CHAPTER THREE

Coastal Ecology of the Northeastern Gulf of California and the Puerto Peñasco-Bahía Adair Region

Richard C. Brusca

Native Americans began exploiting the coastal resources of the Puerto Peñasco-Bahía Adair region at least as early as 4000 B.C. (Mitchell and Huckleberry, Chapter 6) and possibly much earlier. Studies of shell middens have shown that Indigenous groups used the same food resources in the past that occur in this area today. Other than post-glacial, gradual sea-level rise, there is no ecological or oceanographic research suggesting that the Northern Gulf of California ecosystem has changed substantially throughout the Holocene. The Northern Gulf has probably never been an estuarine or brackish-water region, given the small amount of Colorado River input and the massive daily exchange of ocean water with the extreme tides of the region (Brusca and others 2017; Rojas-Bracho and others 2019a, 2019b). Although the coast of northern Sonora is very dry, perennial springs, shallow water tables, and the Sonoyta River (flowing above or below ground) likely sufficed for Native Americans. Because the Northern Gulf is one of the most productive marine regions on Earth, finfish, shellfish, and sea turtles probably always occurred in abundance in this region (until the modern era of fisheries over-harvesting). Even today, with virtually all of the commercial fisheries in the Gulf exceeding sustainable levels, the Northern Gulf remains the largest producer of seafoods in the country. It is the highly productive nature of the Northern Gulf that has drawn people to the region for at least the past 6,000 years.

THE NORTHERN GULF OF CALIFORNIA

Physical Oceanography

The Gulf of California occupies a large rift valley between the Pacific and North American tectonic plates. It is the only semi-enclosed sea in the Eastern Pacific. It is commonly divided into three regions (and one subregion), based on oceanographic and ecological parameters (Figure 3.1). The Northern Gulf extends from the estuary of the Colorado River (Isla Montague) south to, and including, the Midriff Islands; it is surrounded by the Lower Colorado River Valley subdivision of the Sonoran Desert. Thus, the Puerto Peñasco-Bahía Adair region lies within the Northern Gulf (Figure 3.2). Because the Gulf is a subtropical sea, it maintains a high net evaporation rate. The Colorado River is the only perennial river in the Northern Gulf. Annual evaporation, less precipitation and runoff, has been estimated at 0.61 m yr^{-1} over the entire Gulf (Beron-Vera and Ripa 2000). Lavín and Organista (1988) estimated the evaporation rate for the Northern Gulf at 0.9 m yr^{-1}, and Lavín and others (1998) estimated an evaporation rate in the Upper Gulf subregion of 1.1 m yr^{-1}. Average annual rainfall is only about 68 mm yr^{-1} and is highly variable (Miranda-Reyes, Reyes-Coca, and García-López 1990). Unlike some other semi-enclosed seas (e.g., the Mediterranean and Red seas), the Gulf gains heat on an annual average and it has long been recognized as the only evaporative basin in the entire Pacific Ocean (Roden 1958, 1964, Bray 1988; Lluch-Cota and others 2007; Paden, Abbott, and Winant 1991). Because of heat gain and evaporation, salinities and sea surface temperatures in the Northern Gulf have always been slightly higher than in the adjacent open Pacific at the same latitude, although from a biological perspective this slight difference is probably insignificant. Offshore surface salinities in the Northern Gulf range from 35 to 36.7 parts per thousand (ppt), becoming lower with increasing distance from the shallow area around Isla Montague. Onshore salinities in the Northern Gulf range from 36 to 39 ppt, although in coastal wetlands (bays and esteros) of the shallow Northern Gulf salinities can be even higher (Brusca 1980). The flora

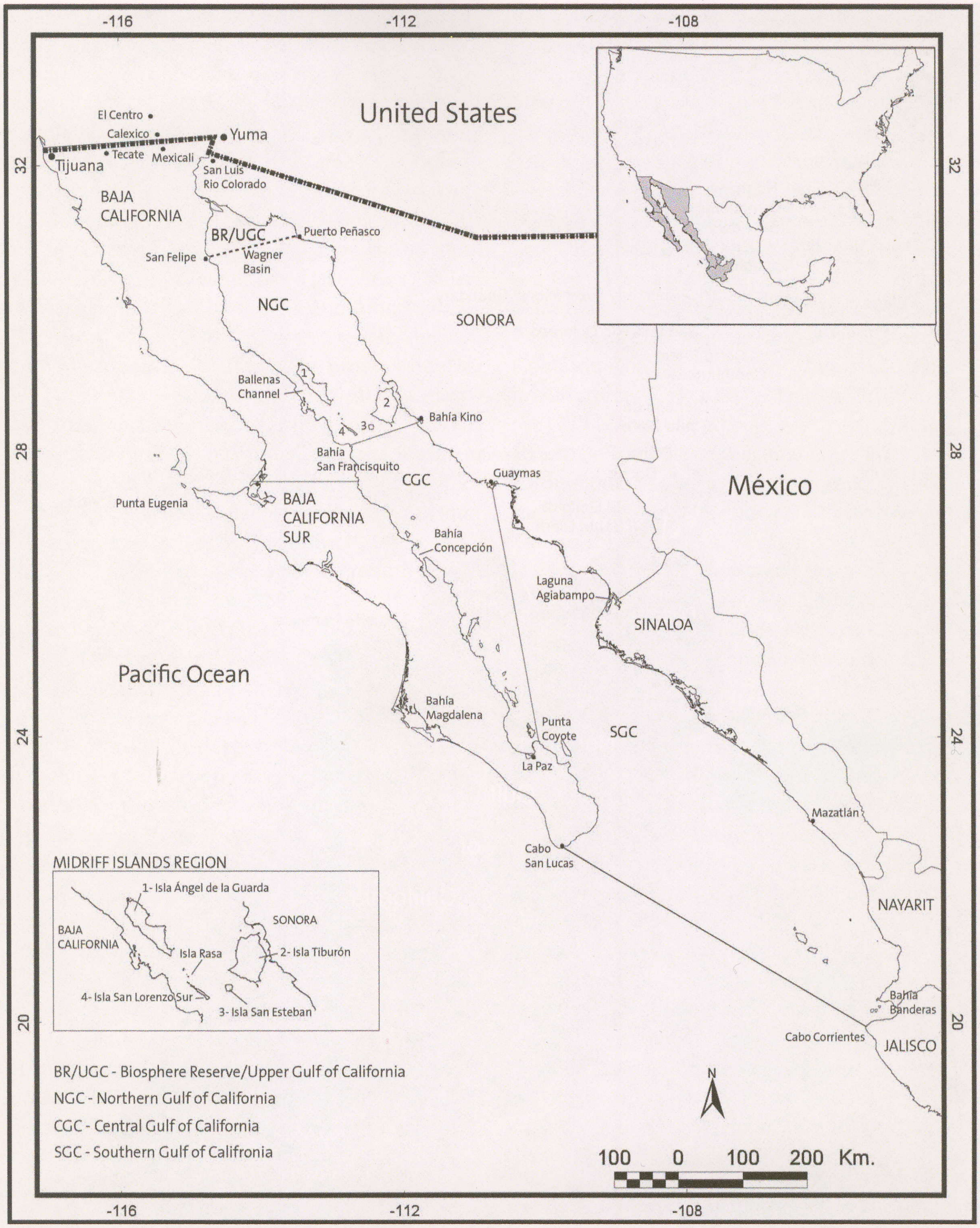

Figure 3.1. Gulf of California (Sea of Cortez), showing the commonly recognized biogeographic regions based on oceanographic and ecological data. The Northern Gulf extends from the Colorado River Delta (Isla Montague) southward to the Midriff Islands. The Central Gulf ranges from the Midriff Islands to Guaymas (Sonora), and to Punta Coyote (Baja California Sur). The Southern Gulf extends southward to Cabo Corrientes (Jalisco) on the mainland side, and to Cabo San Lucas on the Baja California Peninsula. At the head of the Sea of Cortez is the Upper Gulf of California/Colorado River Delta Biosphere Reserve, established in 1993. Prepared by Catherine Gilman.

