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Annual Review

TRANSBOUNDARY POLLUTION: PERSISTENT ORGANOCHLORINE PESTICIDES IN MIGRANT BIRDS OF THE SOUTHWESTERN UNITED STATES AND MEXICO

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Abstract—The hypothesis that migratory birds accumulate persistent organochlorine pesticides (POPs) during the winter in Latin America has been prevalent for many years, particularly since 1,1,1-trichloro-2,2-bis(*p*-chlorophenyl)ethane (DDT) was banned in the United States in 1972. It has been suggested that peregrine falcons (*Falco peregrinus*), black-crowned night herons (*Nycticorax nycticorax*), white-faced ibises (*Plegadis chihi*), various migratory waterfowl and shorebirds, and other avian species accumulate higher concentrations of POPs while on migration or on their wintering grounds in Latin America. Nonetheless, the data obtained thus far are limited, and there is no clear pattern to suggest that such accumulation occurs on a widespread basis. In this review wildlife contaminant studies conducted along the U.S.–Mexico border and throughout Mexico are discussed. The results for the most part seem to indicate that no major accumulation of 2,2-bis(*p*-chlorophenyl)-1,1-dichloroethylene) (DDE), the most persistent organochlorine compound, has occurred or been reported for most parts of Mexico. The majority of the DDE values in birds from Mexico were similar to those reported in birds from the southwestern United States during the same years. More work needs to be done, particularly in those cotton-producing areas of Mexico where DDT was applied heavily in the past (e.g., Chiapas and Michoacan). Because DDT is still used for malaria control and may still be used in agriculture in Chiapas, this state is probably the one where most migrant species would still be at a significant risk of increased accumulation of DDE and DDT.

Keywords—Organochlorine pesticides DDE Migratory birds Southwestern United States Mexico

INTRODUCTION

The theory that migratory birds accumulate persistent organochlorine pesticides (POPs) during the winter in Latin America has been prevalent for years, particularly since DDT (1,1,1-trichloro-2,2-bis(*p*-chlorophenyl)ethane) was banned in the United States in 1972 [1–12]. One reason for the popularity of this theory is that many important wintering areas in Mexico and Latin America are located near major agricultural areas, where pesticide applications are often high. It is also widely suspected that DDT is still used in Mexico and throughout Latin America. Thus, it is often argued that migratory birds acquire most POPs, particularly DDE (2,2-bis(*p*-chlorophenyl)-1,1-dichloroethane), a metabolite of DDT, on their wintering grounds.

Peregrine falcons (*Falco peregrinus*), black-crowned night herons (*Nycticorax nycticorax*), white-faced ibises (*Plegadis chihi*), and other avian species have been suspected to accumulate higher concentrations of POPs while on their wintering grounds in Latin America than on their breeding grounds in North America, north of Mexico [3–6,9–13]. One common assumption is that because DDT and other POPs have been banned in the United States and Canada, the organochlorine residues detected in eggs and tissues in North American migrant birds are acquired mostly during migration or wintering [11]. Nonetheless, others have pointed out that data are limited and that there is no clear pattern to suggest that such accumulation occurs [14–16]. Avian studies conducted in the southwestern United States have suggested that heavy pesticide contamination occurs in Arizona, New Mexico, and southern California [15].

Approximately 40,000 migratory birds, primarily waterfowl, died during the winter of 1995 at Presa Silva, a reservoir near León, Guanajuato, in central Mexico (International Silva Reservoir Panel, unpublished report). This die-off received wide publicity in many newspapers and magazines throughout North America. The general perceptions among the scientific community and public were that birds were dying in this area because of increased concentrations of environmental contaminants, including pesticides, and that this contamination might be a reflection of the state of the environment in Mexico and many Latin American countries. In this review I address wildlife contaminant studies conducted along the U.S.–Mexico border and throughout Mexico. Data on POPs (represented by DDT and its main metabolite, DDE) in resident and migrant birds in Mexico are presented and compared with data on POPs in birds of the southwestern United States (including Texas). Also, the hypothesis that DDE residues in migratory birds wintering in Mexico are higher than those in resident or wintering migrants of the southwestern United States is examined. One of the most persistent organochlorine compounds is DDE, which has been directly associated with eggshell thinning and decreased reproductive success in raptors and fish-eating birds in North America [17]. Other frequently detected POPs include hexachlorocyclohexane, hexachlorobenzene, heptachlor, heptachlor epoxide, chlordane isomers, dieldrin, endrin, and endosulfan. The occurrence of these POPs in wildlife, however, is not as common as that of DDT and its metabolites. Consequently, this review is based on the occurrence of DDE and DDT in birds. Also, to complement the limited information available on POPs in birds from Mexico, data on organochlorin in other biota are presented.

