Pacific Coast of Mexico

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28.1 THE REGION

The Mexican Pacific (MP) comprises several types of ecosystems, from coastal lagoons to continental slopes, and abyssal zones with hydrothermal vents and manganese nodules. It extends from 14°N to 32°N, encompassing the Gulf of California (GC) and the upwelling regions off Baja California, Jalisco and Colima, and Oaxaca coasts. The richness and uniqueness of this region is attributable to its geographic location and the presence of a variety of atmospheric and oceanic climates (Fig. 28.1).

The Pacific coast of Mexico forms 68% of the country’s coastline and comprises several different ecoregions at local, regional, and global levels, and thus a particularly wide range of habitats (Lara-Lara et al., 2008). This results in a substantial coastal and marine diversity. The presence of numerous endemic or flagship species that live there permanently or transiently, the GC and several upwelling regions with high biological productivity enhances this trend. The great natural diversity offers not only many opportunities for development but also implies a great challenge for conservation, since the area is showing increasing signs of being influenced by climate change, urban population growth, industrial development, contamination, and overfishing. Even though new marine protected areas have recently been established (Fig. 28.2), there is a wide debate about their effectiveness. On one hand, there is evidence that show they are the most effective way to preserve biodiversity if restrictive policies on resource use are enforced, but on the other hand, some voices have challenged this (Hilborn, 2016).

The MP is a dynamic and complex subregion within the well-studied “Eastern Tropical Pacific” (ETP). Its oceanography has been explored since the early 19th century and is described in numerous papers, with major reviews provided by Wyrtki in the 1960s and by Fiedler and Lavin in 2006.

The MP has contrasting oceanographic characteristics. It is mainly set on the eastern Pacific warm pool but has important coastal upwelling regions, and is influenced by eastern boundary currents and variable wind conditions, particularly in the south where the extremely strong Tehuano winds, funneled between the mountain ridges in the south of Mexico, modify the ocean dynamics. In its middle section, distant water masses converge in the GC where the microtidal regime of the MP is intensified, creating a unique biological environment. The MP is located at the south of the recently detected “Blob” region and at the north of the Costa Rica Dome, both of which may influence the MP dynamics depending on their seasonal and interannual variability.

Given the different physical processes, the physical description of the MP will be covered in four regions, each of which has different physiographic characteristics. The regions are: (a) the northwestern Pacific, (b) the GC, (c) the central region of the MP, and (d) southern region of the MP (see Fig. 28.1).

(a) Northwestern Pacific region

This region is the western coast of the Baja California Peninsula. It is on the Pacific Plate and is a tectonically active subduction zone with a very narrow continental shelf. It lies at the southern end of the California Current (CC) System. The CC occupies the uppermost 500 m, is surface intensified, and exists year round (Sverdrup, Johnson, & Fleming, 1942). Coastal, wind-driven upwelling results in nutrient enrichment that drives high biological production along a southward coastal jet (Checkley & Barth, 2009).

Information on physical features of this subregion has been obtained through the monitoring conducted by the California Cooperative Oceanic Fisheries Investigations program (CalCOFI, http://www.calcofi.org). Using these data,
FIG. 28.1 Map of the Mexican Pacific coast. The four regions marked have different dynamics: (a) region influenced by the California Current, (b) Gulf of California, (c) central region, and (d) southern region. The red line is the approximate boundary of the Warm Pool, blue line is boundary of the Tehuantepec Bowl, a lowered sea surface due to oceanographic effects.
Lynn and Simpson (1987) have described the Mexican part of the CC as a current flowing toward the coast at 30–31°N that separates into two branches: one flowing northward, feeding the North Equatorial Current, and the other moving eastward and southward near the coast along the Peninsula coastline. New and more detailed information has come from the IMECOCAL program (http://imecocal.cicese.mx), in particular on the seasonal latitudinal displacement of the transition zone where subarctic waters (SAWs) meet tropical and subtropical waters (Durazo, 2015).

The winds in the region flow southwards, with intense seasonal variations. During the winter and into spring, the region has subarctic low-temperature and high-saline waters in the upper layers of the ocean. When the wind speed is almost zero, blowing gently toward the south in summer-autumn, only the region north of Punta Eugenia (28°N) maintains subarctic characteristics, and the southern region receives tropical and subtropical waters, allowing northward advection of surface waters (Durazo, 2015). Winds are largely responsible for coastal upwelling, with important biogeochemical implications. Upwelling may also be driven by horizontal differences in the surface wind stress in regions of positive wind-stress curl near the coast and downwelling offshore (Risien & Chelton, 2008).

Interannual variability is dominated by El Niño with coastal sea-level variations extending from Mexico to the Aleutian Islands (Chelton & Davis, 1982).

(b) Gulf of California (GC)

The GC, also known as the Sea of Cortés, is located between 20°N and 32°N, and between 105.5°W and 114.5°W (Fig. 28.3). It is a narrow and partially closed sea with an approximate length of 1400 km, width of 150–200 km in the inner region, and is connected to the Eastern Tropical Pacific Ocean in the south. The GC has different basins that deepen to the south, with a maximum depth of ~3000 m between El Dorado and Cabo San Lucas (the inner mouth) (Espinosa-Carréon & Valdez-Holguín, 2007). Its bathymetric characteristics dictate most of its dynamics and several characteristics of its biological productivity.

The GC lies between two arid zones: the Desert of Sonora to the east and the Baja California Peninsula to the west, and is isolated from Pacific influence by high mountain ranges along the Baja California Peninsula. This reduces the thermoregulatory effect of the Pacific Ocean and generates a continental, rather than oceanic, climate. A semidesert climate is a climate in which evaporation considerably exceeds precipitation (Pérez-Cruz & Urrutia-Fucugauchi, 2009). Climatic conditions are regulated by seasonal processes related to monsoon activity, with tropical and subtropical characteristics present during the summer, while temperate conditions prevail during the winter (Pérez-Cruz & Urrutia-Fucugauchi, 2009).

