a major environmental gradient associated with differences in coastal oceanography (Camus, 2001). The extensive region of overlap of biotas from the Peruvian and Magellan provinces defines the transitional nature of the intermediate province, which is underpinned by the conditions alongshore, including seasonally favorable upwelling conditions (Strub et al., 1998; Broitman et al., 2001; Hormazábal et al., 2004; Letelier, Pizarro, & Nuñez, 2009). The coastline of the transitional region is marked by extensive soft-bottom habitats, where broadly distributed species, chiefly peracarid isopods and anomuran mole crabs dominate (Fernandez et al., 2000). Most of the coastline is rocky, where much experimental work on ecological dynamics has been carried out (Navarrete, Gelcich, & Castilla, 2010), notably the role of consumer species as determinants of community structure, and the keystone role played by humans in these food webs (Castilla, 1999; Fig. 29.8). Mobile consumers are supported by numerous algal species, notably Rhodophyta such as *Mazzaella* spp. and *Gelidium* spp. in the mid- and low-intertidal zone, and with the tidal zone dominated by a belt of large Phaeophyta, notably *Lessonia* spp. (Broitman et al., 2001; Santelices & Marquet, 1998). Intense consumer pressure at all tidal levels maintains extensive primary cover of fleshy and crustose algae (Broitman et al., 2001).

The Patagonian fjordland, or Magellan biogeographic province extending from 42°S to 54°S, is dominated by species broadly distributed around the Southern Ocean, such as the rafting kelps *M. pyrifera* and *D. antarctica* (Fraser, Nikula, Spencer, & Waters, 2009; Macaya & Zuccarello, 2010). These widely distributed species coexist with endemic species originating from vicariant processes driven by habitat fragmentation during the Last Glacial Maximum (LGM) and the extreme topographic complexity left by glacial processes, particularly around glacial refugia at the endpoints of the ice sheet. These historical and ecological processes have generated at least three inverse latitudinal gradients in diversity: algae, molluscs, and peracarid crustaceans (Rivadeneira et al., 2011, 2015; Santelices & Marquet, 1998; Santelices & Meneses, 2000; Valdovinos, Navarrete, & Marquet, 2003). For example, the coastal area around the 42°S endpoint was a glacial refugium during the LGM, from where subantarctic species colonized lower latitudes during the glacial period and recolonized higher latitudes after the end of the glaciation (Guillemin et al., 2016; Montecinos et al., 2012).

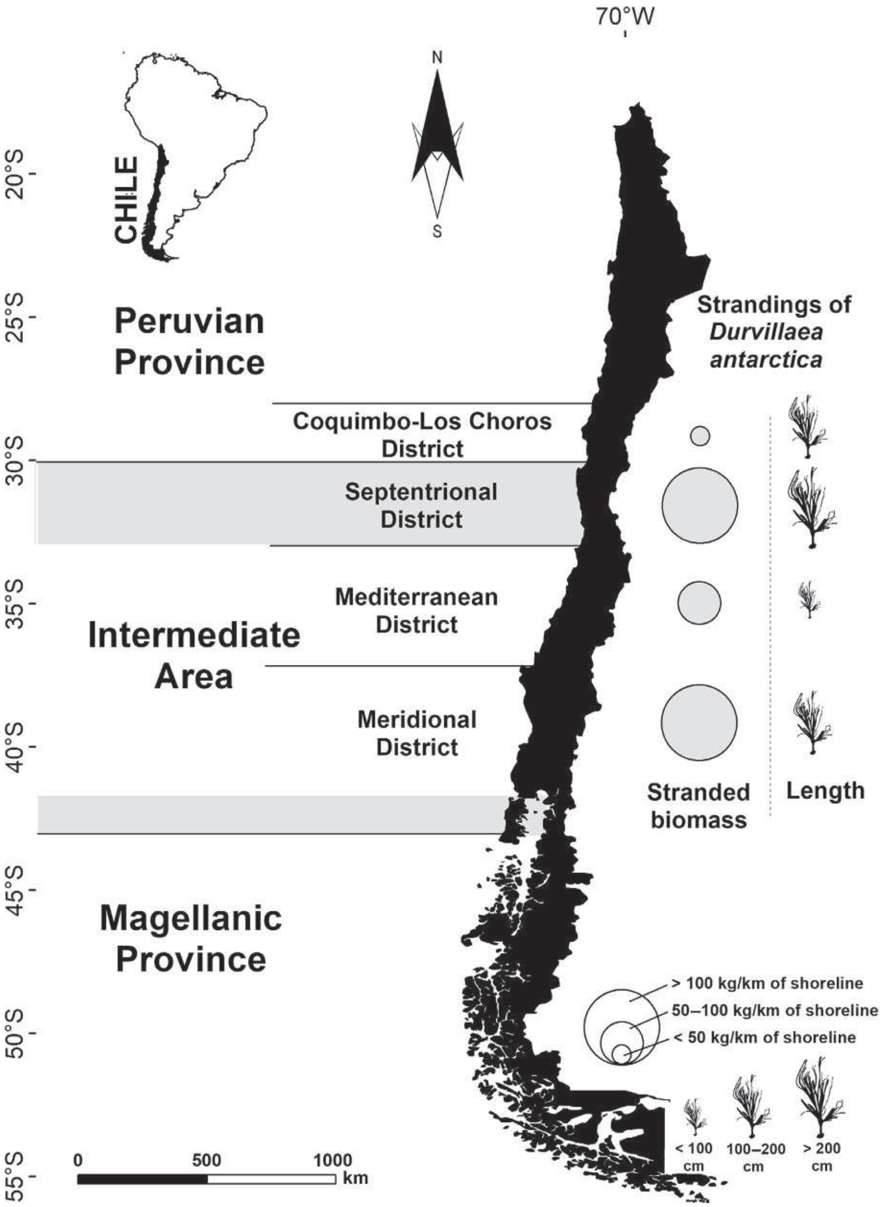

FIG. 29.7 Schematic overview of stranding biomass of bull kelp *D. antarctica* along the coast of southern-central Chile. The bull kelp together with the giant kelp, *M. pyrifera*, have major floating populations along the Chilean coast (Hinojosa, Rivadeneira, & Thiel, 2011). *Figure based on data from López, B. A., Macaya, E. C., Tala, F., Tellier, F., & Thiel, M. (2017). The variable routes of rafting: stranding dynamics of floating bull kelp Durvillaea antarctica (Fucales, Phaeophyceae) on beaches in the SE Pacific. Journal of Phycology, 53, 70–84.*

In summary, processes operating at broad scale, mesoscale, and local scale determine the biodiversity and biogeography of macrobenthic communities in Chile. The question of how these complex mechanisms are being altered in the current scenario of global change is still open.