SALE AND USE OF PESTICIDES IN MEXICO

Recent reports of pesticide sales in Latin America indicate that the amount of pesticides used in each country increased nearly three-fold from 1980 to 1990 [18]. The amount of pesticide sales during 1990 varied from $17 million in Chile to

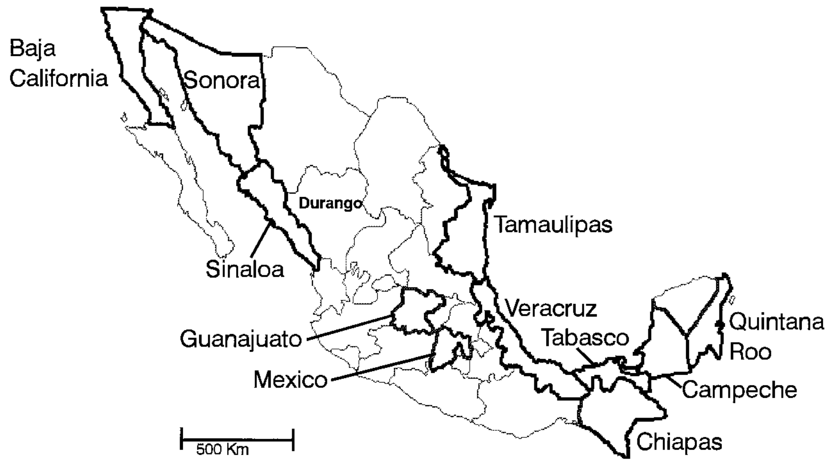

Fig. 1. Map of Mexico with names of states for which contaminant data were available.

about $2 billion in Brazil. Mexico ($565 million) was second only to Brazil in sales in 1990. Pesticide sales in Brazil and Mexico combined amounted to approx. 78% of the total volume sold in 11 Latin American countries [18]. Thus, in terms of expected environmental impacts of the use of pesticides, Brazil and Mexico deserve special attention.

The production of DDT in Mexico by FERTIMEX (a company formerly owned by the Mexican government) varied from 4,379 tons in 1969 to 3,490 tons in 1979, with an average of about 3,500 tons/year [19]. Production of DDT increased during the 1980s, when the average was about 5,000 tons/year [20], possibly in response to a decrease in the amount of DDT imported from the United States. The agricultural use of DDT in Mexico continued until 1978 [19,21], when nearly 4,000 tons of DDT were used in Mexico and about 275,000 kg were used in the states of Baja California, Sonora, and Sinaloa in northwest Mexico [19]. After 1978, DDT continued to be used legally for agricultural purposes only in the state of Chiapas (Fig. 1). Presently, DDT is still used for malaria control in most tropical regions of Mexico and as far north as Sinaloa [22] (Fig. 1). In Chiapas, DDT is sprayed twice a year in villages with more than five reported cases of malaria [23].

Some irregularities in the application of pesticides in Mexico have been reported recently [24]. Results of a study on pesticide use and impact on farm workers in Mexico indicated that pesticides were often applied without concern for the environment or human health [24]. From 1986 to 1989 workers in northwest Mexico were observed loading chemical mixtures into crop dusters by the edge of irrigation canals (M.A. Mora, personal observation). Additionally, a few crop duster pilots also washed their airplanes by irrigation canals or drainages after they had finished spraying a field (Secretaria de Desarrollo Urbano y Ecologia [SEDUE], personal communication). This practice resulted in at least one fish kill attributed to synthetic pyrethroids at Caimanero lagoon in Culiacan Valley, Sinaloa, in 1987 (SEDUE, personal communication). Most incidents, and possibly associated wildlife mortalities, however, are not documented.

ORGANOCHLORINES IN MIGRANT BIRDS

Southwestern United States

Elevated concentrations of organochlorine pesticides (especially DDE) in birds from the southwestern and western United States were reported throughout the 1970s and 1980s [4,6–8,14,15,25–32]. Some cases of elevated DDE residues in birds from the southwestern United States have been attributed to local sources resulting from high use of DDT in the past or from impurities in dicofol, an acaricide widely used in the southwest [14,25,26,29]. However, high DDE residues in birds generally have been attributed to use of wintering grounds in Mexico or Latin America [2,4,6–13].