The GC has several regions (Lavín & Marinone, 2003). The Upper Gulf is shallow with depths <30 m, close to the delta of the Colorado River. It has a tidal range of 9 m and strong tidal currents. The Northern GC, north of the midriff islands (Tiburón and Ángel de la Guarda), has a wide continental shelf with maximum depths of up to 300 m. Semidiurnal tides are amplified because the GC is almost resonant at these frequencies. Here, the water mass (GCW) undergoes transformation via processes of evaporation, aided by vertical mixing produced by tidal currents (Lavín & Marinone, 2003), and is an area of consistently high chlorophyll concentrations (Santamaria-del-Angel, Álvarez-Borrego, & Muller-Karger, 1994).
It is the main habitat for two endemic species under threat of extinction: the vaquita and totoaba, both victims of illegal fishing. The areas of strong tidal mixing are the most biologically productive of the GC (Alvarez-Borrego & Lara-Lara, 1991). The circulation is dominated by a seasonally reversing gyre, cyclonic from June to September and anticyclonic from November to April, with speed $\approx 0.35$ m/s in both seasons (Lavín & Marinone, 2003). A net surface outflow occurs through the archipelago, which is compensated by a permanent inflow close to the bottom over the San Esteban sill.

The Southern GC covers a large and diverse region from Cabo San Lucas—El Dorado line (the so-called inner mouth) to an area located just south of the sills of the large islands. It has fairly deep basins like the Guaymas, Carmen, and Farallon of depths $>2000$ m and fairly narrow continental shelves. North of Santa Rosalía (27.25°N, middle GC) is an amphidromic point; tidal oscillations are mainly diurnal with spring ranges of $\sim 1.8$ m, but at the inner mouth (Cabo San Lucas), tides become mixed again, predominantly semidiurnal, with maximum spring tidal range of 1.7 m. There is limited tidal mixing in the Southern GC, although mixing can occur in the center and over the sills by breaking internal waves. This internal mixing is tidally modulated (Lavín & Marinone, 2003). In the southern GC, upwelling processes occur during the winter on the eastern coast, but during the summer, when winds blow from the SE, most of the southern GC shows low values of chlorophyll, since the Surface Eastern Tropical Pacific water enters, with high temperatures and low nutrients (Santamaria-del-Angel et al., 1994). In the southern GC, outflow takes place in the upper layer, with the flow being 200 m deep, at 0.02–0.03 m/s. In the inner mouth there is an average outgoing flux of salty water close to the peninsula and an ingoing flux of fresher water along the mainland coast. There a reversing pattern of inflow in the central part and outflow mostly on the peninsula side during May and September (Lavín & Marinone, 2003).

The region between Cabo San Lucas and Cabo Corrientes at the outer mouth of the GC has a complex thermohaline structure influenced by the confluence of three main water masses (Roden, 1964; Wyrtki, 1965): cold, low salinity water transported southwards by the CC (temperature $< 22^\circ$C, salinity $< 34.6$); warm Eastern Tropical Pacific water (temperature $> 25^\circ$C and salinity 34.6–34.9); and temperate water of high salinity from the interior of the GC (temperature 22–25°C, salinity $> 34.9$). The encounter of these water masses causes marked horizontal thermal gradients, the formation of eddies, intrusions, and ocean fronts that can extend between 0 and 200 m depth. This region functions as a mixing zone (Espinosa-Carreón & Valdez-Holguín, 2007; Lavín & Marinone, 2003).

The GC has exceptionally high primary productivity and a fish diversity of approximately 821 species of bony fish and 90 species of cartilaginous fish. Large populations of sardines (Sardinops sagax caeruleus) and crinuda (Opisthonema...
libertate, Opisthonema bulleri, and Opisthonema medirastre) are found. Abundant shrimp fishing grounds, especially at the eastern coast, are also present in the vast coastal lagoons in Sinaloa and Nayarit.

(c) Central region of the Mexican Pacific (CMP)
This region comprises the coasts of Jalisco, Colima, Michoacán, Guerrero, and part of Oaxaca, all having similar oceanographic conditions. It has a very narrow continental shelf along the Cocos tectonic plate, which slides beneath the neighboring North American plate, at a rate of about 7 cm per year.

The region is located south of the GC and east of the North Pacific subtropical gyre. This region is subject to wind-driven offshore Ekman transport so the near-surface flow is south-southwest (Kessler, 2006).

The CMP is seasonally covered by the “warm pool,” which forms during the spring off Central America and expands through the summer, reaching its maximum extent in September–October, when it reaches the entrance of the GC. Very few data exist on this coastal region, and its current patterns are not well known, though Kessler (2006) includes the most detailed view of the CMP. This shows a subsurface current, the West Mexican Current (WMC), flowing to the north close to the coast. Gómez-Valdivia, Pares-Sierra, and Flores-Morales (2013) showed that the coastal WMC flow mainly below the 20°C isotherm from the Gulf of Tehuantepec to Cabo Corrientes, where it approaches the surface and continues flowing into the GC. The model suggests that WMC is stronger in spring and fall, when it reaches an average velocity of 10 cm/s. The semiannual variability of the WMC is related to nonlocal subsurface forcings such as the semiannual extension of the Subsurface Equatorial Current System (SECS) that reaches the coast in spring and fall and turns poleward as a coastally trapped flow that extends to the southwest Mexican coast (Gómez-Valdivia et al., 2013).

Intense thermodynamic exchange between the ocean and the atmosphere takes place in this region, particularly in the summer and autumn. Hence, the thermohaline characteristics of the surface water masses are extremely variable (Trasviña & Barton, 2008).