29.8 HUMAN ACTIVITIES

29.8.1 Coastal Human Populations and Economic Activities

From northern (18°S) to southern (56°S) Chile, the country is divided into 15 political regions, which reflect the inherent heterogeneity of socioeconomic systems. Coastal cities in northern to central Chile have developed economic activities related to tourism, including important harbors dedicated to fishing and shipping. Northern cities (18–30°S) are located within the boundaries of the very dry Atacama Desert, and provide increasing opportunities for living and recreational

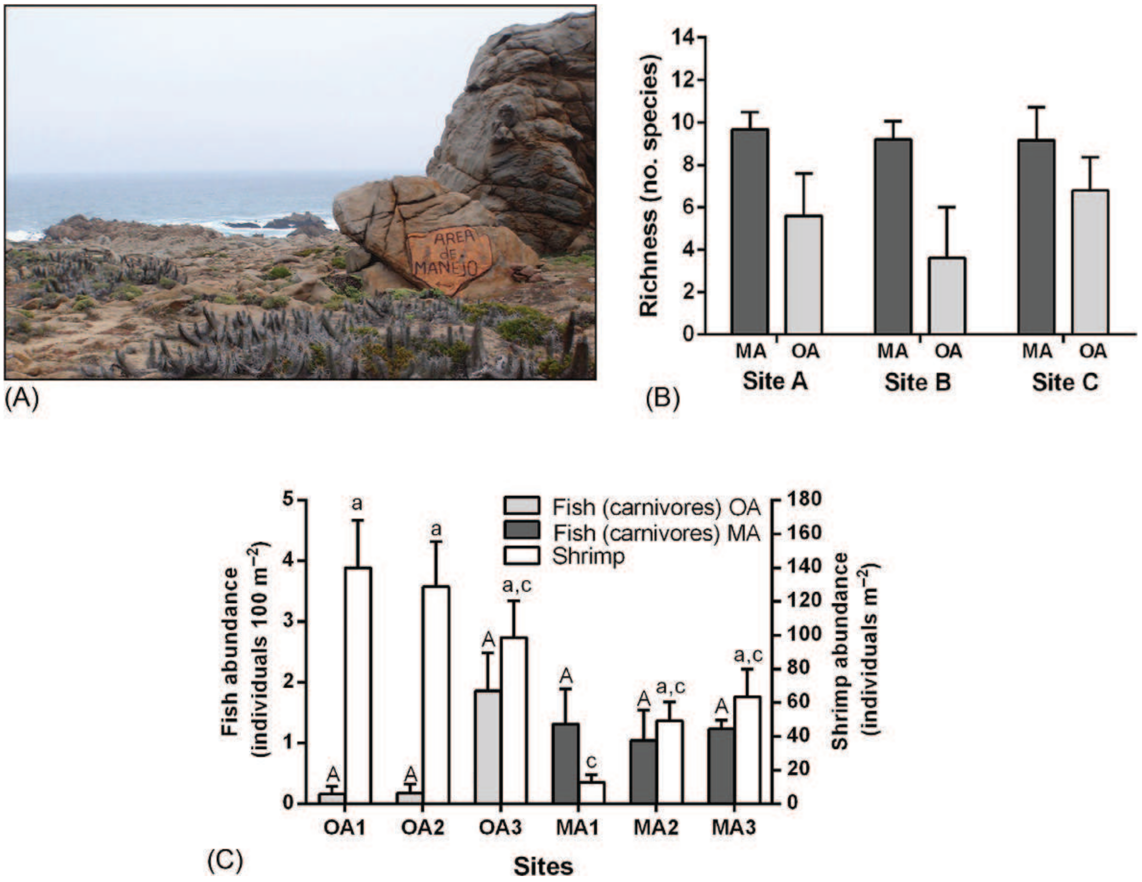

FIG. 29.8 Examples of changes in subtidal communities under different extraction regimes. (A) Some areas of the coast are designated as Management and Exploitation Areas for Benthic Resources (AMERBs for its initials in Spanish),which are called “Areas de Manejo” by the local community; in these areas only members of the local fishing community can extract resources according to assigned “cuotas”, and no other fishermen have access to these areas. (B) Differences in species richness of coastal fishes in Management Areas (MA) and Open Access areas (OA); modified after Gelcich, Godoy, Prado, and Castilla (2008). (C) Differences in abundance of coastal fishes of rock shrimp (*Rhynchocinetes typus*, a typical prey item of many rocky shore fishes) in MA and OA; modified after Ory et al. (2012).

activities on the coast. There are important ports dedicated to mining activities throughout this area. Coastal cities here are the most important urban centers in the region, with high human population pressures on coastal ecosystems. Moreover, activities related to mining (e.g., shipping, energy production, and other facilities) also occupy extensive coastal areas. Coastal cities in central Chile are the most populated coastal localities in the country (e.g., Valparaíso, Viña del Mar, INE, 2012), including the capital of the country (Santiago), and contain important tourism and port activities. Coastal cities in central-southern Chile are mostly harbors related to forestry, fishing, and intense aquaculture. In the farthest south where there are fjords, human population density is low and most activities are dedicated to aquaculture, fishing, and tourism.

29.8.2 Coastal Artificial Structures

Human activities and diverse coastal artificial infrastructures have caused habitat loss and changes in intertidal community structure (Aguilera, 2018). Artificial infrastructures like breakwaters, seawalls, pontoons, groynes, etc., are directly associated with coastal urban development and ports, stabilization of the shoreline, and with aquaculture. Therefore, most constructions are concentrated in cities with large ports. Most of these infrastructures generate novel habitats (Aguilera, Broitman, & Thiel, 2014), and some invertebrate groups (e.g., mussels, holothurians, worms) do not seem to be able to colonize these novel environments (Aguilera et al., 2014) even though some artificial structures resemble the spatial complexity found in other habitats like boulder fields (Aguilera et al., unpublished).

Coastal artificial infrastructure occupies ~200 km of the Chilean coastline from 18°S to 41°S (Aguilera, 2018), but future expansion of coastal cities and new port facilities will lead to an increase in these structures in coming decades, resulting in the imminent modification of natural habitats and the potential for nonindigenous invasive species colonization/expansion (see Bulleri & Airoldi, 2005). Given the expected sea-level rise and increase in storm frequency in coming decades, it is expected that more of these structures will be established (MOP-DOP, 2017). In addition, in northern Chile, the construction of artificial beaches for tourism purposes is also increasing, thereby enhancing the vulnerability of local ecosystems to accumulation of anthropogenic litter (Aguilera, Broitman, & Thiel, 2016) and to invasion by nonindigenous species (NIS) (Bulleri & Airoldi, 2005).

29.9 URBANIZATION AND COASTAL LAND RECLAMATION

Terrestrial coastal habitats also face coastal reclamation, construction, and privatization. Many coastal dunes and wetlands are being eroded (Marquet et al., 2012; Peña-Cortés et al., 2008). On older dunes in central Chile (~33°S), for example, destruction of vegetation cover is a consequence of agricultural, residential, or recreational uses, and not only results in an impoverishment of biodiversity, but also increases sand movement (Paskoff & Manriquez, 1999). In southern Chile, interventions to control sand movements have been made by extensive planting of "marram grass" (*Ammophila arenaria*), pines, and eucalyptus, causing many native species to be lost from these habitats (Paskoff & Manriquez, 1999). In northern Chile, for example, in La Serena, coastal urbanization for tourism purposes completely eroded the coastal dunes, leaving only incipient remnants of foredune patches (Fig. 29.9). In this way, the natural role of coastal dunes to mitigate wave action was replaced by seawalls, which collapsed during the tsunami produced when an 8.4-Mw earthquake hit the coast