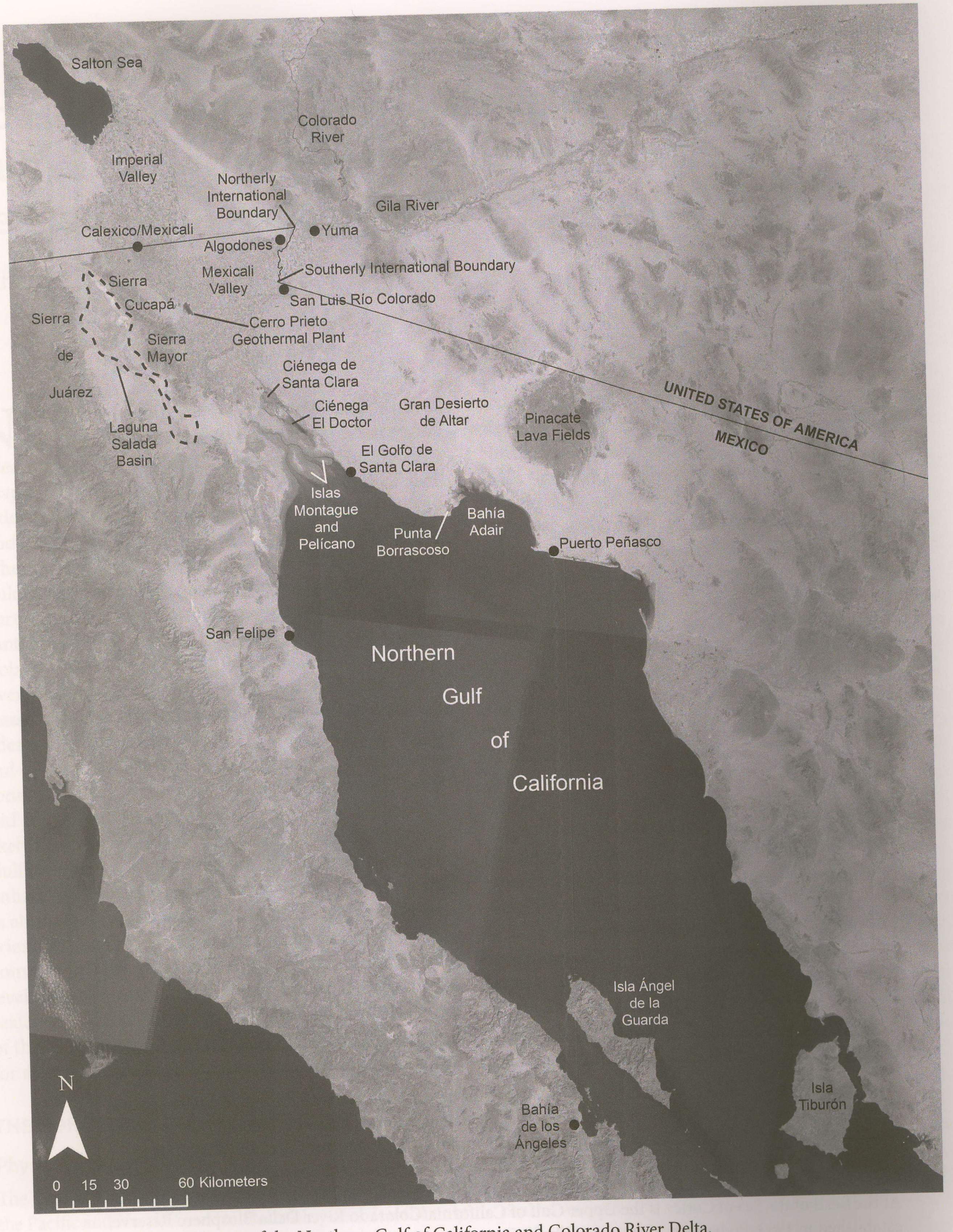

Figure 3.2. GIS-based map of the Northern Gulf of California and Colorado River Delta.

and fauna of the Northern Gulf have long been adapted to life at slightly higher-than-open-ocean salinities.

The principal surface circulation of the Northern Gulf consists of a cyclonic (counterclockwise) gyre in the summer (June to September), and a much weaker anticyclonic (clockwise) gyre from November to March (Lavín and others 1995; Lavín, Beier, and Badan 1997; Lavín, Durazo, and others 1997; Lavín and others 2014; Beier and Ripa 1999; Martínez-Díaz-de-León 2001; Palacios-Hernández and others 2002; Carrillo and Palacios-Hernández . 2002; Lavín and Marinone 2003; Lluch-Cota and others 2007; Peguero-Icaza and others 2008). Current speeds during the cyclonic phase reach ~0.20 m/s (in June), whereas winter flows are much weaker (~0.03 m/s). Because the large spring-summer Colorado River flows (due to snow melt in the Rocky Mountains, combined with the summer monsoon rains) largely coincide with the period of cyclonic circulation in the Upper Gulf, most of the river's sediments historically were carried to the west-southwest, where they formed broad littoral mud flats between the mouth of the river and San Felipe (Thompson 1968).

The Upper Gulf is vertically well mixed throughout the year (Lavin, Godínez, and Alvarez 1998), largely due to strong tidal currents. This mixing results in a stratification front that delimits the well-mixed shallow areas of the Upper Gulf from the deeper, stratified areas of the Northern Gulf (Argote and others 1995; Lavín, Godínez, and Alvarez 1998), the latter carrying oceanic waters at depths of more than 200 m. This stratification front (with temperature, salinity, chlorophyll *a*, and dissolved oxygen concentration gradients) is a permanent feature located on the southern edge of the Upper Gulf, although it varies seasonally in position. During the summer, the front is close to the 30-m depth contour, whereas in winter it is positioned over the 60-m contour (Argote and others 1995, Lavín, Godínez, and Alvarez 1998). Models and connectivity matrices suggest high particle retention along the front (Garcés-Rodríguez and others 2018). These authors suggest the stratification front might function like a barrier that prevents larval advection of coastal demersal species (including planktonic larvae of sciaenid fishes—drums and croakers) towards the oceanic zone, and it could have even been a factor contributing to the process of endemism in the region (Garcés-Rodríguez and others 2018, 2021; Munguía-Vega and others 2017). Of the five species of sciaenids studied by Garcés-Rodríguez and others (2018), none was found south of the stratification front, supporting the idea that the front functions as a barrier that prevents larval advection towards the south.