Studies of transboundary pollution in wildlife of the U.S.–Mexico border were initiated in the late 1960s. In 1969 analyses of eggs of double-crested cormorants (*Phalacrocorax auritus*) of southern California and Baja California suggested that there was a north/south gradient of DDE concentrations [31]. Dichlorodiphenyldichloroethylene was higher in eggs of cormorants from Anacapa Island in southern California (mean = 32 μg/g wet weight [ww]) and lower in eggs of cormorants from San Martin Island in Baja California (mean = 1.8 μg/g ww). Eggshell thinning and reproductive failures were observed at the Anacapa Island colony but not at the Mexican colony. A similar situation was observed in brown pelicans (*Pelecanus occidentalis*) from the same area [32]. In 1969 concentrations of DDE and DDT in intact eggs of brown pelicans from Anacapa Island (southern California) and Coronados Island (northwestern Baja California) were nine-fold higher than those in eggs of brown pelicans from west-central Baja California [32]. In both cases the source of DDE for birds in Anacapa was attributed to DDT residues in sewage that was disposed of by a former DDT manufacturing company in Los Angeles [31]. Further investigations in the Gulf of California from 1971 to 1972 indicated that DDE residues in eggs of ospreys (*Pandion haliaetus*) were among the lowest (mean = 4.2 and 1.2 μg/g ww, respectively) reported for ospreys in North America [33].

Birds collected in specific areas of Arizona, New Mexico, and Texas at different periods during the mid-1970s to early 1990s have consistently had elevated levels of DDE residues. National monitoring surveys of POPs in European starlings (*Sturnus vulgaris*) and waterfowl in the United States have indicated that birds from southwestern regions have the highest DDE residues in carcasses and wings [27,28]. The highest mean DDE residues in carcasses of European starlings collected nationwide in 1979 were in those collected near Roswell, New Mexico (15.8 μg/g ww), and Maricopa, Arizona (6.4 μg/g ww) [28]. Similarly, nationwide monitoring of organochlorine residues in ducks in the United States indicated that DDE residues were highest (3.3 μg/g ww) in duck wings from Arizona and New Mexico [34]. In 1980 organochlorine residues continued to be high in birds collected in portions of the Gila and Verde Rivers in Arizona [27]. Residues of DDE in duck wings and European starling carcasses from the Verde River averaged 3.12 and 6.44 ppm ww, respectively [27]. Furthermore, ducks collected in 1982 from New Mexico and Arizona continued to have elevated DDT and DDE residues that were attributed to local contamination rather than to accumulation on wintering grounds [14]. The results of these studies suggested that some areas in New Mexico and Arizona were possibly contaminated with DDT or related compounds and that further biological studies were warranted to address the issue of local DDT contamination [14].

Black-crowned night herons from the intermountain west migrate in winter to the southwestern United States and Mexico [4,35]. Studies of organochlorines in these colonies from 1978 to 1980 indicated that the highest DDE residues in eggs were in those from birds nesting at Ruby Lake, Nevada (geometric mean = 8.2 μg/g ww), the southernmost location sampled. At this colony, neither DDT nor DDE was found in regurgitated material or in fish from the lake, which suggested that the DDE and DDT contamination came from a source away from the breeding ground, that is, along the migration route or on the wintering grounds in the southwestern United States and Mexico. A follow-up study conducted in 1983 to locate the wintering grounds of black-crowned night herons with radiotelemetry provided more useful information [35]. Three of 15 radiotagged night herons from the Ruby Lake colony (the most contaminated) were located at the Salton Sea, California, and the Gila River, Arizona, whereas only one was located in Mexico during the winter [35]. Similarly, eight of 14 night herons radiotagged at the Pocatello, Idaho, breeding colony (the cleanest) were located in Mexico [35]. Recoveries from night herons banded in Oregon and Idaho also indicated that all records (12) from wintering birds came from Mexico. However, of four recoveries of night herons banded at Ruby Lake, two came from the southwestern United States, and two were from Mexico. The results from the recoveries and telemetry locations of night herons banded at both areas led the authors to conclude that birds from the Ruby Lake area probably did not winter in Mexico, whereas birds from the Oregon and Idaho colonies did. Thus, the results on band recoveries, telemetry, and DDE residues in eggs suggested that the possible source of DDE and DDT for the night herons nesting at Ruby Lake, Nevada, was in the southwestern United States, not Mexico [35].

