


CONSERVATION SCIENCE IN MEXICO'S NORTHWEST

ECOSYSTEM STATUS AND TRENDS IN THE GULF OF CALIFORNIA




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PESTICIDES, HEAVY METALS, AND ARSENIC LEVELS IN COASTAL NORTHWESTERN MEXICO

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Over 40 studies from the published literature and data available from government agencies were gathered and reviewed in an effort to collect information on the environmental conditions on the coasts of northwestern Mexico with respect to pollution caused by heavy metals, arsenic and organochlorine y organophosphate pesticides in water, sediments and biota. Generally speaking, the amount of information is scarce and not up-to-date, as studies are localized and were conducted in diverse matrixes with significant spatial and temporal variations using non-standardized analytical methodologies at the national and international levels; circumstances that impede making any meaningful comparisons of the observed results. Several studies of contamination in biota were carried out on species characterized by high mobility (birds, marine mammals, reptiles) so the information is inadequate for evaluations on a regional scale. The most frequent organic pollutants detected were DDT and its metabolites, DDD and DDE, as well as lindane, two compounds whose use is currently banned or restricted. The presence of DDE in various animal species suggests recent utilization of DDT, though at lower levels than before its use was prohibited. Pesticide levels reported in turtles, whales and sea lions from the Gulf of California are significantly lower than those detected in other regions (the US, Mediterranean Sea, Gulf of Mexico). Due to their toxicity, some of the chemical compounds detected are covered by the Stockholm Convention. Studies conducted in coastal lagoons in the states of Sinaloa and Sonora (important agricultural regions) that analyzed water, sediments, fish, oysters and wild and cultivated shrimp detected such organochlorine pesticides as DDT and its metabolites, lindane, dieldrin, chlordane, oxychlordane, heptachlor, heptachlor epoxide, endosulfan, endrin and endosulfan phosphate, as well as 6 of the 19 organophosphate pesticides included on the European Economic Community's priority list: demeton, dimethoate, disulfoton, ethyl parathion (banned for all uses in Mexico), methyl parathion, and malathion, as well as phorate sulfoxide (restricted in Mexico). Analyses in birds, whales, sea lions and turtles detected the presence of DDT and the metabolites hexachloro cyclohexane, dieldrin, aldrin, endosulfan, lindane, chlordane, oxychlordane, heptachlor epoxide, endosulfan and endrin. High levels of cadmium and lead were found in plants and animals that exceeded the allowable limits determined by the US Food and Drug Administration, but arsenic and mercury were not reported in high concentrations.

1. INTRODUCTION

Over the past 30 years, ocean pollution has become a subject of increasing international concern. The marine environment is being severely affected by chemical substances of both anthropogenic—residual urban, industrial and agricultural waters—and natural origin (primarily geological weathering). Terrestrial activities cause at least 80% of this pollution, which reaches the coast through such processes as surface runoff and groundwater seepage, as well as from the atmosphere. As the capacity of coastal areas to assimilate or disperse these contaminants is limited, they cause significant environmental deterioration that affects natural ecosystems (Colborn *et al.* 1993, Fry 1995, Heeren *et al.* 2003, Depledge and Galloway 2005).

Upon reaching the ocean, these contaminants mix directly with the water column, migrate with currents, or settle on the sea floor, where they may subsequently be absorbed into the food chain by bottom-feeders, or reintroduced into the water column by upwelling currents. Whatever their mechanisms of dispersion and transmission, pollutants accumulate in biota through the food chain and, in some cases, reach humans through consumption of contaminated marine products (Escobar J. 2002, Alavanja *et al.* 2004). With regard to the effects induced by chemical substances, the phenomena of residue transference and magnification through the trophic chain are described repeatedly and judged to constitute the principal risk for the environment and the health conditions of populations both wild and human (Colborn *et al.* 1993, Fry 1995, Heeren *et al.* 2003, Alavanja *et al.* 2004, Depledge and Galloway 2005). These compounds can alter various biological functions or processes, including reproductive cycles and development, while also inducing hormonal, neurological or metabolic dysfunctions (Colborn *et al.* 1993, Fry 1995, Soengas *et al.* 1997). Moreover, according to the International Agency for Cancer Research (IACR), the European Union (EU), and the US Environmental Protection Agency (EPA), some are known, or suspected, cancer-causing agents in humans. One French study of farmers afflicted with Parkinson's disease estimated that exposure to lindane and DDT doubled the risk of contracting this illness (Elbaz *et al.* 2009).

Generally, ingested metallic elements are not readily absorbed; however, the organic compounds they form may have long half-lives in large herbivores and carnivores. Even at moderate exposures such organic metallic compounds can have detrimental effects over time, depending on the ingredients and chemical composition of the foods consumed.

The chapter reviews the information available in the scientific literature and from government sources on problems of environmental pollution due to pesticides, heavy metals and arsenic in northwestern Mexico: *i.e.*, the Peninsula of Baja California, Sonora, Sinaloa and Nayarit (see Figure 1).

2. PESTICIDE USE IN MEXICO

More than 800 chemicals are used to control urban, woodland and agricultural plagues, including organochlorine (OC) and organophosphorus compounds (OP), carbamates and pyrethroids. In Mexico, information on pesticide use as it relates to both public health and agricultural activities is incongruent. For example, the report issued by Mexico's Institute for Environmental Health and Work (ISAT) on the use of DDT in Mexico and Central America, commissioned by the Panamerican Health Organization and conducted in 2001, states that the country banned all use of DDT in agriculture in 1991 and in public health (where it was used to combat malaria) in 2000. However, Gonzalez-Farías *et al.* (2002) report that although OC were officially banned, their use was still permitted under certain conditions or restrictions: for example, dichlorodiphenyl-trichloroethane **(**DDT) to control diseases transmitted by mosquitoes; chlordane, dicofol and methoxychlor for insect pests that affect specific crops; and endosulfan for pests on coffee plantations.DDT is found in the environment in several isomeric forms: *p,p*'-DDT, *o,p*'-DDT and *m,p*'-DDT, that contain residues that are even more toxic, such as dichlorodiphenyl-dichloroethylene (DDE) and dichlorodiphenyl-dichloroethane (DDD), and may be present in diverse forms, including *p,p*'-DDE, *o,p*'-DDE, *p,p*'-DDD and *o,p*'-DDD (US-EPA 1980).