The long narrow shape of the Gulf of California creates a "bathtub effect." The tidal range (amplitude) is very small at the center "nodal point" (near Guaymas, where it is less than 1 meter). It increases northward and southward from there, like water sloshing back and forth in an elongate trough. The tidal range is greatest in the shallow, narrow Upper Gulf where water from each tidal flow piles up higher, as in a fjord. The Upper Gulf is thus a tidal-dominated region, with a maximum tidal range (lowest low to highest high of the year) of approximately 10 m (33 ft) near Isla Montague (Matthews 1969; Grijalva-Ortíz 1972; Stock 1976; Brusca 1980). Flood tides move up the estuary/river channel of the Colorado River as a tidal bore attaining velocities of 300 to 400 cm/sec (Sykes 1937). Tidal amplitude at the head of the Gulf is about four times greater than at the mouth. At Puerto Peñasco the annual tidal range is 7.3 m (24 ft). Tides throughout the Gulf are typically mixed semidiurnal (two high tides and two low tides of differing amplitude daily). Due to the extreme tidal range, tidal flats and esteros in the Northern Gulf are broadly exposed during low tides, and during spring tides these habitats are almost entirely drained of seawater, exposing large expanses of littoral sea floor from which humans have harvested a seafood cornucopia for millennia.

Historically, and throughout the Holocene, there have been long dry periods in the U.S. Southwest that resulted in reduced Colorado River flow to the Northern Gulf and periods during which the river's flow did not reach the Gulf at all (La Rue 1916; Kniffen 1932; Sykes 1914, 1937; Thompson 1968; Luecke and others 1999; Cohen and Henges-Jeck 2001; Cohen, Henges-Jeck, and G. Castillo-Moreno 2001; Brusca and others 2017). Thus the flora, fauna, and ecosystem of the delta and the Upper Gulf have long been adapted to broadly fluctuating freshwater flows and salinities. Although used by some researchers in the past, measurements of Colorado River water flow at the Yuma (Arizona) gauge, or even crossing the border into Mexico, do not provide a reliable proxy for how much water (if any) actually reaches the Gulf because of the complex nature of internal basins and diversions on the delta. Much, if not most of the surface water that has historically crossed the border has probably been trapped in various below-sea-level sinks on the delta before ever reaching the Gulf. Two of the largest sinks are the Salton Basin (to 85 m below sea level) and Laguna Salada (to 10 m below sea level). Both of these depressions can, and have multiple times in the past, held most or all of the water that the Colorado River annually carried to the U.S.-Mexico border region (La Rue 1916; Kniffen 1932; Sykes 1914, 1937; Thompson

1968; Luecke and others 1999, Cohen and Henges-Jeck 2001, Cohen, Henges-Jeck, and G. Castillo-Moreno 2001, Brusca and others 2017). The Colorado River Delta slopes into the Salton Basin at a gradient of ~0.8 m/km, thus the river's natural "preference," were it not for uplifts, outcrops, and channeling, is to drain into the Salton Sink (Thompson 1968). The Laguna Salada Basin is ~1000 km^2 and has a capacity to hold 4- to 8-million acre-feet (5 to 10×10^9 m^3) of Colorado River water. The Laguna Salada Basin is already filled to a depth of 4 to 6 km with river sediment—testimony to many centuries of capturing the Colorado River's sediment-laden flow. For a period of time, steamships plied the river between the Gulf and Yuma. But this occurred during a period of unusually high precipitation and increased river flow in the U.S. Southwest; it was this climatic anomaly that allowed for very shallow draft boats to move on the river. The period of boat traffic lasted only 25 years and was plagued with problems. Even with the specially made boats, with 12- to 18-inch drafts, many boats got stuck or sunk trying to negotiate the river.

The Colorado River flow pattern suggests that the Upper Gulf has never been brackish in nature. This is confirmed by four independent data sources: nineteenth-century (pre-Hoover Dam) oceanographic data, oceanographic data taken during a large 1993 Colorado River flood release, estimates of pre-1935 natal salinities of clam shells, and calculations of tidal flux in the Upper Gulf (Rojas-Bracho and others 2019a, 2019b). Mean daily tidal exchange in the upper Gulf ranges from 20.3×10^6 acre-feet (25×10^9 m^3) (Punta Borrascosa/Punta Gorda-San Felipe delineation), to 34.9×10^6 acre-feet (43×10^9 m^3) (Puerto Peñasco-San Felipe delineation), which is twice or more the entire mean annual Colorado River flow into Mexico. Even at its peak past flows, the river's impact on Gulf salinity was inconsequential. The southernmost delineation of the Colorado River estuary and its active modern delta is Isla Montague, at the mouth of the river itself, and there is no evidence that the Northern Gulf Holocene ecosystem has ever been an estuarine or brackish-water environment.

Biological Oceanography

The Northern Gulf of California is, historically and currently, one of the most biologically productive marine regions on Earth. This high productivity is driven by a unique mix of factors, including year-round coastal upwelling, wind-driven mixing, strong tidal currents and intense tidal mixing, thermohaline circulation that moves intermediate waters into the mixed layer, coastal-trapped waves, a well-defined seasonally reversing circulation pattern and associated eddies, abundant solar radiation, and regular sediment resuspension. Adding to the mix, to a lesser extent, are agricultural runoff, released nutrients from erosion of ancient Colorado River Delta sediments, and input from decomposing tidal-flat plant debris. The high primary (phytoplanktonic) productivity of the Northern Gulf has a long history of documentation (reviewed in Brusca and others 2017). This high primary productivity moves up the food chain to drive the massive upper-trophic-level productivity of finfish, shellfish, sea turtles, and marine mammals. All of this lured humans to the coast. The main (legal) fisheries of the Northern Gulf today are blue shrimp (*Litopenaeus stylirostris*), blue swimming crab (*Callinectes bellicosus*), Gulf sierra (*Scomberomorus* spp.), Gulf corvina (*Cynoscion othonopterus*), shovelnose guitarfish (*Rhinobatos productus*), and Gulf coney (*Epinephelus acanthistius*). Marinone and others (2008) and Peguero-Icaza and others (2008) analyzed plankton samples and hydrographic data collected in the Northern Gulf, concluding there was a clearly discernable larval fish assemblage (a "planktonic habitat") in the Northern Gulf. Using 3D numerical models of particle tracking they showed a 64 percent retention of fish larvae in the region over a 15-day period during the anticyclonic circulation season (November to April) in the Northern Gulf.

The Gulf of California is ranked as a Class I "highly productive ecosystem (>300 g C m^{-2} yr^{-1})" based on global SeaWiFS primary productivity estimates (Sea-Viewing Wide Field-of-View Sensor; the widely used plankton chlorophyll sensor), and it is one of the five marine ecosystems with the highest productivity in the world (Enríquez-Andrade and others 2005). Overall phytoplankton production is on the order of >1 g C m^{-2} day^{-1} to >4 g C m^{-2} day^{-1} (Álvarez-Borrego and Lara-Lara 1991; Santamaría-del-Ángel, Alvarez-Borrego, and Muller-Karger 1994; Santamaría-del-Ángel and others 1999; Gaxiola-Castro and others 1995; Thunnell 1998). This high productivity of the Gulf generates about half of Mexico's total fisheries production and supports more than 50,000 jobs (Cisneros-Mata, Hamman, and Nevárez-Martínez 1995; Cisneros-Mata 2010; Cinti, Shaw, and Torre 2010; Cinti and others 2010; Erisman, Aburto-Oropeza and others. 2012b; Erisman and others 2015; Lluch-Belda and others 2014). Most of this fishery is in the Northern Gulf. There is no evidence that the Colorado River has ever been an important driver of primary productivity in the Northern Gulf, and nutrient/chlorophyll studies show no relationship to Colorado River flow (or, if anything, reduced nutrient/chlorophyll levels occur during high river-flow periods). The sum of these data suggest that the Colorado River has never played an important role in the ecology of the Northern Gulf of California (though it clearly has been important for the river's delta area).