There are four layers with distinct thermohaline characteristics: the Tropical Surface Water (TSW), a warm (>25°C) and low salinity (<34.4) surface water; the subtropical underwater (STUW), a low temperature (13°C) and higher salinity (34.7–35.0) subsurface layer; a cold layer located below 500 m containing the Antarctic Intermediate Water (AAIW); and the North Pacific Deep Water (NPDW), found below 1200 m, with temperature <2°C and salinity >34.6 (Fiedler & Talley, 2006).

(d) Southern region of the Mexican Pacific (SMP)
This relatively small section comprises the Gulf of Tehuantepec, adjacent to the state of Chiapas and the southern part of Oaxaca (Fig. 28.4). It has unique characteristics, with coastal lagoons and several rivers, and in contrast to the other regions, the SMP is indented and has a wider shelf.

FIG. 28.4  Fishing in coastal lagoon—coast of Oaxaca. Photograph Pim Schalkwijk.
The mountains of the Sierra Madre Occidental flatten out on the Isthmus of Tehuantepec, which spans 200 km from the Gulf of Mexico to the Pacific at its narrowest point. Here, winds are funneled from the north, creating a narrow wind jet that blows from land to sea: the Tehuantepec Jet (Amador, Alfaro, Lizano, & Magaña, 2006). This wind is intermittent and occurs from November to April, and results in thermocline lifting. Sea surface temperature and chlorophyll anomalies are caused by intense vertical mixing below the wind jet (Willett, Leben, & Lavín, 2006). The SMP is the only area of the MP where surface mixing is more important than upwelling in enriching the surface waters (Lavín et al., 2006).

Further south, a seasonal northwestward flow on the east side of the Costa Rica Dome, known as the Costa Rica Coastal Current, flows into the Gulf of Tehuantepec (Kessler, 2006).

In general terms, the SMP is influenced by coastal currents, upwelling, and continental discharges due to the large number of marshes and coastal lagoons along the coastline (Tapia-García, García-Abad, Carranza-Edwards, & Vazquez-Gutierrez, 2007). During the dry season, the CC and the North Equatorial Countercurrent (NECC) dominate, while during the rainy season the Costa Rican Coastal Current (CRCC) is well established (Monreal & Salas de León, 1998).

The Gulf of Tehuantepec has two subsystems (Tapia-García et al. 2007). The Oaxacan subsystem covers most of the coast of the state of Oaxaca and is located southwest of the Port of Salina Cruz to Tonalá in Chiapas. Here, the continental shelf is narrow with rocky and sandy substrates. An upwelling of cold and nutrient-rich waters occurs in the dry season as a result of the action of Tehuantepec winds. The Chiapaneco subsystem comprises most of the Gulf, from Tonalá to the Suchiate River. Soft, muddy sands, dominate across a wide continental shelf. In the rainy season, water temperature and nutrients are high and salinity is low (Tapia-García et al., 2007; Cervantes-Hernández & Egremy-Valdez, 2013).

The Southern Mexican Pacific (SMP) holds the greatest biodiversity. Despite its importance, this region is much degraded environmentally because of the expansion of agriculture over lands that used to be vast forests. Impoverishment of soils, immoderate logging and illegal wood trafficking, forest fires, extraction of protected species, extraction of minerals, and poor freshwater management are among the threats.

In the SMP some of the best-preserved mangrove forests and the unique zapotonal swamp forests, extensive marshy areas known locally as pampas, as well as forest fragments, are found. These areas are of vital importance for migratory birds and diverse species of endangered fauna, as well as being among the most productive and best-developed wetlands of the American Pacific. There are also areas of coral reefs in the Huatulco Bays (Reyes-Bonilla, Calderón-Aguilera, Cruz-Piñón, López-Pérez, & Medina-Rosas, 2010) and several protected areas. Fishing and ecotourism are thriving due to the natural wealth of this region.

Another important aspect of this region is that 30% of the country’s surface water is concentrated in Chiapas, with the two largest rivers in Mexico: the Usumacinta and the Grijalva River. In the Montes Azules Biosphere Reserve, there are >10 water basins that generate 54% of the hydroelectric energy in all of Mexico. However, in recent years, Chiapas has been increasingly affected by heavy rains that have caused severe flooding in several parts of the state. These natural catastrophes are related to the effects of global warming and uncontrolled felling of trees.

**28.2 GLOBAL PROCESSES THAT AFFECT THE PACIFIC COAST OF MEXICO**

The entire MP is strongly influenced by large and mesoscale processes of the Pacific Ocean that closely interact with climate conditions. The warm and cold episodes of large-scale atmospheric circulation (Deser & Wallace, 1990) or the El Niño/Southern Oscillation (ENSO) (Cai, Santos, Wang, et al., 2015) are among such processes, and their variations associated with recent climate change can seriously affect the coastal zones of the MP.

Changes in sea level measured locally may vary due to a variety of phenomena acting at different scales. One example is the seasonal (May–June) arrival of extreme waves generated in remote sites, as far as the Antarctic Ocean (50–60°S), to the coasts of the southern region of the MP. This phenomenon, locally known as “mar de fondo,” has caught media attention in recent years because of the damage caused by coastal flooding (Fig. 28.5). Many locations affected by this process are important tourist destinations. Detailed information on local wave characteristics, behavior, duration, levels of inundation, and projections of sea-level rise need to be obtained to aid local management procedures.