An extremely toxic substance, hexachlorocyclohexane (HCH), and its isomer, γ -HCH (or lindane) fit the criteria for inclusion on the list of Persistent Organic Contaminants for future elimination worldwide, according to the Stockholm Convention (2009). As a result, 37 countries have severely restricted its use. But in Mexico lindane is still utilized in agriculture and in treatments for pediculosis and scabies. The federal government estimates that the volume authorized for importation into

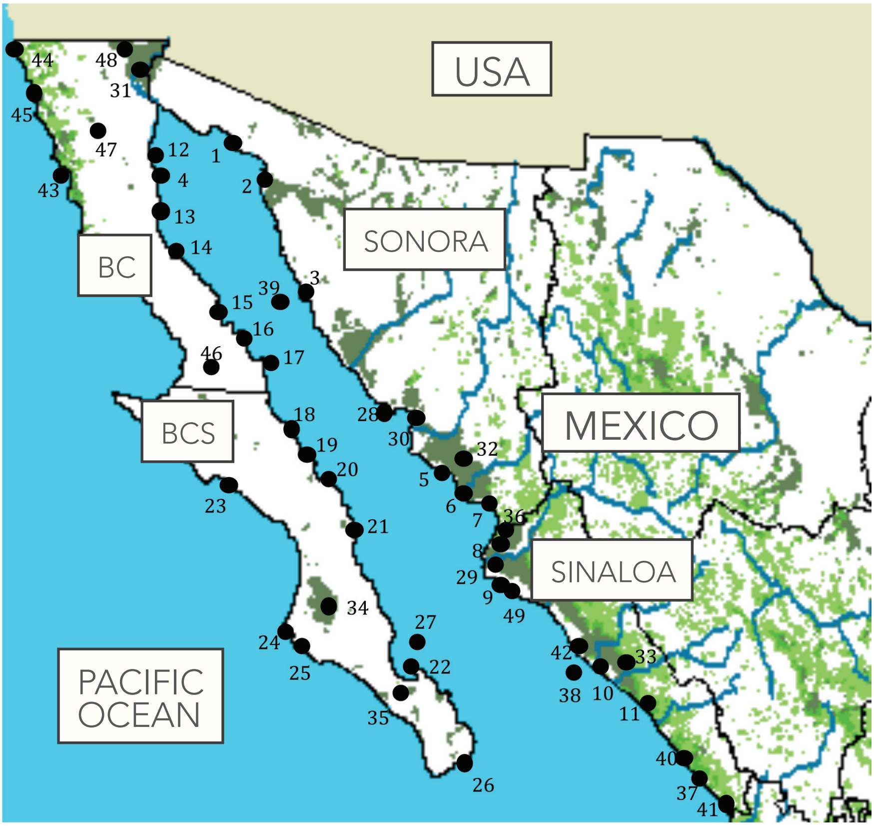

FIGURE 1. Sites where environmental pollutants have been studied in Northern Mexico (Bi = Birds, FS = Farmed shrimp, Fi = Fish, Li = Sea lions, Mu = Mussels, Oy = Oysters, Se = Sediments, Tu = Turtles, Wa = Water, Wh = Whales, and WS = Wild shrimp): BC = Baja California, BCS = Baja California Sur. 1. Estero Morua (Oy), 2. Bahía San Jorge (Oy, Bi), 3. Bahía Kino (Oy), 4. Bahía de Guaymas (Oy), 5. Riito (Oy), 6. Huatabampito (Oy), 7. Bacorehuis (Oy, Se), 8. Bahía Lechuguita (Oy), 9. Bahía Navachiste (Oy), 10. Bahía Altata (Oy), 10. Ensenada del Pabellon (Se), 11. Bahía Ceuta (Oy, Se, Wa), 12. Punta Estrella (Mu), 13. Puertecitos (Mu), 14. Bahía de San Luis Gonzaga (Mu), 15. Bahía de los Ángeles (Mu), 16. San Rafael (Mu), 17. San Francisquito (Mu), 18. Santa Rosalia (Mu), 19. Estero Lucas (Mu), 20. Mulegé (Mu), 21. Bahía de La Paz (Tu), 21. Nopoló (Mu), 22. Bahía de La Paz (Mu), 23. Punta Abreojos (Tu), 24. Barra San Lázaro (Tu), 25. Bahía Magdalena (Tu), 26. (Tu) Los Cabos, 27. Los Islotes (Li), 28. Isla Nolasco (Li), 29. Bahía Ohuira (Se, Wa, WS), 30. Atanasia Santo Domingo (FS), 31. Valle de Mexicali (Bi), 32. Valle del Yaquí (Bi), 33. Valle de Culiacán (Bi), 34. Valle de Santo Domingo (Bi), 35. Chametla (Bi), 36. El Colorado (Fi), 37. Laguna Huizache Caimanero (Fi, Wa), 38. Etchoropo Laguna Yameto (Fi), 39. Center of the Gulf of California (Wh), 40. Estero de Urias (Wa), 41. Estero de Teacapan (Wa), 42. Bahía de Santa María (Wa), 43. Bahía, 44. Coronado (Bi), 45. Todos Santos (Bi), 46. San Martín (Bi), 47. San Pedro Mártir (Bi), 48. San Idelfonso (Bi), 49. Farallón San Ignacio (Bi).

the country from 1997 to 2002 exceeded 900,000 kg. Indeed, it has admitted, first, that it has no precise information on production volumes of this substance and, second, that due to budgetary limitations it does not measure the presence of DDT in the environment, workplace exposures, or the numbers of patients with pediculosis or mange (Patiño and Rodríguez 2005). According to Ecobichon (2001) and Goldman and Tran (2002), the high risk from pesticide exposure in Mexico is a result of several specific sources:

Authorized use of pesticides that are banned in other countries due to high toxicity (CICOPLAFEST 1994); in some cases because expired patents or simplified manufacturing procedures result in substantially lower costs.

Continued use of pesticides despite the fact that they are prohibited or restricted by CICOPLAFEST (1998).

Mexico's extensive areas of tropical or subtropical climates present complications that were not anticipated in the original applications and quantities of pesticide use.

The proper use, control and handling of pesticides are not commonly practiced.

There is little or no governmental oversight of imports, registration, marketing, application procedures, worker training and disposal of contaminated waste.

Legal regulation and monitoring of pesticides released into the atmosphere is inadequate.

The generally low educational level of the population, especially ignorance of the dangers involved in using and storing pesticides, and health hazards from exposure.