In addition to having high nutrient levels and productivity, the Gulf is also biologically diverse, harboring more than 6,000 named and described animal species, more than 2,800 of which inhabit the Northern Gulf including more than 130 Gulf endemic species (Brusca and others 2005; Brusca 2007, 2010; Brusca and Hendrickx 2008; Herrera-Valdivia, López-Martínez, and Castillo Vargasmachuca 2015). The rich Gulf fauna includes a third of the world's cetaceans (31 species), five species of sea turtles, an endemic fishing bat (*Myotis vivesi*), a sea snake (*Pelamis platura*), and the American crocodile (*Crocodylus acutus*). The last, *el cocodrilo del río*, today does not range north of the Río Fuerte, but in the past it probably ranged as far north as Guaymas, and perhaps even farther. The marine ecosystem of the Northern Gulf is rich in nutrients, high in biodiversity and productivity, and is very healthy, except for the impacts of historical and current unsustainable fisheries. Human extraction of shrimp, Gulf corvina, totoaba (illegally), and other marine resources remains very high in this region, has serious ecological impacts, and is the primary conservation concern (All 2006; Valenzuela-Quiñónez, Garza, DeAnda-Montañez, and García de-León 2014; Valenzuela-Quiñónez and others 2015; Valenzuela-Quiñónez and others 2016; Mercado-Santana and others 2017; Brusca and others. 2017; Johnson and others 2017; Brusca 2018a, 2018b; Rodríguez-Quiroz and others 2018). At the time of this writing, it appears likely that the vaquita marina (*Phocoena sinus*), a small porpoise endemic to the Upper Gulf, will go extinct within a few years due to illegal fishing practices directed out of the towns of San Felipe and El Golfo de Santa Clara (Rojas-Bracho and others 2019; Jaramillo-Legorreta and others 2019).

COASTAL ENVIRONMENT OF THE PUERTO PEÑASCO-BAHÍA ADAIR REGION

The Upper Gulf of California (Figures 3.1 and 3.2) is a subregion of the Northern Gulf demarcated by an imaginary line running between Punta Machorro in Baja California, and Punta Pelícano in Sonora (Brusca and Bryner 2004). It is also a Mexican Biosphere Reserve and UNESCO World Heritage Site (Reserva de la Biosfera del Alto Golfo de California y Delta del Río Colorado; the Upper Gulf of California and Colorado River Delta Biosphere Reserve, or "Upper Gulf Reserve"). Bahía Adair lies within the Upper Gulf Reserve, but the towns of San Felipe and Puerto Peñasco (and Estero de Morúa) lie just outside this Reserve (Figure 3.2).

All of the Northern Gulf (including Puerto Peñasco and San Felipe) experiences large seasonal fluctuations in onshore sea surface temperatures. At Puerto Peñasco this annual fluctuation commonly exceeds 18° C (32.4° F) annually. Onshore water temperatures may reach 30°-32° C in the summer and may drop to 10°-12° C in the winter, although the usual winter temperatures are around 13°-14° C (Brusca 1980). The intertidal region experiences an even greater range of temperatures because of periods of exposure to atmospheric conditions, and temperatures as high as 36° C have been recorded in tidepools at Puerto Peñasco. The temperate (Californian) species that live in the Upper Gulf generally disappear from the littoral region during the warm summer months. Offshore sea-surface temperatures are cooler, ranging from 17° to 30° C. The Northern Gulf also periodically experiences exceptionally cold winters, during which onshore sea surface temperatures drop to 8° or 9° C (or less), and tidepool temperatures as low as 4° C have been recorded at Puerto Peñasco. When this happens, a large die-off of intertidal marine animals can occur and it is these winter cold events that prevent mangroves from penetrating into the Upper Gulf. These data suggest that the Northern Gulf functions as a warm-temperate marine environment in the winter, but a tropical environment in the summer. This is a common feature of subtropical coastlines the world over.

There is a diverse mix of coastal geomorphology in the Northern Gulf, including sand beaches (and sand dunes), rocky shores and nearshore rocky reefs, esteros, and broad tidal flats that experience several kilometers of exposure during low spring tides (see Chapter 2). This habitat diversity supports a large "pantry" of seafoods that has long been exploited by birds and terrestrial mammals, including humans. Although most of the Northern Gulf's Sonoran coast comprises sand beaches, bays, esteros and tidal flats, isolated rocky shores do occur and these harbor the greatest diversity of animals and algae in the region. The fauna of rocky shores is largely (though not entirely) distinct from that of esteros and tidal flats. From northern Bahía Adaír to Desemboque de los Seris (Desemboque del Río San Ignacio) and Punta Tepopa on the Sonoran coast, there are intertidal outcrops of beachrock that support this highly diverse rocky-shore flora and fauna. In geological terms, beachrock is defined as "lithified littoral sediments"; it is most common in arid regions of the world (such as the Northern Gulf). In some areas, such as the Florida coast, it is composed primarily of sand. But in the Northern Gulf it forms a composite of sand, mollusc shells, and sometimes small-to-large rocks. When shells are included in the calcified matrix, beachrock is often called coquina. The precipitated calcium carbonate that cements this material together comes both from the seawater and from the dissolving shells themselves. More-or-less continuous coquina outcrops have been traced to about 13 km east of Puerto Peñasco, in the shallow subtidal region or partially buried under intertidal sands. Some of the outcrops east of Puerto Peñasco include boulders more than a meter in diameter. Littoral outcrops of coquina also occur at Punta Borrascosa/Punta Gorda and can be found discontinuously all along the coast of Bahía Adair.

Paleontologists have assigned a Pleistocene age to the Upper Gulf coquinas. Uranium-thorium dating has estimated an age of approximately 130,000 yr B.P., supporting the paleontological age assignment (Hertlein and Emerson 1956; Davis and others 1990). Ortlieb (1979, 1991a, 1991b) correlated the beachrock in the upper intertidal at Bahía la Cholla to the 120,000 yr B.P. sea-level high stand (during the last interglacial). One form of coquina is notably high in *Chione* clam shells (the "*Chione* coquina") and is considered an index bed. Today, *Chione* coquina occurs at an elevation of 5 to 23 m above mean sea level between Punta Borrascosa/Punta Gorda and Estero la Pinta. Ancient, higher than present sea levels are also indicated by subsurface coquina beachrock located beneath sand dunes several hundred meters inland from Estero de Morúa (DeCook and others 1980), some of which was measured to be 24 m thick.