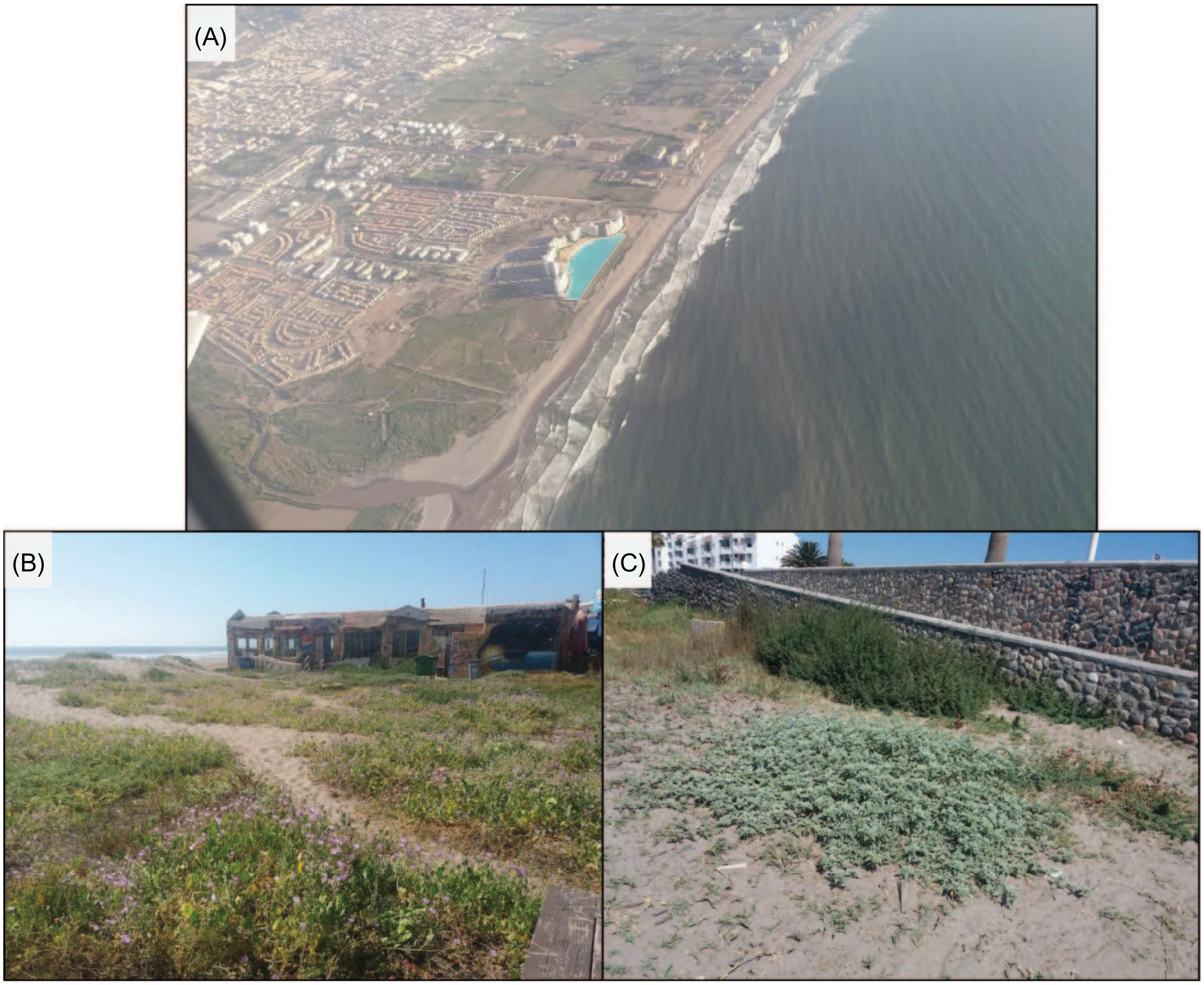

FIG. 29.9 Urbanization along La Serena coast. (A) Aerial view of La Serena city coast close to the Elqui river mouth (photo left), showing recent buildings with artificial lagoon close to the beach. (B) Remnant foredune and vegetation (e.g., *Cristaria* sp.) close to a building (restaurant) constructed onto the dune, and (C) a close view of concrete infrastructure for walkways and to stabilize the beach, and remnant patches of vegetation (e.g., *Ambrosia chamissonis*).

of the Coquimbo region in September 2015 (Rodil et al., 2015). Similar coastal erosion by urbanization occurs in coastal wetlands, where many private owners fill the wetland areas for construction purposes. Cattle grazing and disturbance of shorebirds by domestic dogs are also important factors altering biodiversity patterns in these ecosystems and are of great concern (e.g., Fariña, He, Silliman, & Bertness, 2016). Given privatization of many coastal areas along Chile, strong conflicts arise between economic activities and conservation priorities of these coastal systems and will become even more common in future decades.

Many coastal natural ecosystems have been "squeezed" by urbanization, especially coastal dunes and coastal wetlands, but some fragments still persist in some coastal cities. The challenge is to reconcile coastal urbanization and habitat conservation, and the Chilean Ministry of the Environment, created in 2010, must focus on protection and rehabilitation of urban coastal habitats. Coastal planning could consider, for example, preserving the "urban-natural habitat mosaic" based on optimization of ecosystem services provided by natural habitats, and give social values to them. Also, it could control the rate of urban expansion in small towns or villages with touristic interest, or in informal settlements of marine harvesters.

29.9.1 Land Use: Agriculture and Forestry

The Chilean coastal terrestrial ecosystems span a climatic gradient from one of the driest deserts in the world, the Atacama desert, through the Mediterranean climate region, some of the wettest temperate rainforests of the world, the Valdivian rainforests, to the subantarctic ecosystems on the southernmost tip of South America. Much of this area is part of the Chilean biodiversity hotspot generated by the high rates of endemism in the narrow strip of land between the Andes mountains and the Pacific Ocean.

The first records of human settlements date back to 14,500 BP (Dillehay et al., 2015). The abundant resources and the high accesibility were also important for the first European settlements in Chile. The central coastal area was especially suitable for Mediterranean types of crops familiar to Spaniards (Vargas, Torrejon, Pauchard, & Urrutia, 2017). Valparaiso, for example, has not only abundant native biodiversity but also the ideal climatic conditions for the settlers. In fact, Chile was a producer of wheat and other crops that were exported to Peru and even California until the late 1800s.

As populations grew along the coast, the terrestrial ecosystems started to suffer intense pressures, mainly due to the clearing of the land for crops and livestock and for heavy logging for city and vessel construction. *Nothofagus* and conifers such as *Fitzroya cupressoides* and *Pilgirodendron uviferum* were logged extensively in central and southern Chile. Forests and shrublands were decimated for charcoal production and firewood. In the north of Chile, where forests were quite limited and restricted to riparian areas, most of them disappeared when used for fuel in mining activities in the 1800s and early 1900s.

The devastation caused by forest logging and agriculture, and the unrestrained use of fire, in the coastal areas was so intense, that by early 1900s, naturalists and scientists called for remediation of the problem of erosion and soil loss. Erosion has led to extensive sedimentation of rivers and estuaries along the coast, but construction of many water reservoirs along all Chilean rivers again changed the sediment regime of many rivers, now severely reducing sediment transport to the coast; the consequences of these changes for the dynamics of estuaries and coastal wetlands are only poorly understood. Furthermore, reforestation programs were carried out along the coast, using exotic tree species that were much easier to grow. Industrial agriculture has continued to encroach into native ecosystems (Pauchard, Aguayo, Peña, & Urrutia, 2006). Along with the expansion of cities into wetlands, dunes, and other seminatural ecosystems, there is also an increasing surge of second home and vacation and resort developments outside the urban areas, which are especially impacting sensitive coastal habitats such as dunes and wetlands.