3. PRESENCE OF PESTICIDES IN BIOTA

3.1. Birds

One effect of organochlorine pesticides (OC) in birds is that it thins the shells of their eggs, thus altering their reproductive success. Historically, northwestern Mexico has hosted important breeding colonies of marine birds. Since the 1970s, however, high levels of DDT and DDE have been detected and associated with problems observed in the reproduction of brown pelicans (*Pelecanus occidentalis*) (Jehl 1973, Anderson *et al*. 1975), and double-crested cormorants (*Phalacrocorax auritus*) (Gress *et al*. 1973). Mora and Anderson (1991) confirmed the presence of organochlorine residues in 8 bird species in agricultural zones of Mexicali, Sinaloa and Sonora. DDE was found in all samples collected and at higher levels than other OC. Mean DDE concentrations varied from 0.04 μg/g in mourning doves (*Zenaida macroura*) to 5.05 μg/g in double-crested cormorants. HCH was detected in 95% of samples, but at lower levels than DDE. Other OC, such as DDT, DDD, dieldrin, oxychlordane, heptachlor epoxide, endosulfan and endrin, were found at lower levels and less frequently (see Table 1). Mellink *et al.* (2009) analyzed the presence of OC and

TABLE 1. Organochlorine concentrations (ppm) in birds from Northwest Mexico (Mora and Anderson, 1991). BC = Baja California; ND = Not detected.

Species	Location	HCB	HCH	DDE	Dieldrin	DDT
DC cormorant	Mexicali; BC	0.006	0.018	11.46	0.026	0.018
	Yaqui, Sonora	0.006	0.015	0.82	0.025	0.007
	Culiacán, Sinaloa	ND	0.043	5.05	0.026	0.023
Ol cormorant	Culiacán, Sinaloa	0.012	0.065	3.77	0.025	0.02
Cattle egret	Mexicali, BC	0.012	0.009	1.99	0.022	0.016
	Yaqui, Sonora	0.005	0.007	0.75	0.043	0.02
	Culiacán, Sinaloa	ND	0.018	0.27	0.012	0.008
GT grackle	Mexicali, BC	0.006	0.007	3.06	0.007	0.009
	Yaqui, Sonora	0.005	0.008	1.93	0.001	0.012
	Culiacán, Sinaloa	0.029	0.011	0.46	0.012	ND
RW blackbird	Mexicali, BC	0.006	0.008	1.68	0.009	0.008
Mourning dove	Mexicali, BC	ND	0.007	0.04	ND	0.019
	Yaqui, Sonora	ND	0.01	0.03	0.009	ND
	Culiacán, Sinaloa	0.015	0.025	0.06	0.006	ND
WW dove	Yaqui, Sonora	ND	0.009	0.02	ND	ND
	Culiacán, Sinaloa	0.019	0.013	0.04	0.009	ND

TABLE 2. Mean DDE (ppm), eggshell thickness (mm) and eggs volume (cc) of brown booby (*Sula leucogaster*) eggs along of islands from California Gulf (Mellink *et al.*, 2009).

Colony	DDE	Thickness	Volume
San Jorge (Sonora)	0.0533	0.5434	52.402
San Pedro Mártir (BC)	0.0529	0.494	50.595
San Ildefonso (BC)	0.0344	0.4996	51.897
Farallón de San Ignacio (Sinaloa)	—	0.5133	48.232

eggshell thickness in colonies of *Sula leucogaster* at 4 sites in the Gulf of California (see Table 2) and found DDE in every sample examined, though in concentrations insufficient to cause thinning of the eggshells. Rivera-Rodríguez (2007) detected low concentrations of OC in a pristine population of osprey hatchlings *(Pandion haliaetus)* located 80 km from an agricultural plain in Laguna de San Ignacio, Baja California (see Table 3). The concentrations recorded were lower (0.0002-6.856 parts

TABLE 3. Pesticides incidence (%) in birds from Baja California Sur, Mexico (Rivera-Rodríguez, 2007). N = Number of birds tested; HCH = Isomers of lindane; HC = Heptachlor; DDE = Isomer of DDT; ESI = Endosulphane I.

Species	N	α-HCH	β-HCH	δ-HCH	γ-HCH	HC	AD	ED	DE	DDE	ESI
Columbina passerina	49	61	57	55	47	88	82	73	100	100	71
Melanerpes uropygialis	5	33	0	0	0	67	67	67	100	100	100
Myarchus cinerascens	5	20	20	0	20	60	40	40	100	100	60
Toxostoma cinereum	6	50	50	17	50	50	33	83	100	100	100
Icterus cucullatus	9	67	78	78	44	89	67	78	100	100	78
Falco sparverius	3	67	100	100	67	100	100	67	100	100	100
Picoides scalaris	5	0	0	0	0	100	80	100	100	100	100
Colapses auratus	2	100	50	50	50	50	50	100	100	100	50
C. brunneicapillus	13	50	43	50	43	79	71	100	100	100	79
Mimus polyglottos	23	61	48	57	43	91	74	83	100	100	83
Molothrus ater	4	75	50	75	50	75	75	75	100	100	100
Icterus parisorum	7	38	38	38	38	75	75	75	100	100	100
Passer domesticus	4	50	50	50	50	75	50	75	100	100	100
Callipepla californica	4	75	75	75	50	75	50	75	100	100	100
Zenaida asiatica	2	100	100	100	50	100	100	50	100	100	100
Zenaida macroura	6	50	50	50	50	100	100	100	100	100	75
Sturnella neglecta	4	100	100	75	100	75	100	100	100	100	75
Carpodactus mexicanus	10	90	90	90	90	90	90	90	100	100	80

per billion), than those reported in other studies and considered a threat to the survival of the species. In effect, surveys conducted by Danemann in 1992 (1994), and Rodríguez-Estrella *et al.* in 1998, 2002 and 2003 (2006) suggest that reproduction of this species has not varied.

In summary, data on the presence of pesticides in birds in northwestern Mexico is limited and shows no clear pattern. The mobility of some species makes it impossible to identify the precise origin of the pesticides found. Also, the reproductive success of some species—eg., *Pelecanus occidentalis*—that seemed to have been altered by ingesting OC apparently returned to earlier levels once the indiscriminate use of DDT was controlled in 1972 (Jehl 1984, Anderson *et al.* 1996). However, studies of diverse species carried out between 1981 and 2010 continued to detect a metabolite of DDT: DDE. This metabolite breaks down quickly, but its mere presence indicates that this dangerous pesticide is still being utilized despite the ban, though perhaps at lower concentrations, as there have been no reports of variations in the reproduction of species like the osprey since 1992.

3.2. Turtles

Though the eastern and western coasts of Baja California are considered among the main feeding and breeding areas of *Chelonia mydas, Lepidochelys olivacea* and *Caretta caretta*, there are only two documented studies on the presence of pesticides in turtles collected in this region (Gardner *et al.* 2003, Juárez-Cerón 2004). These authors detected the presence of significant concentrations of DDT and its metabolites in the organisms they studied, though levels were lower than those recorded in other sites (Mediterranean Sea, Atlantic and Pacific Ocean). Also found were levels of other OC, including dieldrin, aldrin, endosulfan, lindane and chlordane (see Table 4), though identifying the sources of these contaminants is difficult. Turtles are long-living, relatively large animals that occupy different places in the food chain and migrate from a few kilometers to transoceanic journeys that expose them to numerous potential sources of pollutants that may accumulate at the high end of the food chain. As agriculture in Baja California Sur is not extensively developed, the contaminants detected in wildlife from its coasts have been attributed to DDT residues carried by ocean currents and marine upwellings from California (US).