Sea-level data in Mexico show trends similar to global ones. Measurements made by the National Autonomous University of Mexico (UNAM) are one of the most important efforts to monitor environmental variables in Mexico (Zavala-Hidalgo, de Buen Kalman, Romero-Centeno, & Hernández Maguy, 2010). Trends of mean sea level show regional variations and, although in some cases the uncertainty is significant, in most sites positive trends are observed. The effects of sea-level rise on coasts vary considerably from region to region. In the south, sea level in the state of Oaxaca show rates of increase of 1.7 ± 1.7 mm year⁻¹. In Colima, the trend is 3.3 ± 2.5 mm year⁻¹, while in Sinaloa the trend is 3.0 ± 4.3 mm year⁻¹. In Sonora, a higher rate was found: 4.2 ± 1.7 mm year⁻¹. Baja California has one of the longest time series and a trend of 2.7 ± 1.7 mm year⁻¹ was found. In Guerrero, however, in 1962, a movement of the Earth’s crust caused by a double
earthquake (Ortiz, Singh, Kostoglodov, & Pacheco, 2000) caused an elevation of the Earth’s crust of 22 cm, leading to a local decrease in mean sea level. But trends obtained before and after this event show an increase in the mean sea level.

Short-term effects of sea-level rise include increase in frequency and extent of coastal flooding. In the medium term, changes in wave and coastal currents patterns, as well as changes in coastal morphology and fluvial hydrology of drainage basins affect the resilience of coastal defense structures, both natural and man-made (Botello, Villanueva-Fragoso, Gutiérrez, & Rojas Galaviz, 2010), increasing the vulnerability of unique socio-ecological systems and shifting the principal activities that drive some local economies.

The coastal zone is highly vulnerable to a wide range of high-impact weather events, including hurricanes, tropical storms, and drought. Climate change is expected to exacerbate current problems concerning water, energy, agriculture, biodiversity, and coastal vulnerability. Although Mexico is committed to the 2030 Agenda for Sustainable Development, there are large asymmetries in the capacities of municipal and state governments along the Pacific coast to implement the resolutions of the United Nations Conventions on Climate Change, United Nations Conventions on Biological Diversity, United Nations Conventions to Combat Desertification, and United Nations Conventions on Housing and Sustainable Urban Development (Habitat III). Streamlining the implementation of these conventions is a necessary step toward a sustainable development of this region.

The effects of climate change on marine environments will affect temperature and precipitation patterns, oceanic and atmospheric circulations, the rate of sea-level rise, ocean warming, and the frequency and intensity of tropical storms. An example is bleaching of coral reefs in the MP (Glynn, 2017). Also, on the MP coast, the rise in sea level will cause an inland displacement of the mangroves, and the increase in water temperature will, in turn, affect the geographical distribution of wetlands and favor the establishment of invasive species (Flores Verdugo, Casasola, de la Lanza-Espino, & Agraz Hernández, 2010).

### 28.3 THE OXYGEN MINIMUM ZONE (OMZ) OF THE MP

The OMZ of the MP is the most important in the world and, in Mexico, it extends along the entire coastline, with the exception of the northern section of GC. Typically, vertical dissolved oxygen (DO) concentration profiles in OMZs in the MP are characterized by a steep drop in oxygen from the surface to the OMZ upper boundary, a contiguous water layer of permanent low oxygen, and a gradual increase in oxygen with depth in the OMZ lower boundary (Fig. 28.6) (Levin, 2003). Because of their intensity and shallowness, these areas are, a priori, different from the relatively well-known “classical O minimum,” which is ~50 times more oxygenated than OMZs and which are found at intermediate depths (1000–1500 m) in all oceans (Wyrtki, 1962).

The low DO concentrations in the water in OMZs affect nutrient budgets, biological productivity, and climate, due to modified nitrogen and carbon (including CO₂) cycling (Arrigo, 2005; Voss et al., 2013). Nitrogen cycling in OMZs is fundamentally different from the rest of the open ocean, and only in OMZs can net loss of fixed N occur, likely altering ocean
stoichiometry and primary production locally. This results from denitrification and anammox, the main microbial pathways that lead to net loss of fixed nitrogen, which occur only in the near or total absence of oxygen (Arrigo, 2005). Together with the Arabian Sea and the eastern tropical South Pacific, the eastern tropical North Pacific harbors one of the three strongest OMZs in the world (Paulmier & Ruiz-Pino, 2009) and is one of the three major sites of water column denitrification that accounts for approximately 40% of global oceanic combined nitrogen loss (Horak, Ruef, Ward, & Devol, 2016). It is presumed that the combination of denitrification and anammox can also contribute to increase the N₂O oceanic budget, but this potential remains largely unknown (Voss et al., 2013).

The world’s OMZs occupy ca. 30.4 million km², and 68% is the ETNP OMZ (Paulmier & Ruiz-Pino, 2009). It covers the entire coast of Pacific Mexico except the northern end of the GC. It is a matter of debate whether OMZs are expanding (Bopp et al., 2013; Deutsch et al., 2014; Horak et al., 2016; Stramma, Schmidtko, Levin, & Johnson, 2010), but accumulating evidences suggest both horizontal and vertical expansion and a shoaling of the ETNP OMZ over the last 40 years (Bograd et al., 2008; Horak et al., 2016), with an associated increase of denitrification. This is related to climate-driven mechanisms that may strengthen with global warming. Some authors have suggested a relationship between increased anoxia and positive Pacific Decadal Oscillation phases (Deutsch, Brix, Ito, Frenzel, & Thompson, 2011). Others propose that different mechanisms are the main cause of increased anoxia and total N loss. Increased primary productivity resulting from increased trade wind strength since 1990 (Deutsch et al., 2014) and more intense upwelling in the CC (Narayan, Paul, Mulitza, & Schulz, 2010) during the 20th century, brings about higher supply of organic matter to the water column and hence higher biological oxygen demand for its decomposition (Canfield, 2006). Also, oxygen supplied by currents in the ETNP has decreased by about 0.5 mmol kg⁻¹ O₂ yr⁻¹ over the last 30 years (Stramma et al., 2010). Oxygen depletions have been detected in the SAW (Andreev & Watanabe, 2002), leading to the CC system that supplies oxygenated water from the north above 200 m (Ruelas-Tolentino & Trasviña-Castro, 2017), and in the North Pacific Intermediate Water (NPIW) (Nakanowatari, Ohshima, & Wakatsuchi, 2007), which delivers oxygen-rich water to 600 m north of ca. 26°N (corresponding to the mid-latitude section of the Baja California Peninsula). Finally, ETNP OMZ expansion has been related to changes in the circulation and sources of waters that feed the CC (Tems, Berelson, & Prokopenko, 2014) with oxygen-poor water originating from the tropical Pacific and being transported northward by the California Undercurrent (Pierce, Smith, Kosro, Barth, & Wilson, 2000). Both the vertical and the horizontal expansion of anoxia and denitrification should have a stronger influence on global nitrogen loss and N₂O production, the latter representing a strong greenhouse gas with ozone destroying power, thus affecting climate change.