The future of ecosystems on the Chilean coast looks rather grim due to continuous urban sprawl, increasing influx of invasive species, and the reduction of natural areas for the expansion of traditional and new agricultural and forestry crops. In addition, climate change and human population growth are expected to increase the rate and intensity of wildfires. Thus, conservation planning must urgently address these multiple drivers in order to maintain the biodiversity and ecosystem functions of Chilean terrestrial coastal ecosystems.

29.10 INDUSTRIES, MINING, AND WASTEWATERS

Most human settlement and associated productive activities induce important environmental pressures along the coast of Chile. The nature and degree of impacts will depend on the characteristics of the activities (which shift along the latitudinal gradient), and the commitment to environmentally friendly practices and regulations.

In northern Chile, the presence of the Atacama Desert and substantial mineral reservoirs have resulted in the installation of important mining activities, mostly of copper (Cisternas & Galvez, 2014). Present Chilean regulations do not allow untreated mine tailings to be directly discharged to the coastal environment, but persistent impacts of copper pollution from former historical discharges and current illegal procedures have caused significant negative effects (Fariña & Castilla, 2001). Copper mine tailings have disrupted the structure of coastal organisms and communities, limiting the abundance of sensitive species and favoring the occurrence of other opportunistic ones (Lee & Correa, 2005; Vásquez, Matsuhiro, Vega, Pardo, & Véliz, 2000); for instance, locations with a high degree of copper pollution are dominated by the green macroalga *Ulva compressa*. Indeed, macroalgae have been identified as good biomonitoring species for metal pollution, mostly due to their sessile nature, relative tolerance to metal excess, and accumulation capacity (Moenne, González, & Sáez, 2016). Several locations in northern Chile are iconic representatives of metal pollution diagnosed on the basis of seaweed biomonitoring, such as in Chañaral bay, Caleta Palito, Caleta Zenteno, and Caleta Coloso (e.g., Correa et al., 1999; Ratkevicius, Correa, & Moenne, 2003; Vásquez & Guerra, 1996).

In central Chile the transition from an arid to semiarid and Mediterranean climate parallels a wider range of potentially toxic substances. Here, impacts are mostly related to nutrients, metals, and hydrocarbons. Excess nutrients, mainly phosphorus and nitrogen, have been well described in most of the hydrographic basins (e.g., Aconcagua, Rapel, Maule), and are attributed principally to urban wastewaters and agricultural land use (Donoso, Cancino, & Magri, 1999; Pizarro, Vergara, Rodríguez, Sanhueza, & Castro, 2010). Most large coastal cities have submarine sewage outfalls, some of which discharge only poorly treated wastewaters into the coastal zone and these are fueling PP and eutrophication (Woodland et al., 2015). Metal pollution (e.g., copper, zinc, cadmium) has also been observed near coastal urban and industrialized areas. For instance, the zone of Ventanas at 32.7°S is considered an "environmental sacrifice area," with multiple industrial and urban pressures from copper smelting and refining, a fuel factory, a coal-fired power plant, a harbor, and sewage outfalls, among others. The negative effects of metal pollution in this location correlates with accumulation of ephemeral seaweeds and changes in the structure of coastal communities (Sáez, Lobos, et al., 2012; Sáez, Pérez-Matus, et al., 2012). Although to a lesser extent, metal impacts have also been described from coastal waters near other central Chilean cities, such as Valparaíso and Constitución (Tapia et al., 2010; Valdés, Lobos, Díaz, & Sáez, 2017). Likewise, hydrocarbon impacts due to marine traffic and accidental spills have been recently reported, although principally from a sociological perspective (Saravia-Ramos, Armingol-Jaime, & Garland-Castro, 2014). Ecotoxicological research is pending in terms of oil and hydrocarbon impacts on coastal ecosystems of central Chile.

In southern Chile, most of the pressures are attributed to nutrient inputs (Fig. 29.10). Agriculture and livestock breeding, urban and industrial (mainly forestry) wastewaters generate important nutrient loads to river basins as is the case of the Itata, Bio Bio, and Las Cruces rivers (Leonardi, Vera, & Tarifeño, 2009; Marin et al., 2014; Pérez et al., 2015; Pizarro et al., 2010). There is also growing concern about the impacts of aquaculture (third most important economic activity in Chile), especially salmon farming, along the fjord areas between Chiloe and Patagonia (Fig. 29.11). Most salmon farms are located within the fjords, protected from strong currents and swells, to facilitate logistics and avoid important economic losses (Buschmann et al., 2009). However, this induces many byproducts, such as organic matter from excess food pellets and excretion, causing eutrophication events in the benthic zone with consequent ecological impacts (Buschmann et al., 2009; Urbina, 2016). Other associated detrimental effects of current concern related to aquaculture are metal contamination from the use of antifouling products, antibiotic inputs, and HABs caused by excess local nutrient (Apablaza et al., 2017; Buschmann et al., 2009).

Sediments from important shipping harbors contained high concentrations of PAHs and heavy metals, and bioassays showed strong effects on the fertilization potential of sea urchin sperm (Aguirre-Martínez, Rudolph, Ahumada, Loyola, & Medina, 2009). Even though this and other investigations show different levels of pollution, current information is insufficient to develop successful strategies to protect and remediate impacted ecosystems, especially from effects related to hydrocarbon pollution and from aquaculture. Moreover, there is scarce to almost nonexistent information on the effects of emerging pollutants, including antibiotics and endocrine disruptors.

29.11 WASTE MANAGEMENT AND PLASTIC LITTER

Most solid waste is deposited in municipal landfills, which generates a number of environmental impacts (Calvo, Moreno, Ramos, & Zamorano, 2007; Hérnandez-Berriel, Benavides-Márquez, González-Pérez, & Buenrostro-Delgado, 2008). Landfill disposal causes major cost for Chilean cities (Vásquez, Álvarez, Silva, & Muga, 2014) and so the need for efficient recycling has been long recognized (Vásquez et al., 2014). A new law for solid waste management and recycling has only recently been established (Ministerio del Medio Ambiente de Chile, 2016), but its implementation is lagging behind. Legal and illegal landfills also cause a number of social conflicts (Aliste & Stamm, 2016), highlighting the need for better recycling and reduction of solid waste. Given the costs of landfill deposition and the limited potential for recycling of most solid waste generated in Chile, it is not surprising that illegal waste dumping is ubiquitous (e.g., Vásquez et al., 2014). Illegal littering is especially common along river shores, and there is a high potential for this litter to reach the sea (Rech et al., 2015).