3.3. Marine mammals

In marine mammals, exposure to OC pesticides produces alterations in their immunological and reproductive systems (Niño-Torres *et al.* 2009). In cetaceans, persistent compounds accumulate in fatty tissues and affect the organisms' health by reducing their capacity to disintoxicate their lipid reserves. The compounds most frequently

TABLE 4. Comparison of concentrations (ng g^{-1}) of the most common pesticides in marine turtles in the world (Juárez-Cerón, 2004). (1) Rybitski *et al.*,1995; (2) Mckenzie *et al.*,1999; (3) Juárez-Cerón, 2004; (4) Aguirre *et al.*, 1994; (5) Gardner *et al.*, 2003;(6) Lake *et al.* 1994.. ΣDDT = o.p.'-DDT, o.p.'-DDE, o.p.'-DDD, p.p.'-DDT, p.p.'-DDE, p.p.'-DDD; DD = Dieldrin; CD = Chlordane. BCS = Baja California Sur (Mexico). ND = Not detected. NR = Not reported.

Species	Location	ΣDDT	DDE	DD	CD	Year
Caretta caretta	Atlantic Ocean (1)	121	108	NR	NR	1991
	Mediterranean Sea (2)	508	491	5	18	1994–1995
	BCS coast (3)	45	44	ND	34	2001–2003
	BCS coast (5)	ND	NR	ND	ND	2003
Chelonia mydas	Mediterranean Sea (2)	9	NR	3	NR	1995–1996
	Hawaii (4)	ND	ND	ND	ND	1994
	BCS coast (3)	2	2	ND	23	2001–2003
	BCS coast (5)	ND	NR	5	ND	2003
Lepidochelys olivacea	BCS coast (3)	15	15	ND	24	2001–2003
	BCS coast (5)	18–May	NR	7	Aug–45	2003
Lepidochelys kempii	Atlantic Ocean (6)	454	386	NR	NR	1985
	Atlantic Ocean (6)	261	232	NR	NR	1989
	Atlantic Ocean (1)	288	176	NR	NR	1991

detected are DDT and its metabolites, DDD and DDE. Because the most important, and rapid, product of the breakdown of DDT is the isomer p.p'-DDE, it is calculated in relation to total p.p'-DDE/DDTs to determine the recent entry of DDT into an organism from the environment (Borrel *et al.* 1995, ATSDR 2002). Studies conducted in blue whales from the Gulf of California (Balaenoptera musculus) detected maximum levels of total DDTs on the order of 2833 ng/g-1 of lipids, of which 75% corresponded to p.p'-DDE (Flores Lozano 2006). In 2004, Valdés and Márquez detected total DDT concentrations of 4510 ng/g-1 of lipids, and a percentage of p.p'-DDE of 71% in this species. The sources of this contamination are hard to ascertain. The blue whales seen in the Gulf of California come from high latitudes and migrate in winter to Mexican waters to give birth, breastfeed their young and feed. From August to early October, the whales feed primarily in the coastal area of central California, US, where they could be contaminated. However, Niño-Torres *et al.* (2010) suggest that the most important source of the pollutants found in whales is

TABLE 5. ΣDDT, ΣHCH, and ΣCHLOR concentrations (mean, ng g^{-1} lipid weight) in fin whales *Balaenoptera physalus* (Niño-Torres *et al.*, 2010). (1) Gauthier *et al.* 1997; (2) Hobbs *et al.* 2001; (3) Marsili and Focardi, 1997; (4) Marsili *et al.* 1998; (5) Niño-Torres *et al.* 2010.

Location	ΣDDT	ΣHCH	ΣCHLOR
Northwestern Atlantic (1)	3,800	210	570
Northwestern Atlantic (2)	26,900	165	1,500
Mediterranean Sea (3)	5,700	—	—
Mediterranean Sea (4)	1,770	—	—
Gulf of California (5)	1,200	24	21

agricultural activity in Sonora and Sinaloa, where 40% of Mexico's national production takes place, and not contaminants carried down from the US by atmospheric and marine currents.

There is only one report with data on concentrations of different classes of OC in the fatty tissues of *Balaenoptera physalus* whales, a year-round resident of the Gulf of California and one of this species' most isolated populations (Niño-Torres *et al.* 2010). The rank order of OC was total DDTs (maximum values: 2400 ng g^{-1} lipid weight), and the most abundant OC pesticide measured was p.p'-DDE, which represented 60% of total DDTs. These authors found this population to be generally clean (see Table 5) compared to other marine mammal species, or fin whale populations from other regions (*e.g.*, Mediterranean Sea, Atlantic Ocean).

The California sea lion (*Zalophus californianus*) is the most abundant species among the pinnipeds present in Mexico. There are two populations, one of which inhabits the Gulf of California. Though its migratory behavior is still unknown, studies have established that 35% of males remain in the rookeries year-round (Zavala 1990). The second colony is found on the Pacific coasts of Baja California and migrates in search of food along the coasts of the US and Canada, where it stays until the onset of the mating season (Antonelis *et al.* 1990). Niño-Torres *et al.* (2009) conducted a study of the sea lions from the Gulf of California in which they reported finding several classes of OC compounds (see Table 6). The most abundant OC measured was the DDT metabolite p.p'-DDE, which accounted for more than 85% of total DDTs (maximum value 3400 ng g^{-1} lipid weight). Concentrations of the same order of magnitude were reported in 2006 by Del Toro *et al.* for organisms that inhabit the Pacific coast of Baja California. In contrast, the concentrations observed were up to two orders of magnitude lower than the values reported previously by Le Boeuf (2002), Kannan *et al.* (2004), Ylitalo *et al.* (2005), and Greig *et al.* (2007) in samples

TABLE 6. ΣDDT, ΣHCH, and ΣCHLOR concentration ranges (ng g^{-1} lipid weight) in California sea lions *Zalophus californianus*. ΣDDTs=o,p'-DDE,¨p,p'DDE, o.p'-DDT, p,p'-DDT,o,p¨-DDD, and p,p'-DDD; ΣHCHs= α-HCH, β-HCH, γ-HCH, δ-HCH; ΣCHLORs= β-chlordane, γ-chlordane, heptachlor, heptachlor epoxide <LOQ-69, less than the limit of quantification. NA = Not analyzed).1) Niño-Torres *et al.*, 2009, (2) Greig *et al.*, 2007. BCS=Baja California Sur

Location	ΣDDT	ΣHCH	ΣCHLOR
Los Islotes, BCS (1)	1,000–5,200	16–110	25–100
San Pedro Nolasco Island, Sinaloa (1)	1,500–7,700	18–120	<LOQ–69
California Coast, USA (2)	4,600–120,000	NA	NA

collected from whales in coastal areas of the US. The range of total p, p'-DDE/DDT values found in studies from the Gulf of California is similar to that seen in areas where DDT has not been used for the past 30 years (Niño-Torres *et al.* 2009).