FIG. 28.6 Temperature (T, C), salinity (S), and dissolved oxygen (DO) concentration profiles (average and standard deviation) measured in three sampling regions of the Mexican minimum oxygen zone [offshore of northern Baja California (NBC), off southern Baja California (SBC), and in the southern Mexican Pacific (SMP)]. After Papiol, V., Hendrickx, M.E., & Serrano, D. (2017). Effects of latitudinal changes in the oxygen minimum zone of the Northeast Pacific on the distribution of bathyal benthic decapod crustaceans. Deep-Sea Research II, 137, 113–130.
Oxygen limitation within OMZs controls fauna distribution and activity, with serious implications on diversity and biogeochemical cycles. Metazoan macro- and megafauna aggregate at the upper and lower OMZ boundaries and are virtually absent from OMZ cores (DO <0.15 mL L\(^{-1}\) or 6.6 mM, Levin, 2003), where foraminiferal and meiofauna dominate faunal communities (Gooday et al., 2009). Thus, consumption and remineralization of organic matter is depleted within the low oxygen areas, and the massive surface production above OMZs therefore translates to large fluxes of labile organic material through the water column (Gutknecht et al., 2013; Rouiller et al., 2014) and to particularly rich labile organic material in slope sediments beneath the core of the OMZ (Cowie, Calvert, Pedersen, Schulz, & von Rad, 1999; Devol & Hartnett, 2001; Honjo, Manganini, Krishfield, & Francois, 2008). The absence of benthic fauna in hypoxic or anoxic environments is accompanied by the disappearance of functions related to macrofauna such as bio-irrigation and bioturbation. Further, biogeochemical processes that depend on animal-induced transport processes are interrupted (Middelburg & Levin, 2009). All these contribute to the accumulation of labile material with less recycling potential, especially in high surface production areas of the MP. The absence of large fauna within anoxic areas also strongly affect the economy of the areas affected, limiting fisheries to areas with enough DO to sustain large swimming fauna.

Although the thickness, intensity, and vertical distribution of the ETNP OMZ vary with latitude (Helly & Levin, 2004; Papiol, Hendrickx, & Serrano, 2017), it is shallow throughout the MP: the upper 0.5 mL L\(^{-1}\) oxygen isopleth is distributed between depths of ca. 38 m, in the SMP, and 290 m, off northern Baja California. The subsurface layer with DO <0.2 mL L\(^{-1}\) lies between ca. 250 and 1000 m (Papiol et al., 2017), so the fisheries activities in shallow and mid-waters are strongly restricted, especially in the south (Hendrickx & Serrano, 2010). Given that in this OMZ, lower boundary water with enough oxygen to sustain fisheries’ targets (>0.2 mL L\(^{-1}\)) is found below 700 m, development of a deep-sea fishery does not seem a promising option in the MP either. Deep-water communities are highly sensitive to environmental variations and fisheries activities (Althaus et al., 2009; Gray, Dayton, Thrush, & Kaiser, 2006; Maynou & Cartes, 2011), and thus any intention to switch part of the current fishery activity in that direction should be carefully evaluated. Recent studies on population distribution do not seem to favor this switch, as species are distributed in patches and either aggregate in very narrow bathymetric strata (e.g., Nephrops occidentalis: Papiol, Hendrickx, & Serrano, 2016) or live in large bathymetric ranges but with low densities (e.g., Benthesycimus tanneri: Papiol & Hendrickx, 2016).

The OMZ expansion can also have serious impacts on fauna, as many economically and ecologically important mobile macroorganisms are stressed, migrate away, or die under hypoxic conditions (Gray, Wu, & Or, 2002; Vaquer-Sunyer & Duarte, 2008). As OMZs expand, hypoxia-intolerant taxa will eventually disappear or change their distribution (Levin et al., 2009). Hypoxia will impinge increasingly on the shelf so the habitat compression will occur, with eventual loss of biodiversity and biomass (Prince & Goodyear, 2006; Purcell, Uye, & Lo, 2007). If past trends in observed oxygen differences continue into the future, accelerated shifts in animal distributions and changes in ecosystem structure are to be expected.

### 28.4 DEMOGRAPHIC TRENDS AND ECONOMIC ACTIVITIES

The population increase over the last 20 years has been 1.3% per year. In some of the states of the Mexican west coast rates have been higher: 3.4% per year in Baja California Sur, and 2.1% per year in Baja California. This growth has two reasons: the effect of capital investment in the exploitation of natural resources, with the development of industrialized centers near some port cities, and the effect of investment for tourism development. In general terms, these Mexican coastal zones experience a spatially irregular population growth, which is focused in a few urban localities, which produces important economic, social, institutional and environmental pressures on these coastal and marine areas.

The increasing economic activities in the Pacific coast of Mexico, particularly ports, aquaculture, tourism, agriculture, and manufacturing, are some of the reasons that contribute to the population growth in some coastal municipalities. The population dynamics of the coastal zones of Mexico follow world trends, with displacements of populations toward these zones. Data from the National Institute for Statistics and Geography (www.inegi.org.mx) show that in 2010 the population of the coastal states was 51,900,847, 4.5 million more than that in 2005, and 7.25 million more than that in 2000. The National Council for Population (www.gob.mx/conapo) expects that by the year 2030, population in the coastal states will increase to 55 million.