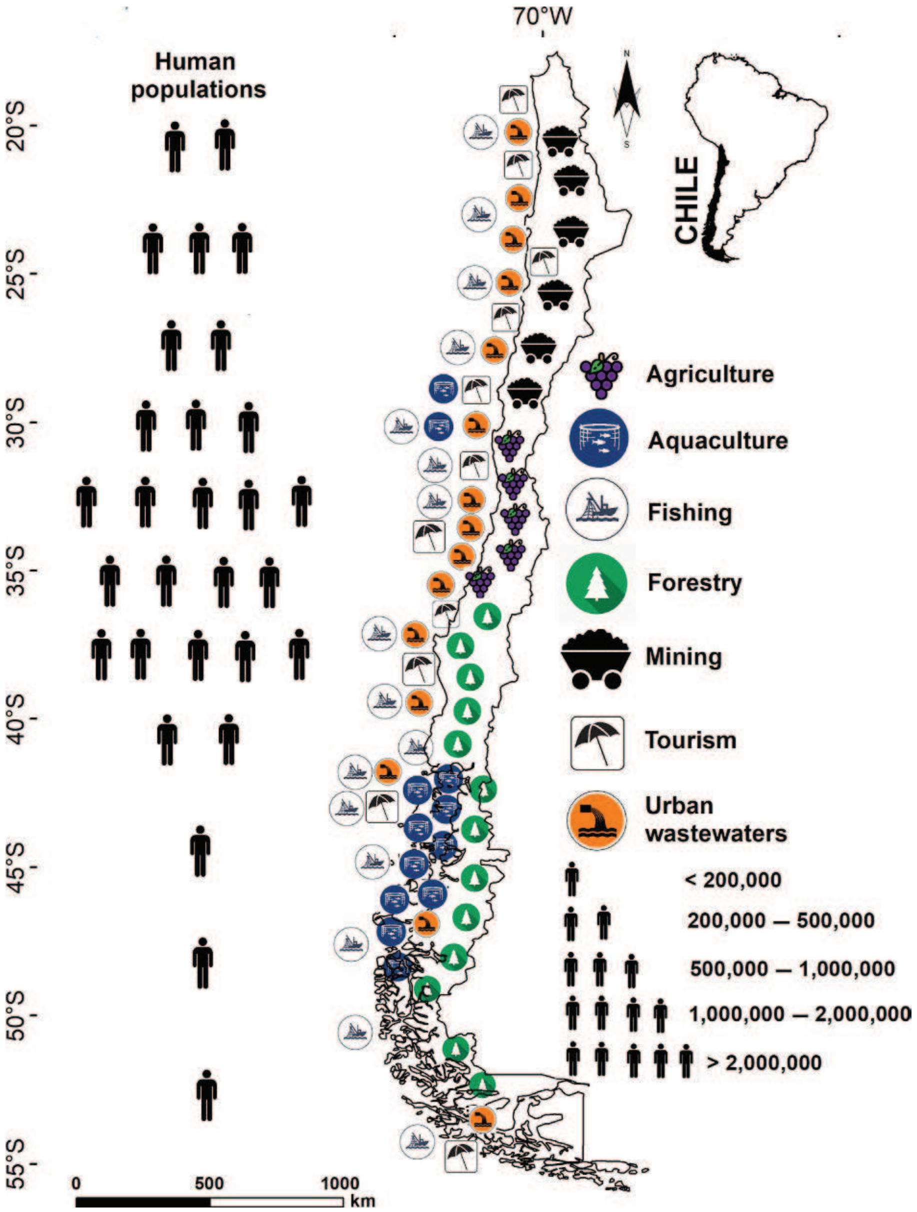

FIG. 29.10 Overview of human activities along the continental coast of Chile.

Anthropogenic marine debris (AMD) has been recognized as a major problem along the Chilean coast (Thiel et al., 2011). Many shorelines are severely contaminated. Sources of litter have been identified as beach visitors in northern Chile (Hidalgo-Ruz et al., 2018), rivers, beach visitors, and local fisheries in central Chile (Rech et al., 2014), and aquaculture in southern Chile (Hinojosa & Thiel, 2009). Rivers in central Chile also discharge large quantities of microplastics (Rech et al., 2015).

Litter impacts range from entanglement (Thiel et al., 2011), transport of (NIS) (Astudillo, Bravo, Dumont, & Thiel, 2009), to litter ingestion, although the incidence of microplastic ingestion by planktivorous coastal fishes within the HCS seems to be low (Ory et al., 2018). However, in some coastal habitats (e.g., tide pools), especially juvenile fishes might face a high risk of microplastic ingestion (Mizraji et al., 2017). Furthermore, artificial coastal infrastructures accumulate marine litter for long time periods (Aguilera et al., 2016), and potential impacts on biota might be higher in these environments. In general, while it is relatively well known that marine litter is an important problem along the HCS, and that sources are almost exclusively local, little is known about its potential impacts. While most sources have been identified, mitigation measures are not very efficient, most likely due to limited legal enforcement (Thiel et al., 2011).

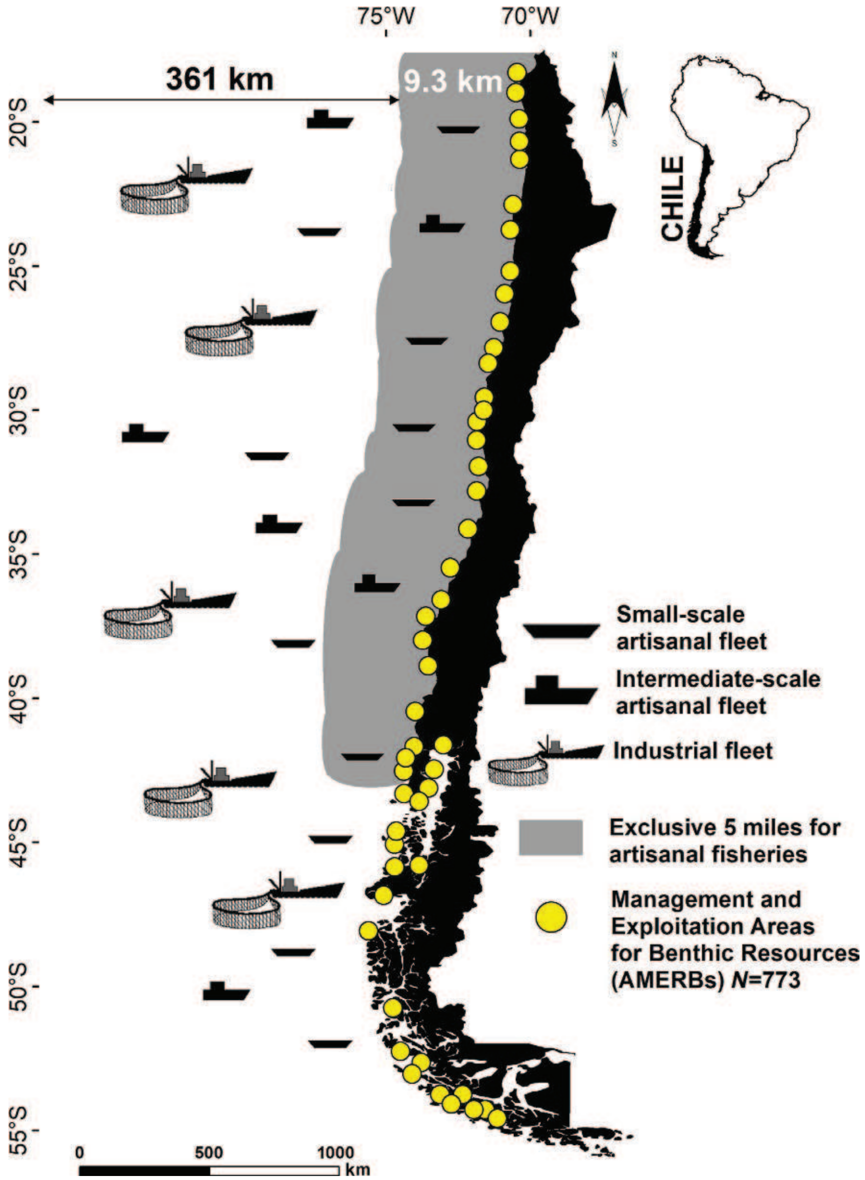

FIG. 29.11 Main fishing zones for the continental coast of Chile; modified after Gelcich et al. (2010).