3.4. Fish

Pesticide contamination in fish has not been extensively studied in northwestern Mexico. Rosales *et al.* (1983) examined concentrations of OC in striped mullet, white mullet, mackerel and flounder in Laguna Yavaros, Sonora, and the Huizache-Caimanero coastal lagoons of Sinaloa, which receive runoff from intensive agro-ecosystems. DDT and dieldrin residues were lower than the range of values reported in the literature and were below the accepted standards for human health (500 ng g^{-1} wet weight for DDT, and 100 ng g^{-1} wet weight for dieldrin). In 2002, Bravo-Garzón detected the presence of hexachlorobenzene (9.5 at 24 µg g^{-1}) and 4'4 DDE (1.5 at 6.7 µg g^{-1}) in liver samples from *Mugil cephallus* monitored in Bahía El Colorado (Sinaloa) and Bahía de La Paz (Baja California Sur). This highly-toxic substance is produced by industrial and natural combustion processes, and accumulates in the fatty tissues of living organisms. This author also observed inhibitions of the order of 27% in acetylcholinesterase activity in the fish collected. Measurements of this enzyme's activity are included as one of the biomarkers in environmental monitoring programs designed to detect the presence of organophosphate and carbamate pesticides (Sturm *et al.* 1999, Bretaud *et al.* 2000) that are difficult to detect analytically due to their rapid breakdown rates in the natural environment.

3.5. Wild and farmed shrimp

Galindo-Reyes (2000) found OC and OP pesticides in shrimp (*Penaeus* sp.) and the surrounding water and sediments in seven coastal zones in Sinaloa (Estero de

TABLE 7. Pesticides in wild shrimp (ng g^{-1}), water (ng L^{-1}), and sediments (ng g^{-1}) of Sinaloa, Mexico (Galindo-Reyes 1999b). *Higher levels than the limits allowed in water by Mexican law. EX = Epoxide, ΣDDT = DDT and its metabolites, ES = Endosulphane, HC = Heptachlor, MP = Methyl parathion, DD = Dieldrin, CD = Chlordane, AD = Aldrin, ED = Endrin.

Location	Sample	*α* HCH	EX	ΣDDT	ES	HC	MP	DD	CD	AD	ED
Estero Urias	Shrimp	0.15	0.08	0.05	210	126	114	ND	ND	ND	ND
Estero Urias	Water	0.79*	ND	3.27*	ND	4.28*	ND	ND	ND	1*	1*
Bahía Ohuira	Water	2	0.23	8	73	ND	11	19	ND	ND	ND
Bahía Ohuira	Sediment	ND	43	ND	155	60	98	51	ND	ND	ND
Bahía Ohuira	Shrimp	132	ND	ND	210	126	113	ND	112	ND	ND
Huizache-Caimanero	Water	3*	ND	ND	ND	ND	0.21*	ND	ND	ND	ND

Urias, Bahía de Ceuta, Bahía de Ohuira and Topolobampo, Laguna de Huizache-Caimanero, Estero de Teacapan, Bahía de Santa Maria, and Ensenada del Pabellón). Table 7 shows only the highest levels of the pollutants registered during monitoring in 1990, 1991 and 1997. The most polluted site was Estero de Urias. OC appear more often than OP, likely because the former are more persistent in aquatic systems. For example, while DDT can last as long as 35 years, methyl parathion disappears in just 4–7 weeks. The highest incidence occurs during the summer months when rainfall carries sediments and pesticides towards the coast.

Osuna-Flores and Riva (2002) measured pesticide concentrations in shrimp, water and sediments in Sinaloa (Bahía de Ohuira) and found 6 of the 19 organophosphate compounds cited in the European Economic Community's priority list: demeton, dimethoate, disulfoton, ethyl parathion, methyl parathion and malathion. Of the organophosphate compounds found in this study, only the pesticide phorate is of restricted use, while the ethyl parathion compound is totally banned in Mexico (INE 1996).

Based on the presence of organophosphate pesticides, we can infer that while the compounds demeton (40%) and phorate sulfoxide (33%) are those most commonly

TABLE 8. Pesticide concentrations in farmed shrimp (ng g^{-1}), and sediments (ppm) from the estuary La Anastasia-Santo Domingo in Cajeme, Sonora (Burgos-Hernández *et al.*, 2005). CPF = Chlorpyrifos, MLT = Malathion, PRT = Parathion, ED = Endrin, DD = Dieldrin, γHCH = Lindane.

Matrix	CPF	4'-4-DDD	MLT	PRT	ED	DD	γ HCH
Sediment	1.25–6.8	2.15	<0.5	<0.5	<0.5	<0.5	<0.5
Shrimp	>13	<0.4	35	12	<0.4	<0.4	<0.4

found in surface water, in sediments the compounds famphur (47%), demeton and chlorpyrifos (40%) show the highest incidences. The latter was determined to have the greatest presence in the organisms studied (50%). There are only a few reports on organophosphate pesticides that contain detailed information on aquatic systems indicating the presence of certain organophosphate compounds in surface water, such as methyl parathion (0.02–0.2 μg/L), dimethoate (0.06–0.6 μg/L), parathion (0.006–0.02 μg/L), malathion (0.007–01(g/L), disulfoton and famphur (0.01 and 0.04 μg/L, respectively). Findings in sediments were as follows: disulfoton (2.9–17.9 μg/g), parathion (<0.1 ng/g–0.02 μg/g) and chlorpyrifos (<0. 1ng/g–0.2 μg/g) (Readman *et al.* 1992, Galindo *et al.* 1997, Galindo *et al.* 1999a, 1999b). Studies with toxicological evaluations of organophosphate pesticides have proven that the compound chlorpyrifos is the most toxic substance for penaeid shrimp (Galindo *et al.* 1996, Osuna *et al.* 1997).

The Agiabampo-Bacorehuis-Jitzamuri lagoon complex in Sinaloa receives water from seven channels that irrigate 4604 farms. There, González-Farías *et al.* (2002) sampled sediments for pesticides and found high levels of heptachlor (49.08 ng g^{-1}), heptachlor epoxide (64.5 ng g^{-1}), DDT (51.56 ng g^{-1}), and HCH (30.36 ng g^{-1}). High concentrations of DDT, compared to its metabolites, DDE (0.49 ng g^{-1}) and DDD (12.95 ng g^{-1}), indicate that the former has not been broken down and strongly suggest that recent illegal applications have taken place, as these data are dissimilar to findings by CICOPLAFEST (1998) regarding the type of pesticides used in this area.