The population in the Pacific coast states grew by 15% between 2000 and 2010, while that of its urban municipalities grew by 25%. This is well above the national average, particularly in the Baja California Peninsula, and the trend is expected to continue. According to the National Institute for Statistics and Geography, in 2015 four municipalities of the Pacific coast experienced accelerated urbanization: Tapachula-Tuxtla Chico, Manzanillo-Zihuatlán, Lázaro Cárdenas-La Unión, and Culiacán-Navolato.
Some of the problems common along the coast originate from the lack of land-use planning, inadequate use of rural and urban spaces, and sudden changes in land use. Some of the consequences are increasing the vulnerability of both the inhabitants and infrastructure. These growing urban areas require increasing resources, which impose greater pressures on the environment in those localities where opportunities for employment are increasing. In the period 2003–2013, the coastal states of the MP contributed 43% of the national gross domestic product (GDP).

Among the relevant economic activities that account for this trend, tourism is one. As in other parts of the world, marine and coastal tourism in Mexico is one of the fastest growing activities. From 2010 to 2015, tourism related income grew about 30% and, in recent years, its contribution to the national GDP has fluctuated around 8.5%. This activity generates >10 million jobs, and is the second most important source of foreign currency in the country. The economic benefits associated with tourism are important but in order to grow, this activity has required converting land into private property, causing not only social conflicts (Ibarra García & Badillo Salas, 2015) but also environmental concerns from microplastic concentrations along beaches to effluents discharged from hotels and restaurants in many resort areas of the Pacific coast (Retama et al., 2016). Tourists visiting the natural and cultural richness of the country have different mindsets and thus a wide variety of attitudes, sensitivity, and motivations to understand and conserve the natural capital of the region (Ramdas & Mohamed, 2014).

28.5 FISHING AND AQUACULTURE

Fishing and aquaculture are also very important economic activities in the MP (Fig. 28.7). Mexico is the world’s 17th largest fishing nation (FAO, 2014). The productive waters of the Pacific coast include a large array of commercially valuable species. Yield has remained relatively constant at around 1.5–1.7 million tons year\(^{-1}\) over the last two decades, with nearly 60,000 fishing vessels registered in Pacific states (48% of the national inventory). The number of vessels >15 m in length has not grown over the last two decades, and number of fully operational vessels show a tendency to decrease as a natural reaction to the decline of the catch per unit effort applied to the main fisheries.

Sardine, shrimp, tuna, octopus, and squid accounted for 60% of the total volume of national fish production in 2014 with the national production strongly determined by fishing activities in the Pacific coast: the production of the states of the continental edge of the GC, such as Sonora and Sinaloa, exceed 200 thousand tons year\(^{-1}\) and, together with the states of Baja California and Baja California Sur, have produced over two-thirds of the total annual catch of the country for last 20 years.

Enforcing fishery regulations, including bans, minimum catch sizes, the type of fishing gear allowed, and monitoring to avoid activities such as poaching in restricted areas or catching threatened species, are the issues that require attention to reduce the impacts on biodiversity arising from the overfishing, bycatch, and degradation of habitat. An example that has captured the world’s attention in recent years is the current critically endangered status of the vaquita (Phocoena sinus), the world’s smallest porpoise, whose population is estimated at a few dozen individuals (Taylor et al., 2017). Vaquitas are a bycatch of the illegal totoaba (Totoaba macdonaldi) fishery, which continues despite fishing gear restrictions and the implementation of a surveillance program in the upper GC.

FIG. 28.7 Tuna mariculture in Baja California, within the northwestern Pacific region.
To achieve sustainability in fishery management it is necessary to enhance scientific and technological capacities in several fields such as population assessments of targeted species, improvement of fishing gears to reduce or eliminate bycatch, implementation of fishing management plans including considerations on the illegal, unreported, and unregulated fishing, and the construction of a reliable record of fishery statistics (Espinoza-Tenorio, Espejel, & Wolff, 2011).

From 2000, aquaculture has increased steadily, reaching now over 10,000 aquaculture units throughout the country that represents nearly 40% of the total value of the national fish production. It is worth noting that the states of Baja California, Baja California Sur, Sonora, and Sinaloa accounted for 75% of the total volume of national fisheries and aquaculture production in 2014, and new cultivation areas have been added in the last decade in the Sonora, Nayarit, and Colima. In Nayarit, Jalisco, Colima, and Michoacán, four-fifths of the total value of production is attained by fishing and aquaculture activities (Delgado-González et al., 2011). The shrimp-farming industry has expanded along the Pacific coast and constitutes a threat to the coastal wetlands, especially where farms have been placed in mangrove swamps. These mangrove wetlands not only provide crucial habitat for countless resident and migratory species, but also for those that constitute the important commercial fisheries of the region. In the last two decades, major mangroves have been lost to shrimp farms or where the natural water flow has been interrupted (Valderrama-Landeros et al., 2017).

The federal government of Mexico enacted a federal law to create special economic zones (SEZ) in some of the poorest regions of the country. The initiative aims to reduce the markedly unequal levels of economic development inside Mexico. The SEZ are conceived as geographically delimited areas designed to attract foreign investment and to ease regulatory processes. Three of these zones are planned in the MP, associated with the ports of Lázaro Cárdenas: on the border of the states of Michoacán and Guerrero, in the Isthmus of Tehuantepec (in Oaxaca), and in Puerto Chiapas (Chiapas). These geographic areas offer incentives for companies and industries to invest there, but are strategically located in areas characterized by their natural wealth and productive potential. If local phenomena such as population growth and its associated environmental impacts are not addressed, these modernization reforms to increase economic revenues will not assure the sustainable economic transformation that is sought (Richardson, 2004). Local and federal governments need to generate policies that help building regional capacities in order to promote activities and build infrastructure resilient to climate change. In this sense, innovations in environmental impact assessment and suitability analysis (legally known as “ordenamiento territorial” across Latin America, a process that includes urban, coastal, and marine spatial planning), the primary platforms for social-ecological planning, and enforcing the environmental legislation, are required.