29.12 SHIPPING, TRANSFER, AND INVASIVE SPECIES

Along the Chilean coast, at least 51 marine nonindigenous invertebrate and algae species have been reported (Castilla & Neill, 2009). However, only a few localities have been studied, and thus the number of NIS in Chile may be underestimated (see Villaseñor-Parada, Pauchard, & Macaya, 2017 for review). Furthermore, in Chile the taxonomic expertise for many groups is insufficient so many NIS may go undetected. Aquaculture operations are one of the main mechanisms facilitating the proliferation of NIS (e.g., *Codium fragile* var. *tomentosoides, Ciona intestinalis*) (Neill, Alcalde, Faugeron, Navarrete, & Correa, 2006; see also Naylor, Williams, & Strong, 2001; Villaseñor-Parada et al., 2017 for review) along with activities related to shipping (Castilla & Neill, 2009; Camus et al., unpublished), especially in coastal cities with developed ports and harbors (see Keller, Drake, Drew, & Lodge, 2011). For example, the invasive ascidian species *P. praeputialis* was introduced into Antofagasta Bay in northern Chile (~24°S), most likely by intense ship traffic during the early 1900s (Castilla, Guiñez, Caro, & Ortiz, 2004). Nowadays, *P. praeputialis,* which is found exclusively inside the Bay of Antofagasta, is considered a bioengineer species which enhances intertidal biodiversity (Castilla et al., 2004), but is currently under intense pressure by unregulated extraction (Castilla et al., 2004; Manríquez et al., 2016).

Management and official regulations to reduce NIS introduction by aquaculture and/or by ship ballast water are incipient (PA. Camus personal communication). Given port development motivated by the neoliberal economic politics of the country, there is an increase in shipping traffic and reports of ballast water discharged along the central and southern coasts during the last 3–10 years suggest that intense shipping traffic can bring species from diverse ecoregions worldwide (Camus et al., unpublished results). This has the potential to affect native species abundance and distribution (see Keller et al., 2011).

Some studies have focused on the role of artificial or man-made infrastructures as a habitat for different NIS (Dumont, Harris, & Gaymer, 2011; Manríquez, Fica, Ortiz, & Castilla, 2014; Turon, Cañete, Sellanes, Rocha, & López-Legentil, 2016). They provide suitable habitats for the establishment and subsequent spread of both intertidal and subtidal NIS (Bulleri & Airoldi, 2005; and see Firth et al., 2016 for review). With changing temperature regimes associated with climate change, the risk of range expansions of already established NIS along the Chilean coast might also increase during the coming decades (Jofré, Rivadeneira, Tala, & Thiel, 2014). Thus, there is a challenge to deal with the presence and future introduction of NIS into natural habitats, and with their associated impacts on biodiversity patterns and on the aquaculture economy (see Camus, 2005; Castilla & Neill, 2009 for discussion). Environmental monitoring plans are required to prevent introduction, and ongoing research based on ballast water risk assessments (Camus et al., unpublished results) is an important attempt to develop official protocols.

29.13 ARTISANAL AND INDUSTRIAL FISHERIES AND AQUACULTURE

Chile is the sixth largest exporter of seafood (FAO, 2016). According to SUBPESCA (Chile's national fishery and aquaculture agency), in 2016 the Chilean fleet produced 1.7 million metric tons of wild-caught fish, and aquaculture farms produced 694.382 tons, of which over 50% was Atlantic salmon. Chilean seafood exports were worth $3.45 billion USD in 2016 and account for an estimated 1.0% of the gross national product (GNP). Wild and cultivated fish, invertebrates, and algae are processed (mainly for export) in over 700 processing plants along the Chilean coast.

Salmon is by far the highest value species farmed in Chile and is an important activity in the south of Chile. It is the most important animal production system, and Chile has become the second largest salmon producer in the world. Currently, salmon farming provides direct and indirect employment to more than 70,000 people, often in remote areas with few other economic opportunities. Salmon farming has faced numerous challenging issues including production stability, sustainability, invasion, pollution, social transformations, and disease outbreaks. One important consequence of salmon farming is the invasion of marine and freshwater environments (Correa & Moran, 2017). Public policies have been trying to overcome these challenges through increased regulations. Infectious diseases have been identified as the major obstacle to further growth of salmon farming. Diseases have increased steadily since the beginning of the industry, and official fish health reports indicate that at least 15 different infectious agents have been diagnosed. These can cause from ca. 9% to 50% of the total mortality during a production cycle. Salmonid rickettsial septicemia (SRS) or piscirickettsiosis has historically been the most important health problem during the grow-out production phase (Mardones et al., 2018). The SRS is linked to the high use of antibiotics, causing effects on the environment and public health, raising public concerns (Buschmann et al., 2012) and market instability. Solving these issues is key for the future development of the industries.

The mussel aquaculture industry has undergone a rapid expansion for the past 20 years. The main expansion occurred in the 1990s, prompted by external market demand (Díaz, 2010). Its continuous growth is unparalleled by any other industry in the region (Bagnara-Vivanco & Maltrain-Donoso, 2008), and can be attributed to the simplicity of the culture system, low initial investment, and the existence of favorable oceanographic conditions (Díaz, 2010). Three mussel species are harvested in Chile: *Mytilus chilensis* (Hupé, 1854), *Aulacomya ater* (Molina, 1782), and *Choromytilus chorus* (Molina, 1782). The species with the highest economic and social importance is *M. chilensis* (Uriarte, 2008), and by 2014 it comprised 98% of the total mussel harvests in Chile. Over 99% of the mussel aquaculture industry is located in administrative region X (the Los Lagos Region) between 41°S and 44°S. An important aspect of the mussel aquaculture industry in Chile is that it is done by producers with limited technological developments (Díaz, 2010), who rely heavily on the prevailing environmental conditions (Uriarte, 2008). Mussel landings in Chile have increased exponentially by over 5000% from 1990 to 2011. A similar exponential growth was observed in the area used for mussel aquaculture area. In a 10-year time period the aquaculture area has expanded by over 900%, from 804 to 8413 km^2. Since 2005, mussel prices have remained relatively stable. Ocean acidification presents a threat to the industry, which is exacerbated due to the reliance on the environment for mussel spat and the current lack of adaptive capacity within the supply chain. Mussel aquaculture is also susceptible to HABs (Rivera et al., 2017).

Fisheries resources are key to economic, social, and environmental well-being in Chile. By nature, their extraction is based on a complex socioecological system that imposes severe governance challenges (Ostrom, 1990). The need to balance competing uses in the oceans has led Chile to try and aim for an ecosystem-based approach to fisheries management that involves the integrated management of species and other natural commodities/services. The trend toward multi-scale ecosystem-based governance has begun to be manifest in a rescaling of small-scale fisheries governance, mixing “top-down” directives from government with “bottom-up” approaches in which fishers participate directly in policy implementation (Gelcich et al., 2010). Initially, this trend took the form of a comanagement approach, which granted exclusive territorial user rights [territorial users rights for fisheries (TURFs), or AMERBs, see below] to artisanal fishers for the management of benthic resources (Castilla, 1994; San Martín, Parma, & Orensanz, 2010). More recently, in 2013, Chile acknowledged that the comanaged AMERB system was not sufficient to achieve coastal sustainability and that new complementary overlapping governance approaches were necessary to include the management of multiple species in areas which are not part of the AMERBs (Gelcich, 2014). Consequently, Chile passed legislation to create what have been termed Management Plans (Planes de Manejo; Fisheries and Aquaculture Law 20657, 2013).