Similar to the black-crowned night herons, white-faced ibis populations nesting at Carson Lake, Nevada, had elevated DDE and DDT residues in 1985 and 1986, and their reproductive success was seriously affected [6]. Levels of DDE ≥4 μg/g ww caused a decrease in the percentage of successful nests [6]. Analysis of stomach contents of ibises nesting in the area did not show any DDE; thus, concentrations of DDE and DDT in eggs and carcasses were not attributed to local sources. Because most band recoveries of ibises nesting at Carson Lake came from the Mexican states of Jalisco, Colima, and Michoacan, it was believed that the likely source of DDE and DDT in this case was in these wintering areas [6], although no studies were conducted there.

Many of the efforts to document accumulation of POPs in North American migrant birds have been studies of raptors, especially the peregrine falcon and its prey [2,3,5,7,8,13]. During 1980 DeWeese et al. [8] found that migrant species had higher DDE residues than resident species in the western United States and that concentrations in migrant species were inversely related to latitude of wintering grounds. Fourteen avian species, known prey of the peregrine falcon, were collected during 1981 in Arizona to determine levels of DDE and to identify threats of contaminants to peregrine falcons in the region [2]. High DDE levels were found in white-throated swifts (*Aeoronautes saxatalis*, mean = 2.3 μg/g ww), one of the most important prey species of the peregrine falcon [2]. Concentrations above 1 μg/g ww in prey of peregrine falcons are considered sufficient to affect their reproduction [7]. Peregrine falcons were also exposed to high DDE residues in migratory shorebirds and red-winged blackbirds (*Agelaius phoeniceus*), both of which had mean DDE residues above 1 μg/g ww [2].

The hypothesis that peregrine falcons accumulate persistent organochlorine pesticides during migration to Latin America was tested by monitoring DDE concentrations in the blood of peregrine falcons collected during fall and spring migrations from 1978 to 1984 and during 1994 at South Padre Island, Texas [3,5,36]. One assumption was that differences in concentrations between fall and spring samples would reflect accumulation at the wintering grounds. Mean DDE concentrations in second-year peregrine females returning from Latin America in spring 1979 were significantly higher (1.43 μg/g ww) than those in birds captured the previous fall (0.03 μg/g) [3]. Blood of peregrine falcons assumed to be returning from Latin America was collected again in spring 1980 and 1984 at South Padre Island [5]. Concentrations of DDE in blood dropped from about 1.5 μg/g ww in 1978 to less than 0.5 μg/g ww in 1980 but remained stable between 1980 and 1984. More recent studies indicate that DDE concentrations further decreased in plasma by 25% overall and by 42% in second-year females from 1984 to 1994 [36]. Because of the wide distribution of breeding and wintering grounds of peregrine falcons migrating through South Padre Island, it has been suggested that the concentrations of DDE and polychlorinated biphenyls in peregrines collected in this stopover area reflect the condition of the environment in North and South America [36].

Concentrations of DDE in wildlife in some areas of Texas have also been much higher than concentrations in wildlife from other parts of the United States [25,26,29]. In 1978 median levels of 34 ppm ww DDE were found in carcasses of laughing gulls (*Larus atricilla*) from Llano Grande Lake, about 65 km west of the Lower Laguna Madre [25]. Excessively high levels of DDE were also found during 1982 and 1983 in carcasses of western kingbirds (*Tyrannus verticalis*, mean = 61 ppm ww), red-winged blackbirds (mean = 28.5 μg/g ww), and great-tailed grackles (*Quiscalus mexicanus*, 15.6 μg/g ww) from Reeves and Hudspeth Counties [29]. The authors suggested that there were probably some local sources of DDE, although low *p,p′*-DDT residues indicated that sources of DDE other than DDT were possible [29; see also discussion of DDE/DDT ratios below]. Early formulations of dicofol or Kelthane, an acaricide used in south Texas, contained *p,p′*-DDE as an impurity; thus, some of the DDE was attributed to use of dicofol in the southwestern United States [14,29]. Western kingbirds from Pecos, Texas, also had very high DDE residues (range=0.11–47 ppm ww) in 1983 [26]. Concentrations of DDE were also high in carcasses of house sparrows (*Passer domesticus*, up to 35 μg/g ww) and whiptail lizards (*Cnemidophorus* spp., 104 μg/g ww) from the same region [26]. Because of the high concentrations of DDE observed in nonmigratory birds in the area, it was suggested that the source was local and not Latin America [26]. Other studies with blue-winged teal (*Anas discors*) and black skimmers (*Rynchops niger*) of Texas and Mexico have reported no accumulation of DDE on wintering grounds [16,37].