The possibility of developing new activities is arising. Marine mining, for instance, has great growth potential in the Clarion-Clipperton Fracture Zone (CCFZ), eastern central Pacific, where reserves have been estimated at 7 billion tons of manganese, 340 million tons of nickel, 240 million tons of copper, and 78 million tons of cobalt. Contracts have already been awarded by the International Seabed Authority (AIFM) for the exploration for polymetallic nodules in the proximity of the Mexican exclusive economic zone. The possibility that exploration will soon transition to exploitation is an indication of the need to strengthen scientific and technological research, and to create the legal and technical-scientific instruments to regulate, attenuate, mitigate, or eliminate the possible impacts of the activities related with the use of deep-sea resources, especially considering that deep-sea habitats are poorly resilient to disturbances. For instance, the nematode assemblage inhabiting the 26-year-old track created by experimental deep-sea mining of polymetallic nodules in the CCFZ had not returned to its initial state 26 years after the experimental dredging (Miljutin, Miljutina, Martínez Arbizu, & Galéron, 2011), highlighting the need to gain knowledge of our natural heritage and preserve it.

### 28.6 POLLUTION

Economic growth and deficient environmental regulations are usually accompanied by pollution, which is increasing throughout the Pacific coast of Mexico, especially in places where urban or industrial development occurs. Examples are increasing in the scientific literature, but are still under-monitored, and consequences to ocean ecosystems are poorly understood. Along the Pacific coast of Mexico, examples of the impact of industrial, urban, agricultural, and aquacultural activities have been shown by Barraza-Guardado et al. (2014).

As in other coastal areas that are currently experiencing eutrophication or hyper-nutritiation worldwide, negative consequences of pollutants present in water and sediments have been documented for numerous groups of substances. For example, antibiotics, disinfectants, algaecides, therapeutic compounds, pesticides, food additives, and sediments and water treatment from aquaculture cause biochemical and physiological alterations in organisms (Frías-Espéricueta et al., 2011). Environmental impacts of pollutants whose concentrations increase due to accelerated urban development and poor environmental planning and regulation have been investigated mainly in the coastal lagoons of the MP. Discharge of untreated waters, dumping of garbage, and habitat loss due to landfill are common concerns along the coastline. Several recent
papers state that stopping the progressive environmental deterioration of the lagoon systems is a priority (Arellano-Aguilar, Betancourt-Lozano, Aguilar-Zárate, & Ponce de Leon-Hill, 2017).

It is clear that the MP is a region with serious sustainability challenges. Prominent among them is the need for diversifying the drivers of economic growth, modernizing infrastructure, reducing socioeconomic inequality, and improving public security, as well as protecting critical ecosystem functions and biodiversity hotspots. The loss of coastal species and the biodiversity decline due to transformation of marine habitats need to be investigated.

28.7 EFFECTIVENESS OF THE NATIONAL STRATEGY FOR BIODIVERSITY CONSERVATION

To ensure the protection and conservation of the environment and the key processes and functions of marine ecosystem in a mega-diverse territory that is home to around 10% of the species described in the world, the Mexican government started to protect marine and coastal areas in the early 1930s. This has led to the existence of 38 coastal and marine protected areas (CMPA) in the MP that cover ca. 784,000 km². These have different categories of protection, objectives, and zonation: biosphere reserves, national parks, sanctuaries, and areas for the protection of flora and fauna (DOF, 2013). National Parks were the most common protection category from the 1930s to the 1980s, but their strong use-oriented, especially tourism-oriented, component has proved unsuitable to cope with increasing pressures on resource use (Brenner & Job, 2011; Íñiguez Dávalos, Jiménez Sierra, Sosa Ramírez, & Ortega-Rubio, 2014). With UNESCO launching the “Man and Biosphere Programme” in 1971, Biosphere Reserves came to be regarded as a paradigm for the management of protected areas (Brenner & Job, 2006). They not only include environmental conservation as one of their main goals, but sustainable socioeconomic development is also considered critical.

The historical relationship of Mexican indigenous communities with coastal systems (Ibáñez-Pérez, 2014), together with the strong population growth in coastal areas (Padilla & Sotelo, 2000) and economic development policies resulting from globalization (Ibáñez-Pérez, 2014), emphasize the importance of an adequate management of development in the CMPAs of the MP. Many current CMPAs aim toward a comanagement, with an implication of utilization- and conservation-centered approach. But conservation and development, either for livelihood or profit, interests, and objectives have not always been easy to reconcile, which has sometimes led to ineffective and socially unbalanced management of CMPAs (Brenner & Job, 2011; Brenner & Vargas del Río, 2010).

Conflicts are found within government institutions, in such a way that government conservation and development institutions may work in opposite directions. Several federal institutions foster regional economic development within, or close to, the protected areas, which sometimes lead to land-use transformation. This is the case of El Vizcaíno Reserve, one of the largest and oldest Latin American reserves, aiming to protect the arid and semiarid biomes and the Nearctic maritime and avian fauna of the GC, particularly the mating sites of the East Pacific gray whale (Eschrichtius robustus) (Young, 1999a). Capital intensive and export-oriented industries shape the economy in El Vizcaíno: the Secretariat of Agriculture (SAGARPA) promotes intensive agriculture and stock farming, and the exploitation of the world’s largest salt production sites which are state owned. To increase these activities, between the years 1976 and 2000, 2% of the reserve surface was diverted from conservation to anthropogenic endeavors (CONANP, 2003) and arid ecosystems were impaired due to the excessive tapping of deep groundwater resources to sustain irrigated, export-oriented agriculture (Young, 1999a, 1999b).