The highest levels of pesticides found in cultivated shrimp, water and sediments in Sonora's Laguna La Anastasia are shown in Table 8. Dieldrin, DDT and its metabolites, chlordane, and heptachlor were all detected in shrimp, though at levels below the standards set by the FDA and EPA in the US, which are 300 ng g^{-1} for dieldrin, 300 ng g^{-1} for heptachlor, 300 ng g^{-1} for chlordane, and 5,000 ng g^{-1} for DDT and its metabolites. However, there are reports that these levels are toxic in shrimp as they alter osmoregulation, glycogen synthesis, respiration rates, and cholinesterase activity.

Analyses of sediments, water and biota from the Altata-Ensenada del Pabellón lagoon complex in Sinaloa showed residues of OC and OP (Carvalho *et al.* 2002). For all pesticides, concentrations were higher in the sediments sampled near water discharge outlets from ponds and drainage channels from farmland. Among the OC, DDT and its metabolites had the highest values in sediments, followed by endosulfan and chlorpyrifos.

Sericano *et al.* (1990) sampled sediments and biota from the Gulf of California and found that DDT concentrations were lower than those of its metabolites, DDD and DDE; results that confirm that DDT use has been reduced. Concentrations ranged from 0.6–45 ng g^{-1} total DDT in sediments, which is below the levels detected in the Gulf of Mexico (range 0.02–3270 ng g^{-1}). Chlorpyrifos was the principal OP detected in those sediments (0.4–8 ng g^{-1}). There is no data available on the toxic effects of this compound in marine fauna, despite its relatively long stability in sediments (160 d). High concentrations of DDE (0.2–450 ng g^{-1}), dieldrin (2.5–13 ng g^{-1}), and endosulfan phosphate (3–530 ng g^{-1}) were found in mussels, oysters and fish (Carvalho *et al.* 2002).

3.6. Sentinel organisms

Mussels and oysters are used as quantitative biomarkers of pollution (Rittschof and McClellan-Green 2005). These mollusks have the ability to accumulate certain pollutants present in the environment where they live (including metals and hydrophobic organic contaminants). Numerous countries in Europe and the Americas have developed monitoring systems using this technique, under the generic name "Mussel Watch" (IFREMER 2011). Such systematic monitoring makes it possible to determine the tendencies of contaminants over time, while simultaneously assessing their effects on biota. In 2007–2008, Vázquez Boucard *et al.* 2008, implemented such a program based on the systematic monitoring of OC, OP and metals in the coastal waters of Sonora, Sinaloa and Nayarit, using the Pacific oyster, *Crassostrea gigas*, as the sentinel species. The oysters were kept in cages on the sea bed for a period of three months and placed precisely on the water inflow drains from 50 shrimp and oyster farms. Samples were collected monthly for a total of 18 months. Of the 22 compounds analyzed, the highest concentrations of OC detected (see Table 9) corresponded to lindane, with up to 72.5 ng g^{-1}; a level that produced genotoxic damage (Comet test) in exposed test organisms (Bigaud 2008). Anguiano-Vega *et al.* (2007) and Anguiano-Vega (2008) found that lindane affected four genes in *C. gigas*, reflected in differential kinetic expression (superoxide dismutase, ferritin, tumoral necrosis protein, and oxidizing stress SHG protein). Chemical analyses did not detect OP; however an assay of acetylcholinesterase activity in these oysters did find a strong

TABLE 9. Pesticides concentrations (ng g^{-1}) detected in sentinel organism *Crassostrea gigas* from coastal waters of Mexico (Vázquez-Boucard *et al.*, 2008). ES= Endosulphane; ED= Endrin. ND= Not detected.

State	Location	γ HCH	DDT	DDD	DDE	ED	ES I	ES II
Sonora	Estero Morua	ND	ND	ND	ND	ND	5.35	ND
	Bahía San Jorge	ND	ND	ND	ND	ND	ND	ND
	Bahía Kino	ND	ND	ND	ND	ND	ND	ND
	Bahía Guaymas	13.61	ND	ND	ND	ND	ND	ND
	Riito	72.50	ND	ND	1.54	ND	ND	2.48
	Huatabampito	ND	ND	ND	ND	ND	ND	ND
Sinaloa	Bahía Lechuguita	ND	ND	ND	ND	9.39	ND	ND
	Bacorehuis	44.48	ND	ND	ND	8.13	2.29	4.43
	Bahía Altata	ND	ND	ND	ND	ND	ND	ND
	Bahía Ceuta	ND	ND	ND	ND	ND	ND	1.45
	Bahía Navachiste	39.80	3.65	3.29	1.19	ND	1.62	1.38

inhibition in organisms from several locations; an inhibition from exposure to OP and carbamates that is amply documented in the literature (Ozmen 1999, Pfeifer *et al.* 2005). Though the method used to detect OP (at two different laboratories) is apparently unable to identify trace levels of this pollutant, the biological effects of this substance have been documented. It is worrisome that several unidentified peaks appear in chromatographic chemical analyses, because they might represent new molecules that have not yet been standardized for the methodology employed. With the exceptions of zinc and cadmium (Mexicans Norms), the concentrations of the other heavy metals studied (copper, nickel, lead) did not exceed allowable limits. Despite the significant levels of zinc detected in that study—and according to the criteria of alimentary innocuity as they relate to the presence of heavy metals—the maximum allowable limit for daily ingestion was exceeded only mildly and on but a few occasions. With respect to lindane and endosulfan, two highly toxic contaminants that were detected in very significant concentrations, there are no studies that allow us to determine the maximum tolerable daily ingestion in relation to alimentary innocuity in oysters cultivated in zones under environmental risk.

In 1987 and 1988, Gutiérrez-Galindo *et al.* (1992) monitored the horse mussel, *Modiolus capax*, as a pollutant biomarker for OC and OP pesticides along the east coast of the Baja California Peninsula. At that time, the most common OC in the waters of the Gulf of California was DDE (5.78–10, 3 ng g^{-1} dry weight). The most severely affected bays were Bahía de los Ángeles, Bahía de San Rafael, and Bahía de San Francisquito along the central coast of the Peninsula. Also present were lower concentrations of heptachlor epoxide, dieldrin, chlordane and endosulfan. Since the adjacent land is desert-like with low rainfall, the authors believe that the source of the DDE is located in the agricultural areas of Sinaloa and Sonora, runoff from which is carried across the Gulf of California by cold water currents, as described by Badan-Dangon *et al.* (1985).