29.14 MANAGEMENT AND CONSERVATION

29.14.1 Fisheries Management

The 1991 Fishery and Aquaculture Law No. 18 892 (hereafter: FAL) drastically reformed the right to fish within and between the industrial and artisanal fishing sectors (Castilla, 2010). Among the regulations addressed in the FAL are the mobility of the fleets throughout fisheries zones, allocated exclusive TURFs, and the differential and individual transferable quota for fully exploited species (Gelcich et al., 2010).

The FAL incorporated two new regulations that established user rights for artisanal fishers. The first is exclusive fishery access rights (to all species) within a zone that extends up to five nautical miles from the shoreline along ca. 2500 km of coast (see Fig. 29.11) and around Chilean oceanic islands, to reduce conflicts mainly between mid-scale, artisanal, and industrial fleets (Castilla, 2010; Gelcich et al., 2010).

The second regulation was the assignment of territorial user rights for benthic fisheries, called Management and Exploitation Areas for Benthic Resources (AMERBs for its initials in Spanish, see yellow dots in Fig. 29.11). The AMERBs were created as a fishery comanagement tool, as a way to find a solution to what was considered a crisis around the economically important small-scale diver fishery of the Chilean abalone *Concholepas concholepas*, called “loco,” during the 1980s (Aburto et al., 2013; Castilla & Defeo, 2001; Stotz, 1997). The AMERB system targets small-scale fisheries and acquired worldwide attention (Aburto et al., 2013), being described as a success to solve problems associated with administration of benthic small-scale fisheries (Gelcich et al., 2010). The AMERB system was conceived in a top-down way and was greatly fostered by the authorities (Aburto & Stotz, 2013; Gelcich, Edwards-Jones, & Kaiser, 2005; Meltzoff, Lichtensztajn, & Stotz, 2002), establishing a *de novo* access regime (San Martín et al., 2010), which assigns exclusive fishing rights for the exploitation of benthic resources, in defined coastal stretches, to legally constituted fisher organizations. The main incentive for fishers to get into the AMERB system was that it became the only way to regain legal access to the “loco” fishery, as that fishery was, and continues to be, completely closed in open access areas (Aburto et al., 2013). The implementation of the AMERB system involved a shift from top-down control by government to comanagement (Aburto, Stotz, & Cundill, 2014).

The fast recovery of “loco” stocks in some AMERBs (Gelcich et al., 2010; San Martín et al., 2010) caused a great demand for coastal stretches by diverse fishers’ organizations in order to establish AMERBs (Aburto, Thiel, & Stotz, 2009; Gallardo & Friman, 2010). The AMERB system, initially developed around the “loco” fishery, currently includes about 27 benthic resources in the management plans (SERNAPESCA, 2009). Officially, there were 773 AMERBs with a total of 114,247 ha (see Fig. 29.11). Of these, 512 are decreed and assigned to an organization, with a total of 74,216 ha of coastline under AMERB regimes (Aburto et al., 2013). This mass replication of a management strategy did not consider the wide cultural, social, economic, productive, and organizational diversity that exists along the Chilean coast.

The AMERB system even called the attention of fishers targeting pelagic resources or occasional fishers from coastal agriculturally based populations (Van Holt, 2012), which saw in the system a way to diversify their productive activities (Aburto et al., 2013). As diverse organizations with multiple characteristics and fishing traditions entered the system, different objectives were agglomerated under the umbrella of this single fishery administrative tool (Aburto et al., 2013). This has led to variable results in the implementation and functioning of AMERBs. While some AMERBs have achieved ecological success, due to resource population recovery, many problems related with unsatisfactory economic outputs have emerged (Gallardo & Friman, 2010). Among the main problems are conflicts due to exclusion of traditional users by the implementation of AMERBs and the erosion of traditional practices by the fishing community after AMERB implementation (Aburto et al., 2013; Gelcich, Edwards-Jones, Kaiser, & Castilla, 2006), by competing organizations over the same space, and even gendered conflicts (Gallardo & Friman, 2010).

The Management Plan legal framework generated for national and local fisheries agencies allows for a joint process with fishers and the fishing industry (industrial and artisanal) to create locally agreed-upon fishery management plans that can operate at different geographical scales (cove, bay, administrative region, set of regions), for different species or multiple species (SUBPESCA, 2014). The law explicitly includes ecosystem-based management principles by allowing the mix of "top-down" directives from government with "bottom-up" approaches in which fishers directly participate in policy implementation (Gelcich et al., 2005; FAO, 2016). One key feature of this law was the creation of a new participatory arena, named management committees, which are responsible for the design of fishery management plans and in which all stakeholders are represented. Another important feature relates to the functioning of Scientific Committees which can now set mandatory fishing limits (Reyes, Gelcich, & Ríos, 2017). This policy change aims to improve the conservation and sustainability of marine resources by applying the precautionary principle and ecosystem-based management through a mandatory management goal for the government agency to reach or maintain fish stocks at their maximum sustainable yield (MSY) level. Since its establishment in 2013, ~ 33 management plans have been drafted. While the law is inherently flexible (e.g., ability to include multiple species), plans to date focus on a single-species approach, and rarely address multispecies or ecosystem processes. Plans should be updated every 5 years (with the first renewals occurring in 2019 which presents an opportunity to improve the plans and their execution). However, there is an urgent need to fine-tune the system, build capacity of governmental fishery managers and private consultants in charge of working on management plans, and investing the necessary funds to articulate these new multi-stakeholder arenas which are being created along the Chilean coast (Reyes et al., 2017).

29.14.2 Conservation

Marine conservation is a recent issue in Chile. The FAL incorporated for the first time two categories for marine biodiversity conservation: marine reserves and marine parks, equivalent to IUCN categories II and I, respectively (Jorquera-Jaramillo et al., 2012). In 1997, the first marine reserve was created (La Rinconada), with a resource-based approach of protecting a bank of the Peruvian scallop *Argopecten purpuratus*, albeit the achievement of this goal remains questionable (Avendaño, Cantillánez, & Thouzeau, 2017). It was not until 2005 that Choros-Damas and Chañaral marine reserves were created (Fig. 29.12), incorporating ecosystem elements such as habitat for charismatic and non-commercial species (Cárcamo & Gaymer, 2013). Choros-Damas MR (marine reserve) was used as a model for developing the first management plan (MP) for marine protected areas (MPAs) in Chile, in a collaboration effort with the Port-Cros National Park in France (Gaymer et al., 2014; Thompson, Dumont, & Gaymer, 2008). This pioneer experience is being used for developing MPs for other coastal MPAs in Chile, such as Chañaral MR.