Many shallow negative estuaries, or esteros, occur along the eastern shore of the Northern and Central Gulf (Lavín, Godínez, and Alvarez 1998; Nagler, Glenn, and Brusca 2004; Glenn and others 2006). Such tidal lagoons are also known from the Red Sea, the Mediterranean Sea, the Adriatic Sea, the Arabian Gulf, and South Australia (Ansell, Gibson, and Barnes 1998). Esteros in the Northern Gulf cover approximately 134,623 ha (Morzaria-Luna and others 2010). Estero de Morúa, near Puerto Peñasco, is a good example of an estero, or negative estuary. In these habitats, evaporation greatly exceeds precipitation, creating a situation in which the salinity (and usually also the temperature) increases from the mouth of the estero toward the head—just the opposite of what occurs in a positive estuary fed by active river flow. In summer months, during slack tide periods, temperatures in the shallows of these esteros often exceed 40° C and salinities skyrocket to 40 to 60 ppt. These shallow, plankton-rich regions serve as nursery grounds for a number of commercially important shellfish and finfish species; people have harvested resources in these environments for at least 6,000 years. Mangroves in the Gulf of California do not occur north of Puerto Lobos, presumably because they are limited by cold winter temperatures (Osland and others 2021).

It is possible that human habitation in this region preceded 4,000 B.C., but older archaeological sites would now be under the sea due to post-glacial sea level rise (see Huckleberry, this volume). During the height of the Last Glacial Maximum, 26,500 to 19,000–20,000 yr B.P., relative sea level was approximately 130 m lower than today (Jansen and others 2007), and sea level in the Northern Gulf would have been 50 to 80 km offshore, near the Wagner Basin (van Andel and Shor 1964, Bischoff and Niemitz 1980). Inland Clovis sites such as El Fin del Mundo indicate humans were in Sonora as early as 13,400 yr B.P. (Sánchez and others 2014) at a time when relative sea level was approximately 80 m below its modern level. Van Andel and Shor (1964) and Thompson (1968) note that "during the Wisconsin lower sea level" most of the Upper Gulf was exposed subaerially and the two large channels leading to Wagner Basin were cut by the Colorado River. Thompson (1968) further speculates that a sand sill interrupted the late Wisconsin rise of sea level and resulted in the formation of an older intertidal mud flat in the western Gulf, recognizable today as a terrace at depths of 12 to 15 m offshore from San Felipe. According to Thompson (1968), both of the two ancient drainages to Wagner Basin and the ancient intertidal mud flat are recognizable today in sonar profiles of the Upper Gulf seafloor.

The Río Sonoyta almost certainly once flowed into and helped create the coastal topography for what are now Estero de Morúa and Estero La Pinta. These two esteros are today separated only by a small alluvial fan at the mouth of an inactive channel of the river. The river still maintains a subsurface flow (the Río Sonoyta aquifer) and this is visible in satellite photographs as a "river" of vegetation (Figure 3.3; Glenn and others 2006). Earlier in time, the Río Sonoyta probably flowed to the Upper Gulf, perhaps shifting its mouth between the areas of El Golfo de Santa Clara and the northernmost end of Bahía Adair (Ives 1964; Donnelly 1974; Turner 1983). The formation of the Sierra Pinacate and associated maar craters of the northern Pinacate region (Figure 3.3) likely deflected the course of the river to its present location a few miles east of Puerto Peñasco. The Río Sonoyta and its aquifer are disappearing today due to drought and groundwater overdraft.

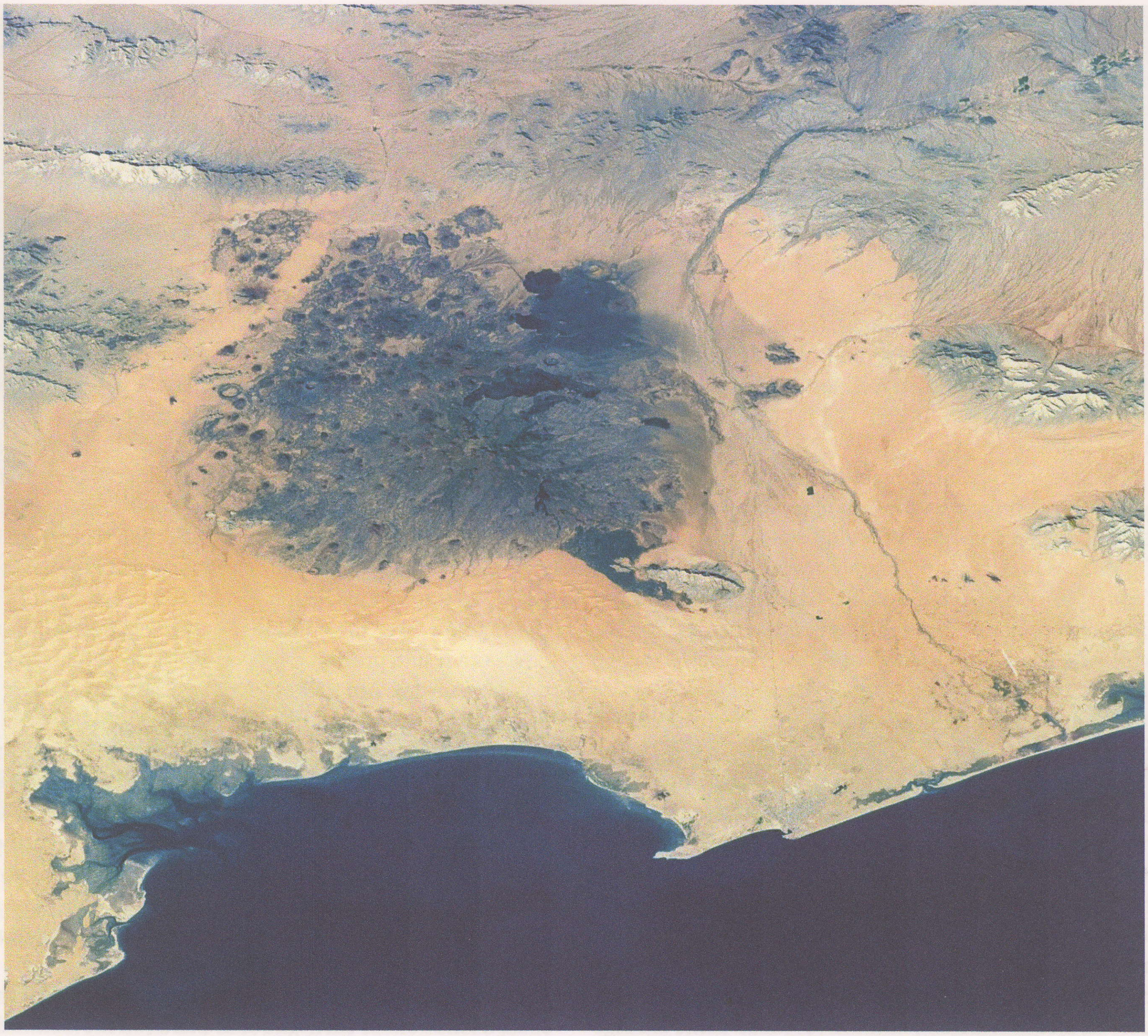

Figure 3.3. The Sierra Pinacate, Bahía Adair, and Estero de Morúa-Estero La Pinta region from space. Note that the track of the Sonoyta River aquifer is visible by the line of large trees and other vegetation leading to Estero la Pinta. Source: NASA.