4. HEAVY METALS AND METALLOIDS

Heavy metals and metalloids, common constituents of the earth's crust, are released continuously into the biosphere by volcanoes and the natural weathering of rocks, but numerous anthropogenic activities—including fuel combustion, industrial and urban sewage, and agricultural practices, among others—also produce heavy metals and metalloids. These are classified as pollutants when they exceed the levels judged as normal by the international guidelines of the World Health Organization, the US Food and Drug Administration, and the US Environmental Protection Agency, among others. This chapter considers only the chemical elements reported in high concentrations in coastal northwestern Mexico as they relate to those guidelines.

4.1. Lead

Lead and cadmium are the most widely studied pollutants in northwestern Mexico. Though found naturally in minerals like galena (PbS), lead is often considered an indicator of pollution from industrial sources and, especially, fossil fuel combustion (Cotter-Howells and Thornton 1991). The FDA (2003) established a limit of 7.5 μg Pb g^{-1} dry weight (or 1.5 μg Pb g^{-1} wet weight) in mollusks as safe for human consumption. Based on these limits, unsafe levels of this element have been reported in fauna from northern Mexico. For the Gulf of Santa Clara, Cadena-Cárdenas *et al.* (2009) report levels of approximately 9.6 μg Pb g^{-1} in white clams, *Chione californiensis*; while Méndez *et al.* (2006) detected concentrations of up to 7.8 μg Pb g^{-1} in the squalid callista clam, *Megapitaria squalid*, collected in an area north of Bahía de La Paz. In addition, Páez-Osuna *et al.* (1988) found lead in samples of *Mytelia strigata* at values up to 11.7 μg g^{-1}, almost double the limit set by the FDA (2003).

In a study conducted on the southeastern coast of the Gulf of California, Soto-Jiménez *et al.* (2008) reported average lead concentrations in the following aquatic fauna (all figures in μg g^{-1}): zooplankton (~32), mussels (2.3–3.9), oysters (1.9–7.9), snails (2.0–7.7), barnacles (0.1–18.5), fish (1.4–8.9), crabs (6.3–40.2), and polychaete (8.5–16.7). In that study, oysters, fish and crabs exceeded acceptable levels for human consumption. However, government standards for lead vary; for example, Mexico's Norm NOM 31SSA1-1993 allows a maximum of 1.0 μg Pb g^{-1}, while the FDA (2003) sets a maximum limit of 1.7 μg Pb g^{-1} (fresh wet weight).

Lead has also been quantified in marine mammals. In Laguna Ojo de Liebre on the Pacific side of the Baja California Peninsula, a kidney sample from the gray whale, *Eschrichtius robustus*, contained 31.6 μg Pb g^{-1} (De Luna and Rosales-Hoz 2004), five times above the highest concentration found a few years earlier by Méndez *et al.* (2002) in lung (4.4 μg Pb g^{-1}) and kidney tissues (6.12 μg Pb g^{-1}). According to Law *et al.* (1992), concentrations that exceed 4.0 μg g^{-1} indicate lead poisoning in marine mammals.

4.2. Cadmium

In mollusks, cadmium has frequently been found at levels over 2 μg g^{-1} (wet weight, or 10 μg g^{-1} dry weight), the limit set by such international guidelines as the Hong Kong Food and Environmental Hygiene Department (Copes *et al.* 2008). Cadmium in the environment is strongly linked to natural physical processes, such as coastal upwelling, and the presence of certain rocks and sediments, including phosphorite, which is mined near Bahía de La Paz (Riley 1989). The circulation of currents in the eastern Pacific Ocean yields concentrations of 100 ng Cd L^{-1}, three-to-five times higher than the levels seen in the western Atlantic Ocean. In general, mollusks collected along most of the North Pacific Coast from Alaska southwards have almost twice the cadmium concentrations as those gathered from the Atlantic coast (Kruzynski 2003). In Baja California Sur, Martín and Broenkow (1975) were among the first to report cadmium levels as high as 20.9 μg g^{-1} in plankton. Cheng *et al.* (1976) found exceptionally high concentrations of 100 to 200 μg Cd g^{-1} (dry weight) in samples of the insect sea skater *Halobates* spp., collected off Baja California. Bahía Tortugas on the west coast, and Bahía de los Ángeles, on the east side of the Baja California Peninsula, are subject to coastal upwellings and it is there that some of the highest cadmium levels have been reported, including concentrations as high as 70.2 and 27 μg g^{-1}, respectively (Gutiérrez-Galindo *et al.* 1999). Along the northern shore of Bahía de La Paz, which has very little anthropogenic activity, Méndez *et al.* (2006) found up to 11.1 μg Cd g^{-1} in the clam *M. squalida*. In kidney samples from two species of turtles, *Chelonia mydas* and *Lepidochelis olivacea*, killed incidentally during fishing activities in Bahía Magdalena, cadmium concentrations reached 653 μg g^{-1} and 274 μg g^{-1}, respectively; the highest concentrations reported in marine turtles (Gardner *et al.* 2004). Elevated levels have also been found in stranded whales in this area, with concentrations equal to, or above, 400 µg Cd g^{-1}, indicative of renal dysfunction (Puls 1988).

High cadmium levels have also been reported in coastal areas on the east side of the Gulf of California, due to the influence of agricultural activities. At Laguna de Navachiste in Sonora, Páez-Osuna *et al.* (1991) sampled the Cortez oyster, *Crassostrea corteziensis*, and found high levels of cadmium, up to 18.2 µg g^{-1}.

4.3. Arsenic and mercury

About one-third of the arsenic in the Earth's atmosphere is of natural origin; mostly from volcanic eruptions. Mining, smelting and fossil fuel combustion are the main industrial processes that contribute to arsenic contamination in air, water and soil. While Mexican legislation does not address this toxin, the FDA (2003) places limits of 76 µg As g^{-1} for crustaceans and 86 µg As g^{-1} for mollusks. Compared to cadmium, arsenic is less frequently sampled in marine animals. No currently available reports have detected levels above the maximum allowable FDA limits in marine animals from northwestern Mexico.

Mercury is a highly toxic element that occurs naturally in volcanic eruptions and rock deposits, but that also appears as an anthropogenic contaminant from chemical plants and coal-fired power plants. The FDA (2003) establishes a maximum allowable limit of 1.0 µg Hg g^{-1} (wet weight) for seafood. Gutiérrez-Galindo and Flores-Muñoz (1986) mention that 11–17 metric tons are added to the Pacific Basin each year between Punta Concepción, on the east side of the Baja California Peninsula, and Punta Colonet, on the west side near Ensenada. A study of mercury emissions in Southern California concluded that 74% of emissions enter the sea via the atmosphere, while the remaining 26% arrives in waste waters from metropolitan centers in that area (Eganhouse *et al.* 1976, Stephenson *et al.* 1979). Mercury levels in marine organisms from northwestern Mexico are below the level established by the FDA for human consumption.