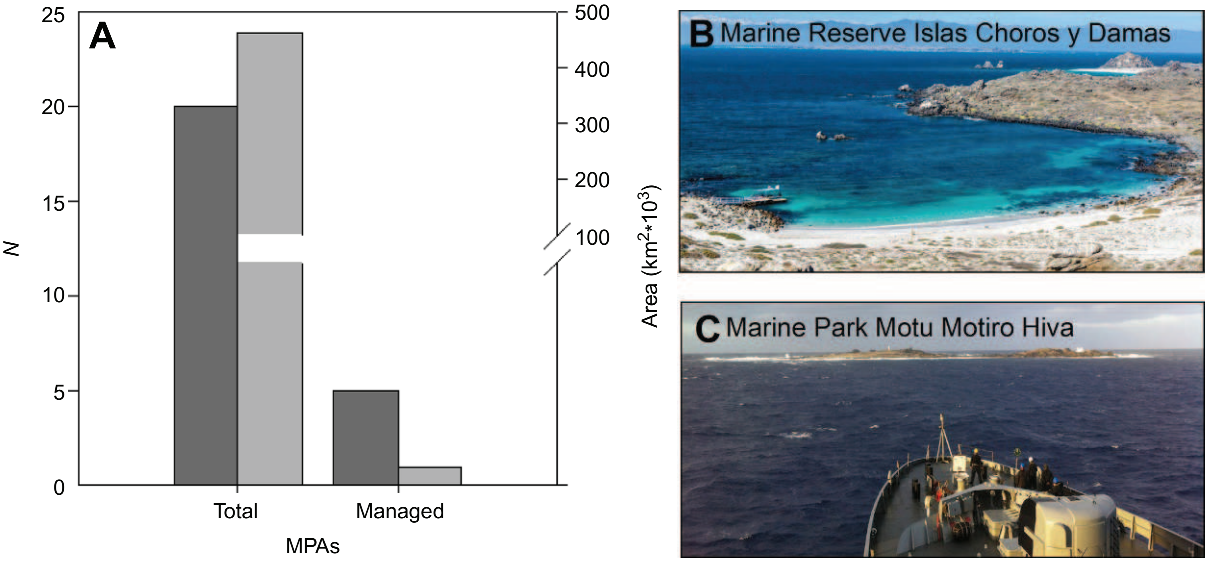

FIG. 29.12 Marine protected areas (MPAs) along the Chilean coast. (A) Number and extension of established MPAs (total) and number of MPAs that have a management plan (managed); figure modified after Petit et al. (2018). (B) "Islas Choros-Damas Marine reserve"; Image courtesy of Felipe Sáez. (C) "Motu Motiro Hiva Marine Park" with the central island of Salas y Gomez; Image courtesy of Diego Miranda-Urbina.

The Chilean legislation has a mosaic of explicit conservation and/or management measures relying on different ministries (Economy, Environment, Defense, and Education), which complicates marine conservation strategies because of the overlap between government agencies, difficulties in inter-agency coordination, and lack of funding (Cárcamo & Gaymer, 2013). Some of these problems should be solved with the creation of the Biodiversity and Protected Areas Service, presently being discussed in the Chilean Congress that will concentrate marine and terrestrial protected areas under the Ministry of the Environment (Squeo et al., 2012).

Under the Aichi Target 11 of the Convention for Biodiversity (CBD) Chile has undertaken to protect 10% of its marine and coastal ecosystems by 2020 (Rojas-Nazar, Gaymer, Squeo, Garay-Flühmann, & López, 2012). Several small coastal areas have been created in the last 10 years, but their small sizes meant that until 2010, Chile had only 0.03% of its economic exclusive zone (EEZ) protected (Jorquera-Jaramillo et al., 2012). However, a substantial advance has occurred in the last few years, with the creation of five large-scale MPAs (LSMPAs), the Motu Motiro Hiva Marine Park (MMHMP) in 2010, the Nazca Desventuradas Marine Park (NDMP) in 2016, the Juan Fernández and the Islas Diego Ramirez-Paso Drake Marine Parks in 2018, and the Rapa Nui Multiple Uses Marine Protected Area in 2018, which has allowed Chile to protect ~>40% of its EEZ (Friedlander et al., 2016; Petit, Campoy, Hevia, Gaymer, & Squeo, 2018; Fig. 29.12). These LSMPAs made a significant contribution to achieve the global protection targets (Toonen et al., 2013; Wilhelm et al., 2014).

Major challenges are still ecological representativeness and effective management of the MPAs. Almost 90% of currently protected areas only represent the three marine ecoregions in oceanic islands, whereas the other MPAs in continental Chile only protect <8% of the total area of the remaining ecoregions, and ~98% of this protection is concentrated in the Channels and Fjords of Southern Chile ecoregion. The reason for this is that both oceanic MPAs are located in remote inhabited areas with limited use and low conflict potentials, in contrast to continental areas that are heavily populated and have multiple uses. This issue has been initially addressed by the creation of a new LSMPA in the Channels and Fjords of Southern Chile ecoregion and another potential one in the Central Chile ecoregion (discussed in the IMPAC4, in Coquimbo 2017). Only 0.1% of the total MPA surface has an MP associated, however, none of them is effective (Petit et al., 2018). Recent advances have been made by the development of the first MP for LSMPAs in Chile, for the NDMP (Gaymer et al., 2014; Gaymer et al., 2018), which means that Chile will have more than 50% of MPA coverage with a management plan associated.

Recently created and announced MPAs have had strong involvement of local communities, which contrasts with previous initiatives that were mostly top-down from the government (Cárcamo & Gaymer, 2013; Jorquera-Jaramillo et al., 2012). Effective participatory processes are crucial for successful conservation measures (Cárcamo, Garay-Flühmann, Squeo, & Gaymer, 2014; Gaymer et al., 2014).

29.15 CONCLUSIONS AND OUTLOOK

Climate change poses multiple risks to natural ecosystems and to the sustainability of activities like fisheries and aquaculture in Chile because of the increased frequency of extreme events that lie outside the realm of present-day experience. In terms of coastal marine economic activities, adaptive capacity to cope with uncertainties derived from ecosystem responses to climate change need to be reached. Adaptive capacity is a latent characteristic that would reflect the ability of the fisheries and aquaculture industries to cope with and recover from the consequences of, and take advantage of, new opportunities arising from change (Cinner et al., 2018). A research agenda to understand and develop the adaptive capacity of the aquaculture and fisheries sectors is key for Chile to be able to navigate transitions toward more sustainable pathways. This research agenda will have to address both social and ecological determinants of adaptation in addition to creating learning platforms where multiple knowledge systems can be integrated and inform new ways of thinking about adaptive opportunities and the necessary policy frameworks.

Managers need sound research to solve practical problems when managing resources and biodiversity. There are urgent needs for studying and proposing measures and governance systems that should be implemented, recognizing the particularities of the different socioecological systems along the Chilean coasts, where one size does not fit all. This is crucial if Chile wants management and conservation measures that are not only declared but also fully implemented.

Recently, the country has established a set of new marine reserves and MPAs in order to fulfil international agreements. However, exploitation of natural coastal resources (even habitats) are intensifying at a pace that poses a challenge for the conservation of the interconnected and diverse local ecosystems distributed along the HCS (i.e., meta-ecosystem; a set of ecosystems connected by spatial flows of energy, materials and organisms across ecosystem boundaries; Loreau, Mouquet, & Holt, 2003). Thus, the HCS, considered as a meta-ecosystem, deserves to be considered as a large-scale multiple-use MPA, similar to the Great Barrier Reef in Australia, the Wadden Sea in Europe, and many other large-scale marine ecosystems around the world. This would ensure the functioning and the integrity of services provided by the coastal ecosystems associated with the HCS, which is one of the most diverse and productive meta-ecosystems in the world.

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