The formation of the Sierra Pinacate was a vicariant event that led to disjunct populations of aquatic species such as the Quitobaquito (or Río Sonoyta) pupfish (*Cyprinodon eremus*), the Lower Colorado River desert pupfish (*Cyprinodon macularius*), longfin dace (*Agosia chrysogaster*), and Sonoran mud turtle (*Kinosternon sonoriense longifemorale*) (Turner 1983; Minckley and others 2013; Echelle, Van Den Bussche, and others. 2000; Echelle and others 2005; Riedle and others 2012). Longfin dace and mud turtles are rare or absent in the delta region today due to drying from over-extraction of Colorado River water. Molecular dating places the age of separation of the two pupfish species at around one million years or less, roughly the same age as the formation of the Sierra Pinacate (Minckley 2002; Minckley, Hendrickson, and Bond 1986; Minckley, Miller, and Norris 2002; Echelle and others 2005; Marshall and Blake 2009).

The headwaters of the Río Sonoyta are primarily on the slopes of the Ajo Mountains and adjacent valleys, including the drying Sonoyta Valley. An excellent description of the river can be found in Rosen and others (2010). In typical years today, the only surface water flow in the river is an intermittent segment (locally known as Agua Dulce) about 1 kilometer in length, just south of the U.S.-Mexico border and Quitobaquito Springs, which is at the southern edge of Organ Pipe Cactus National Monument. In this last little trickle of water live two important native fishes, the endangered Sonoyta pupfish (*Cyprinodon eremus*) and the indigenous longfin dace (*Agosia chrysogasster*), although the later might now be extirpated. Invasive introduced fishes in the Agua Dulce include mosquitofish (*Gambusia affinis*), black bullhead (*Ameiurus melas*), and Gila topminnow (*Poeciliopsis occidentialis*) (Rosen and others 2010).

The northern coast of Sonora is very dry. DeCook and others (1980) reported an average annual precipitation of 93 mm from 1948 to 1977 at Puerto Peñasco. Green (1969), however, recorded an average annual precipitation of 73.5 mm during the drought from 1959 to 1967. Rain is spread through the fall (50%), winter (26%), and summer (18%) (Davis and others 1990). Wind direction in this region is also seasonal, blowing mainly from the south during January through September, but from the north during October through December (Davis and others 1990). The Bahía Adair region is adjacent to the Gran Desierto, one of the hottest and driest deserts in North America, where maximum temperatures reach 46° C and the mean annual temperature is 23° C (Zamora and others 2019).

There is no direct evidence of there ever being perennial flow of the Río Sonoyta to Esteros de Morúa and La Pinta during the Holocene Epoch, nor is it clear what that evidence might be. It is, however, reasonable to suspect that during periods of wet years this probably occurred. For example, the cool and more extreme weather between around A.D. 1300 and A.D. 1550 has long been linked to the abandonment of Chaco Canyon and Mesa Verde cultures in North America, and the so-called Little Ice Age (~A.D. 1350 to A.D. 1850) is known to have resulted in crop failures and famine in Europe. Recently, Zhang and others (2019) have documented a marked cooling of sea surface temperatures in the northwest Pacific during the Little Ice Age. Changes in the monsoons are a consequence of known changes in orbital forcing and insolation, modulated by land- and ocean-surface conditions (Kutzbach and Guetter 1986; Liu and others 2003; Zhao and Harrison 2012; Bhattacharya and others 2018). Paleoenvironmental data show that there were significant changes during the Holocene in regional precipitation patterns in monsoon regions (such as northwest Mexico) on centennial timescales. There has been intensive study of abundant paleoclimatic proxy records for the mid- to late Holocene climate and the impact of insolation on northern latitude climates (Otto and others 2009). Centennial-scale cooling events and periods of increased moisture that occurred in the Northern Hemisphere during the Holocene have been registered in a variety of these records, which include marine sediments, lake level data, glacier records, pollen, and plant and animal fossils (Renssen, Goosse, and Muscheler 2006; Renssen, Goosse, and Fichefet 2007; Brooks and others 2015; Bhattacharya and others 2018). Most of these cooling events have been correlated with periods of reduced solar activity, suggesting a solar-climate link for Holocene cooling (Magny 1993; Bond and others 2001; Magny and Hass 2004; Zhao and others 2014). For example, Renssen, Goosse, and Muscheler (2006) document good evidence for a 2800 to 2600 yr B.P. cooling in the North Atlantic region that corresponds with a widespread cool phase (with wet conditions) in the Northern Hemisphere. They also note a very similar event around 6000 to 5300 yr B.P. (Magny and Haas 2004). Zhao and Harrison (2012) showed that 6,000 years ago North America experienced increased summer insolation that led to a deepening of the thermal low over the continent and intensified onshore flow. As a result, precipitation was enhanced compared to the present-day American Southwest. The atmospheric response to increased summer insolation at 6000 yr B.P. in the northern subtropics strengthened the Northern Hemisphere summer monsoons and led to increased monsoonal precipitation and a wetter North America. Ocean feedbacks amplified this response and led to further increases in monsoon precipitation. Thus, perennial flow of the Sonoyta River to the Gulf during the Holocene is a strong possibility and this could have led to long-term human habitation of sites in the coastal region.

Isolated natural freshwater springs are present near the coast from south of Cienega Santa Clara (on the Colorado River Delta) to El Golfo de Santa Clara and around Bahía Adair (e.g., El Doctór near the fishing village of El Golfo de Santa Clara, El Tornillal with its screwbean mesquite grove, and Salina Grande with its massive salt deposits in Bahía Adair). These pozos form a complex of freshwater sources that are probably less than a day's walk from one another, and which would have been convenient for Native American inhabitants of the region as well as early European explorers. At least 26 species of vascular plants have been reported from these coastal pozos. The springs around northern Bahía Adair also have long been the coastal destination of O'odham "salt treks." All of the pozos are surrounded by prehistoric and historic, human-deposited shell middens (*conchales* or *concheros*). Zamora and others (2019) used stable isotopes and water chemistry to show

Figure 3.4. Some common bivalves found in shell middens in the Northern Gulf and also exploited by fishers today: upper left, clams in Kino Bay *malecón* market (*Dosinia ponderosa* [white shells], *Tivela bryonensis* [small brown shells], and *Tivela planulata* [large brown shells]; upper right, clams (*Chione fluctifraga*) in Puerto Peñasco malecón market; lower left, *Chionopsis gnidia*; lower right, the common rock oyster, *Ostrea* (=*Myrakeena*) *angelica.*

that the freshwater in pozos along the eastern shore of the Upper Gulf was derived primarily from the Colorado River delta aquifer, enhanced by local, sporadic precipitation. Underground flow of river water to the pozos is likely to be primarily along the Altar and Cerro Prieto Faults. Kinsland (1989) suggested that the Colorado River once may have emptied into the Gulf of California at Bahía Adair, and gravity data indicate an appropriate basement configuration (Lock, Davis, Cutler, and Sinitiere 1989; Lock, Sinitiere, and Williams 1989). Many of the salinas, or saltpans around Bahía Adair were mined (for salt) in the past by Native peoples and in recent years by local residents. For a period of time, salt was mined from Salina Grande and loaded onto railroad cars at López Colada. The freshwater springs in Salina Grande are surrounded by 2- to 4-m high mounds of sand with water flowing from central, crater-like depressions. Water quality varies from mound to mound and from season to season (Ezcurra and others 1988). Davis and others (1990) claimed that, from the air, the springs around Bahía Adair can be seen aligned along fault lines, the Salina Grande Basin being linear and controlled by the orientation of the Cerro Prieto Fault.