5. DISCUSSION AND CONCLUSIONS

The extensive bibliographic review carried out during the elaboration of this chapter shows that from a historical perspective pesticide levels in the Gulf of California are low compared to those in other regions, such as the coastal US, the Mediterranean Sea, and the Gulf of Mexico (Carvalho *et al.* 2002, Niño-Torres *et al.* 2009). Differences between the Gulf of California and other regions have been compared to concentrations of HCHs, CHOLRs, and DDTs in turtles, blue whales, sea lions and porpoises (*vaquitas*) (Niño-Torres *et al.* 2009, 2010), and in sediments from many localities along the eastern coast of the Gulf of California (Sericano *et al.* 1990, Carvalho *et al.* 2002).

Of the 17 persistent organic compounds covered by the Stockholm Convention, 9 are OC (DDT, aldrin, endrin, mirex, toxaphene, hexachlorobenzene, chlordane and heptachlor, lindane and Clordecone). As a signatory to the Convention, Mexico is committed to controlling the use of these compounds, but it is clear that some of them are still being utilized. The most frequently detected substance—and the one most often found in high concentrations—is lindane, which is known to have serious effects on human health and on a wide range of animals in natural populations because of its bio-magnification properties in the trophic chain. Significant alterations caused by OC have been documented at both the physiological and molecular levels. Kalantzi *et al.* (2004), for example, noted that tumor cells in breast tissue contain lindane, which induces genotoxic effects. Thus, both human and environmental health is at a high risk from this pesticide. Relatively low concentrations of DDT are found in sediments and in numerous organisms; however, high percentages (up to 100% in some studies) in test samples containing DDE, a rapidly degradable metabolite of DDT, suggest that DDT is currently being used, though at lower levels than in the 1970s–1990s, when DDT was banned in many countries. As elsewhere, DDT residues will continue to cycle for years in aquatic systems until the degradation process is completed.

Despite their implementation several decades ago in other countries, there is little information from systematic monitoring programs of pollution in northwestern Mexico. Instead, most of the data available come from localized studies characterized by high seasonal and spatial variation in different matrixes (water, sediments, biota), which makes it impossible to compare the results obtained, or determine tendencies and their evolution over time, and then relate them to existing sources of pollutants. Moreover, several studies focused on migratory organisms such as birds, marine mammals and reptiles that are not representative of the environment where the data was collected, with the result that the contaminants detected in those organisms may well have originated in other regions.

The presence of pesticides in filtering (mollusks) and benthic (shrimp and fish) organisms, as well as in water and sediments from the eastern coast of the Gulf of California reflect the problematic in this region due to its characteristic intensive agricultural activity. Higher pesticide concentrations occur in the summer months as a result of the high agricultural production and heavy rainfall that release pesticides held in the soil through runoff and agricultural field drains and eventually deposit them as pollutants in coastal waters. Other processes involved are the displacement of sediments, evaporation, and transport by wind in the form of spray. Also, some chemical substances are subject to chemical and biological transformations that may play an important role in pesticide stability (decay rate) and distribution in coastal ecosystems.

The sensitivity of the pesticide detection and extraction methods used with water, sediments, living matter, food, and other matter are keys to the reliability of any environmental diagnosis. But it is important to note that pollutants may be present in the environment in trace amounts that cannot be detected and, therefore, are not subject to analysis. Every year, new pesticides appear on the market to treat a multitude of insect and other infestations. Their effect on human health is unknown though they may accumulate through the ingestion of contaminated drinking water, milk, plants, seafood, and other products (Abou-Arab 1999, Galindo *et al.* 1999b, Burgos-Hernández *et al.* 2005, Nag and Raikwar 2008, Díaz *et al.* 2009).

With respect to cadmium and lead, several areas of northwestern Mexico have registered high levels in plants and animals. In the case of the former, studies have shown that it is of geological origin. Lead pollution, in contrast, is frequently associated with the use of gasoline with a high content of this element, despite the fact that leaded gasoline has not been used since the 1990s. However, high lead concentrations could also be due to the presence of minerals such as galena. High concentrations of arsenic and mercury have not yet been reported in plants and animals in northwestern Mexico.

6. RECOMMENDATIONS

Given the complexity of these chemical compounds, evaluating pollutants in the marine environment is extremely difficult, and is made even more complicated by such factors as diversity, seasonality and geographical location. Using biomarkers that make it possible to measure exposures and the adverse effects of pesticides at different levels of biological organization may provide an effective way of evaluating the severity of these pollutants and the mechanisms of the toxic actions they produce. Bivalves have demonstrated their value as sentinel species in numerous studies and systematic monitoring and surveillance programs in many countries (France, the US, the UK, Scandinavia, and others). In Mexico, however, systematic monitoring programs do not exist except for a few specific, isolated studies, insufficient to conduct evaluations of the behavior and transformation of pollutants. Designing and implementing programs of this kind would lead to collecting the data that the authorities require to adequately regulate the sale and use of persistent toxic compounds.

International standardization of analytic methodologies is another necessity. In addition, all new compounds must be adequately evaluated. The effective identification of potentially toxic substances will make it possible to detect them and, perhaps, to determine how they affect different organisms.

Specific regulations for, and training in, the handling and use of pesticides, accompanied by strict monitoring, should be implemented in this region to prevent the utilization of banned pesticides and the misuse of authorized substances. Also, it is imperative that the potential impact of these compounds on fisheries and human health be communicated to all users and inhabitants of the region.

Finally, the data provided in this study suggest the importance of homogenizing international criteria to better define laws and regulations regarding the allowable limits for heavy metal content in plants and animals destined for human consumption.

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Exploring Mexico's northwest, the Baja California Peninsula, its surrounding oceans, its islands, its rugged mountains, and rich seamounds, one feels diminished by the vastness and the greatness of the landscape while consumed by a sense of curiosity and awe. In a great natural paradox, we see the region's harsh arid nature molded by water through deep time, and we feel that its unique lifeforms have been linked to this desert and sea for thousands of years, as they are now.

These landscapes of fantasy and adventure, this territory of surprising, often bizarre growth-forms and of immense natural beauty, has inspired a wide array of research for over two centuries and continues to inspire the search for a deeper knowledge on the functioning, trends, and conservation status of these ecosystems in both land and ocean.

This book offers a compilation of research efforts aimed at understanding this extraordinary region and preserving its complex richness. It is a synthesis of work done by some exceptional researchers, mostly from Mexico, who indefatigably explore, record, and analyze these deserts and these seas to understand their ecological processes and the role of humans in their ever-changing dynamics.

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ISBN 978-1-4951-2222-4
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9 781495 122224