Inadequate management of land use within the protected areas is reinforced by unclear legislation. For instance, the Ley General de Biodiversidad (General Law on Biodiversity) approved on December 15, 2017 by the Mexican Congress does not explicitly forbid mining or hydrocarbon extraction in natural protected areas. This is especially important in a country with such a large marine mining and oil extraction potential (e.g., phosphate rock deposits in Baja California: Harben, 2006). Some companies have already expressed interest in marine mining in Baja California, near or inside CMPAs, such as the Don Diego offshore phosphate mining project (http://www.dondiego.mx/) proposed by Exploraciones Oceánicas, which is owned by US-based Odyssey Mining and by the Mexican mining company MINOSA. Even though the Federal Secretariat of the Environment and Natural Resources (SEMARNAT) denied permission for this project in 2016, causing controversy among conservationists and developers, the new legislation opened a new door to request permission. In any case, not only is mining within an MPA a threat to conservation, but also the (at least) 3.44 million hectares (23.97% of its surface) subjected to mining in the Baja California Peninsula (Servicio Geológico Mexicano, 2016a, 2016b) defy conservation goals, as high levels of mining-derived pollutants have already been detected (Marmolejo Rodríguez, Sánchez Martínez, Romero Guadarrama, Sánchez González, & Magallanes Ordóñez, 2011; Posada-Ayala, Murillo-Jiménez, Shumilin, Marmolejo-Rodríguez, & Nava-Sánchez, 2016; Rodríguez Figueroa, Shumilin, & Sánchez Rodríguez, 2009).
Furthermore, agreement among all stakeholders within an MPA is difficult to reach, as there is frequently an unbalanced power for decision-making that translates to a lack of acceptance of new regulations, usually by land users (Brenner & Job, 2011; Brenner & Vargas del Río, 2010). Natural protected areas in Mexico depend on governmental agencies that comprise several federal and state environmental departments, as well as numerous subordinate agencies [the federal Secretariat of the Environment and Natural Resources (SEMARNAT), the Environmental Protection Service (PROFEPA), the National Commission on Protected Areas (CONANP), and their respective counterparts at the state level] that are economically and logistically restricted, which has led to the inclusion of international and national nongovernmental agencies, as well as UNESCO, as partners in the management efforts of some areas. In an attempt to coordinate the activities of local, regional, or national governmental institutions, and to address the demands of regional and local resource users, the engaged nongovernment institutions aim to collaborate with centralized national authorities. However, this is not always approved by the local population, and the legitimacy and capacity of conservation-centered actors to intervene in political decisions and management becomes questioned (Brenner & Job, 2011). Besides, the social and political context in Mexico with high levels of corruption and a generalized lack of confidence by the population on the institutions enhances a sense of distrust. As local users perceive that new conservation regulations threaten their livelihood and limit their traditional way of life, the lack of social acceptance becomes a crucial problem that is enhanced by the deficient of power of government for law enforcement. This encourages an unclear management planning, and unbalanced power in decision-making across actors (Brenner & Job, 2011; Young, 2001). As a result, land users may defy centralized management which can lead to either a successful community-based resource stewardship that promotes more sustainable resource exploitation (such is the case of Punta Allen, in the Atlantic coasts of Mexico: Hernández-Valderrama, 2014; Méndez-Medina, Schmook, & McCandless, 2015) or the most common case, an overharvesting of stocks and impacts on protected species by illegal fisheries (e.g., El Vizcaíno: Brenner & Job, 2011). The latter was favored by state-led government programs for economic development have taken in the 1970s, which focused on export-oriented fisheries and fueled large-scale immigration to the coasts, giving rise to increasingly widespread patterns of illicit fishing practices (Young, 2001).

An increasingly common government strategy to cope with the needs of both environmental protection and assuring societal economic growth in CMPAs is tourism, lately seen as a panacea for development (Ibáñez-Pérez, 2014; Molina, Rubinoff, & Carranza, 1998). Coastal areas of the MP that hold attractive landscapes and the presence of emblematic species present a growing touristic demand, especially within CMPAs and in small communities (Ibáñez-Pérez, 2014). Although economic growth is apparent, this is usually accompanied by several impacts such as local people’s displacement, landscape modification or accelerated population growth, among others (Ibáñez-Pérez, 2011). As a result of such problems, the Mexican government has launched numerous strategies to reevaluate the conservation in coastal areas. Still there is a clear inclination toward converting productive areas into touristic activities despite the lack of information to assess its suitability (Bringas, 1999). A clear example is Cabo Pulmo, which possesses one of the greatest barrier reefs of the planet and which was protected in 1995. Although conservation strategies seem coherent with a sustainable use, there are no studies that establish its touristic capacity or record of the number of visitors. In addition, high levels of marginalization, lack of basic services for the local population, and the expansion of the tourist corridor Cabo del Este are considered imminent threats to the local society (Ángeles, Gámez, & Menares, 2008; Ibáñez-Pérez, 2014). The Mexican government has recently declared the largest MPA in North America: the Revillagigedo Islands. With a vast population of giant manta rays, sharks, and whales, it presents an outstanding touristic attraction. Reaching a successful management that integrates conservation, fisheries activities, social welfare, and an adequate growth of touristic activities imposes a new great challenge to this Pacific Mexican situation.

It seems clear that there is still a lot of work to be done in Mexico in order to harmonize the conservation of its great natural heritage and the welfare of its society. In the light of the strong practical and conceptual contradictions between conservation and development, it should be considered whether environmental sustainability is possible in this market-oriented economy.

REFERENCES


**FURTHER READING**