Hundreds of species of molluscs, crabs, and finfish inhabit Bahía Adair and Esteros de Morúa and La Pinta. About two-dozen species of molluscs, swimming crabs, some finfish, and sea turtles have been reported from archaeological remains in this region. All belong to species that are common to the Northern Gulf fauna today. Figure 3.4 illustrates some of the shellfish species. Reports on Pleistocene coastal invertebrates from the Northern Gulf suggest there has been little or no change in the faunal composition over the past 2.6 million years (Meldahl and

Cutler 1992; Johnson and Ledesma-Vázquez 2001, 2009; de Diego-Forbis and others 2004; López-Pérez 2012; Waite and Allmon 2013).

The most abundant fish otoliths in middens of Estero de Morúa and Bahía Adair are from two species of Sciaenidae (the croaker family): *chano norteño* or bigeye croaker, *Micropogonias megalops* (regarded by some as a junior synonym of *M. altivelis*; Sánchez-Pinedo and others 2018) and shortfin corvina, *Cynoscion parvipinnis*. Both species occur in esteros and over tidal flats throughout the Gulf, as well as offshore. A distant third in abundance is another sciaenid, the totoaba (*Totoaba macdonaldi*). All three of these croaker species have probably been extremely abundant in the Northern Gulf throughout the Holocene. All three congregate in spawning aggregations, making them conveniently susceptible to fishers working from shore or in shallow waters of bays and coastal lagoons. Totoaba probably spawn from February to May, with a peak in March and April (Cisneros-Mata and others 1995), whereas bigeye croaker spawn from February to September, with a maximum in the summer (Erisman and others 2010; Erisman and others 2012a, 2012b; Erisman and others 2015; Sadovy and Erisman 2010). Surprisingly, there is still little certainty about where these sciaenid species actually spawn. Garcés-Rodríguez and others (2018) found totoaba larvae only on the northwestern side of the Upper Gulf, in the shallowest region, suggesting that the stratification front previously described has no relationship with the distribution of larvae in this species (they suggest the spawning area of totoaba could be associated with other factors, such as adult habitat).

Bigeye croaker is heavily fished in the Northern Gulf today, mainly from April through September. A commercial fishery for totoaba bladders (for export to China) was established in the 1920s in the Upper Gulf, taking advantage of their late-winter-to-early-spring spawning aggregations. The totoaba fishery peaked at an astonishing 2,300 metric tons per year before declining due to overfishing (Rosales-Juárez and Ramírez-González 1987; Márquez-Farías and Rosales-Juárez 2013). Since totoaba were listed as endangered (by both the United States and Mexico) their population has rebounded (Brusca and others 2017). Occasional otoliths of the Gulf corvina, or Gulf weakfish (*Cynoscion othonopterus*), occur in middens along the Northern Gulf; a corvina fishery in this region has expanded greatly in recent years (primarily February through April). Gulf corvina spawn from February to September, and approximately 1.5 to 1.8 million Gulf corvina are harvested annually from spawning aggregations in the Upper Gulf during 21 to 25 days of legal fishing (Erisman and others 2010; Erisman and others 2012a, 2012b).

Native peoples likely fished for all of these sciaenid fishes in the shallow waters of Estero de Morúa and Bahía Adair with hook and line or spears. Stingray spines that might have been used for spears have been found in middens (stingrays are common in the esteros and tidal flats of this region). Another common fish species (including on tidal flats) is the circumtropically distributed striped mullet (*Mugil cephalus*). Otoliths of this species have not been reported from middens in the area, but these bones are very small and difficult to identify. It is possible they have been overlooked by researchers. Striped mullet are also known to have also occurred in the ancient Lake Cahuilla (Salton Basin, Southern California) from A.D. 900 to 1500 (Gobalet 1992, 1994).

ESTERO DE MORÚA AND BAHÍA ADAIR

Although the description that follows applies primarily to Estero de Morúa, the habitats of Bahía Adair are basically the same with the exception that one is a bay and the other an estero, and pozos occur in Bahía Adair but not at Estero Morúa. The same species found in middens of Estero de Morúa also occur in the middens at Bahía Adair.

Estero de Morúa is a large negative estuary, the opening (mouth) of which is 11 km east of Puerto Peñasco (31° 17.2' N, 113° 26.3' W). The estero is part of an extensive beach-dune ridge-lagoon complex that continues south for about 50 km to Bahía de San Jorge. During spring tides Estero de Morúa fills to depths over 5 m at high water, and it drains completely at low water, leaving only a small shallow (~10 cm deep) drainage channel through the middle of the tidal flats. The estero covers approximately 1,100 ha. The east and west arms of Estero de Morúa have a combined length of about 8 km at high water, and they are separated from the sea by barrier dunes reaching 30 m in height. During tidal exchange flows, current velocities in the narrow mouth can reach 50 cm s^{-1}, and residence time in the estero is less than 6 hours (Morzaria-Luna and others 2014). Due to these rapid twice-daily tidal exchanges, the sediment is well-sorted sand and muddy sand; areas of sustained hypoxia have not been reported. Coarse sand (0.5 mm) occurs near the mouth of the estero, with particle size decreasing toward the heads of the two arms. Silty muds occur only at the highest tidal levels in the low-growing (50- to 60-cm tall) halophyte-dominated salt flat community that includes *Monanthochloe littoralis*, *Sarcocornia pacifica* [=*Salicornia pacifica*], *Batis maritima*, *Suaeda californica*, *Distichlis palmeri*, *Frankenia grandifolia*, *Allenrolfea occidentalis*, and *Atriplex barclayana*. Outcrops of rock (mainly mudstones) occur in some localities that might suggest ancient, freshwater lagoonal habitats. Just above the highest high-tideline, salt-tolerant desert shrubs such as *Frankenia palmeri*, *Ambrosia dumosa*, *Larrea tridentata*, *Atriplex polycarpa*, and *Atriplex canescens* occur.

Morzaria-Luna, Iris-Maldonado, and Valdivia-Jiménez (2010) reported that, from 2005 to 2007 the water temperatures in Estero de Morúa followed a seasonal pattern with highest temperatures in summer (30.3 ±0.3° C in August 2005) and lowest in winter (9.4 ±0.3° C in January 2006), although in shallows during slack tide temperatures ranged from a low of 6° C to a high of 40° C. Place and Hofmann (2001) found that water temperatures in the estero ranged from about 5° to 30° in winter, and 18° to 36° during the summer. Buckley and Hofmann (2004) recorded water temperatures in the estero from January to June 2001 and found a range from <5° C in early January to higher than 33° C in June. Morzaria-Luna, Iris-Maldonado, and Valdivia-Jiménez (2010) reported salinity as ranging from 52.2 ±3.2 ppt (April 2006) to 41.1 ±0.45 ppt (May 2007). They found no seasonal pattern, but as expected, values were higher near the heads of the estero than at the mouth and during slack low-tide periods could exceed 100 ppt. Morzaria-Luna, Iris-Maldonado, and Valdivia-Jiménez (2010) found mean dissolved oxygen concentration in Estero de Morúa to be high (8.68 ±0.07 mg/L), but varied between 11.34 ±0.18 mg/L (July 2006) and 6.21 ±0.22 mg/L (August 2005). Dissolved oxygen varied with sample location.

Nutrient concentrations in Estero de Morúa are low, likely due to minimal precipitation and runoff and only modest growth and decomposition by the halophyte land-plant community. Morzaria-Luna, Iris-Maldonado, and Valdivia-Jiménez (2010) reported that nitrogen concentrations are lower than values reported for other hypersaline wetlands in the Northern Gulf. Accordingly, Morzaria-Luna, Iris-Maldonado, and Valdivia-Jiménez (2010) also reported chlorophyll *a* concentrations in the estero to be low, indicating a system of low productivity (and lower than shown for other Northern Gulf hypersaline lagoons). An unpublished stable isotope analysis of trophic food webs in the estero found that marine-derived phytoplankton contributes the most carbon to the system (Spackeen 2009). Morzaria-Luna, Iris-Maldonado, and Valdivia-Jiménez (2010) found mean Chl *a* concentrations showed a significant variability between sampling locations and surveys, although there was no seasonal pattern, with the highest concentration found at 0.50 ±0.32 mg/m3 (June 2006).

Although paleoecological core studies have not been made in the Estero de Morúa area, Caballero and others (2005) used cores to show that about 6,000 years ago, a freshwater to slightly brackish-water marsh existed on the coastal floodplain along the shoreline at Nuevo Kino (Kino Bay), about 350 km south of Estero de Morúa. Vegetation in that marsh included *Typha domingensis* (southern cattail) and Cyperaceae (sedges). Using core data they were able to track the progressive salinization of the lagoon as post-glacial sea levels rose. The site today is a saline sink, 1 m below sea level, that is separated from the ocean by a 10- to 15-m high sand dune. Both climate and sea-level changes are known to have played important roles in patterns of human occupation in the Gulf of California and Baja California (Petit-Maire and Casta 1977; Procasi and Fujita 2000).

All of the shellfish species found in middens at Estero de Morúa are present on the tidal flats or rocky outcrops inside this estero today; many are currently harvested for local consumption. The following midden-occurring bivalve species inhabit Estero de Morúa today: *Chionista* (= *Chione*) *fluctifraga*, *Chione californiensis*, *Chionopsis* (= *Chione*) *gnidia*, *Dosinia ponderosa*, *Laevicardium* (probably *L. elatum*), razor clams (*Ensis*, *Solecurtus*, and *Solen*), *Trachycardium panamense*, *Glycymeris gigantea*, *Leukoma grata* (= *Protothaca grata*, *Venus grata*), *Tivela* sp. (likely *T. byronensis*), and *Cardita affinis*. The mussel-like *Arca pacifica*, oysters (*Ostrea angelica*, *O. conchaphila*, and *Saccostrea palmula*), "mussel" (probably *Modiolus capax*), *Barbatia reeveana* (= *Arca reeveana*), black murex (probably *Hexaplex nigritus*), swimming crabs (almost solely *Callinectes bellicosus*), and gastropods (*Melongena patula*, *Turritella*, and *Calyptraea mamillaris*) occur on both the outer rocky coast littoral and on rock outcrops inside the estero. Every species of invertebrate found in the middens around Estero de Morúa could have been easily collected from the estero itself. It is possible that green sea turtles also used to enter Estero de Morúa; they, too, would have been easily collected on the sandy beaches outside the estero.

Foster (1975) hypothesized (probably incorrectly) that there had been "major ecological changes" in the environment of Estero Morúa since A.D. 1200. He based this idea on two observations. First was his assessment that 35 percent of the mollusc specimens he recorded from shell middens at Estero de Morúa had been collected from the "intertidal and shallow rocky shore." This, in turn, was based primarily on the large number of oyster shells he found in the middens. Most of Foster's specimens were not identified to the species level, however, and those that were were identified as *Ostrea angelica*. Several species of oysters are native to Estero de Morúa, including *O. angelica*, where they live on mudstone or coquina beachrock outcrops (although *O. angelica* also occurs on rocky shores outside the estuary). The assumption that the presence of *Ostrea* implies foraging on rocky outer shores is not supported by any data Foster (1975) presented. The second basis for Foster's hypothesis of ecological change was that the number of *Chione* and murex shells in the middens was so high that abundance of these species 700 years ago must have far exceeded that seen today. He offered no empirical calculations or other basis for this assumption, however, simply stating, "the *Chione* population has been permanently reduced in the intertidal estuarine zone." He made the same assumption about two species of Muricidae, *Hexaplex nigritus* (as *Muricanthus nigritus*) and *Phyllonotus erythrostomus* (as *Hexaplex erythrostomus*). In both cases, the more parsimonious explanation would be that overharvesting of these species in the estero in modern (historic) times has led to the depletion in abundance in the estero. In addition, Foster (1975) offered no explanation of how he determined the relationship between mollusc species abundance in middens (that are accumulations over many years) and mollusc species abundance in the estero. Further, the two murex snails he notes live primarily on rocky shores outside the estero, where they breed subtidally on sand and mud substrates. A few individuals can be found in esteros such as Estero de Morúa, where they inhabit the rocky outcrops, moving off the rocks to breed on the soft sediments of the estero. But because these murex snails are associated only with rocks, they have probably never been abundant in Estero Morúa.

Many species use esteros in the Northern Gulf opportunistically, entering only during high tides to rest, feed, and reproduce (especially fishes). Others are residents with special adaptations to withstand the extreme environmental conditions of these habitats, especially invertebrates. A few highly adapted fishes are resident in these esteros, such as the longjaw mudsucker (*Gillichthys miriabilis*) and closely-related shortjaw mudsucker (*Gillichthys seta*).

Artisanal shellfishing in Estero de Morúa today focuses mainly on the bivalves *Chionista fluctifraga* (*venus lisa de bah*), *Chione californiensis* (*venus California*), *Chionopsis gnidia* (*venus vistosa*), and occasionally oysters (*Ostrea* and *Saccostrea*). In Estero de Morúa (and Bahía Adair) these are harvested for local consumption and occasionally show up in the fish markets along Puerto Peñasco's *malecon*. In addition, four aquaculture cooperatives farm eastern oysters (*Crassostrea virginica*) in the estero.

SUMMARY

The nutrient-rich waters of the Northern Gulf of California have long supported a highly productive, species-rich coastal environment that has been exploited by Native Americans and modern coastal inhabitants and visitors for at least 6,000 years, and perhaps longer. There is no evidence that the Colorado River ever played an important ecological role in the Northern Gulf, or that it was ever a brackish-water environment. The diversity of habitats in the Northern Gulf, including the Estero de Morúa and Bahía Adair regions, help to sustain a diverse coastal flora and fauna. Evidence from midden excavations in the Estero de Morúa and Bahía Adair regions indicate no significant changes in marine coastal species composition over the past 6,000 years, and many of the species harvested by aboriginal peoples are locally harvested today for food.

ANTHROPOLOGICAL PAPERS OF
THE UNIVERSITY OF ARIZONA
NUMBER 83

Coastal Foragers of the Gran Desierto

Investigations of Prehistoric Shell Middens along the Northern Sonoran Coast

Edited by Douglas R. Mitchell, Jonathan B. Mabry, Gary Huckleberry, and Natalia Martínez-Tagüeña