More recently, data from great-tailed grackles from Texas and Arizona have indicated that DDE residues remain high in this species. Residues of DDE in five grackle eggs collected during June 1988 from Cameron and Hidalgo Counties in south Texas averaged 2.2 μg/g ww [38]. Similarly, mean DDE residues in grackle composites of seven to 10 individuals collected during April 1991 in southeastern Arizona averaged 2.25 μg/g ww, and those in grackles collected in south Texas, also during April 1991, averaged 2.8 μg/g ww [39]. In south Texas DDE levels were highest at the Arroyo Colorado on the Laguna Atascosa National Wildlife Refuge and at the eastern Rio Grande, near Boca Chica (mean = 3.2 μg/g ww) [39]. More recent data on eggs of aquatic birds collected in 1993 and 1994 from the Laguna Atascosa National Wildlife Refuge suggest that DDE residues in aquatic species are lower than those observed in great-tailed grackles in former years (M.A. Mora, unpublished data).

Northwest Mexico

Only a few studies of POPs in Mexican wildlife were conducted during the late 1970s. During the 1980s more thorough investigations of environmental contaminants in wildlife were conducted, although investigations were few. Eggshell thinning related to high DDE levels in eggs was first reported for raptors in Mexico during 1980. Eggshells from bat falcons (*F. rufigularis*) and aplomado falcons(*F. femoralis*) collected in northeastern Mexico from 1954 to 1967 were 18 and 25% thinner respectively, than eggshells collected before 1947 or before DDT was used [1]. Eggshells from aplomado falcons collected in the state of Veracruz during 1977 still had high DDE residues (average = 14.8 μg/g ww, estimate assuming 5% lipid) [1]. Eggshell thickness in these late samples was 24% thinner than in samples taken before DDT was used. This finding led Kiff et al. [1] to suggest that serious DDT pollution still occurred in Mexico in the late 1970s. Except for this study, I know of no other studies that have documented such high DDE residues in resident or migrant birds in Mexico.

One major drawback of the studies designed to address accumulation of POPs in North American birds during migration to Latin America was that samples were collected, for the most part, in the United States and Canada, not in Latin America. To address this problem, in 1981 and 1982 northern pintails (*Anas acuta*) from the Pacific flyway were sampled at one breeding location in northern California (Lower Klamath National Wildlife Refuge) and at four wintering locations, one in southern California (Salton Sea) and three in Mexico (San Quintin, Baja California; Culiacan, Sinaloa; and Toluca, Estado de Mexico) [40]. The most significant findings of the study were that DDE levels were not significantly different between pintail carcasses collected during the breeding (May–July) season and those collected during the wintering (December–March) season for any location. However, there were significant differences in concentrations of DDE between pintail carcasses from the breeding and wintering locations (Table 1), and DDE levels were higher during the winter than the summer. In winter, DDE concentrations were significantly higher in pintails at the Salton Sea than in those at Culiacan and Lerma but were not different from those observed in pintails at San Quintin (Table 1). Residues of DDE in pintails from Lerma, the southernmost region in the sampling program, were as low as those observed during the breeding season in Lower Klamath. Concentrations of DDE in pintails from San Quintin and Culiacan were intermediate between the lowest values found at the northern breeding grounds and the highest values observed at the Salton Sea (Table 1). A similar study in wings of waterfowl from the Pacific Flyway in California showed that the highest organochlorine concentrations were in northern pintails from the southern region (Imperial Valley) and that the lowest were in those from the northern region (Klamath Basin) of the state [41].

Table 1. Mean DDE and DDT (μg/g ww) concentrations in carcasses of northern pintails from California and Mexico, 1981–1982[a]

Period	Location	*p,p′*-DDE	*p,p′*-DDT
Spring–summer	Lower Klamath	0.055 (16)	0.026 (5)
Winter	Salton Sea	0.469 (23)	0.103 (16)
Winter	San Quintin	0.200 (16)	0.036 (12)
Winter	Culiacan	0.157 (10)	0.046 (8)
Winter	Lerma	0.018 (11)	0.007 (7)

[a] Data compiled from Mora et al. [40]. Means were combined for two sampling periods per location since there were no significant differences between periods. Sampling periods were early and late during the breeding and winter seasons. The numbers in parentheses indicate the number of samples with detectable residues.

In addition to northern pintails, other migratory and resident waterfowl were also sampled at Culiacan (Fig. 1), where agricultural pesticides are applied. In this region, DDE residues were not significantly different between migratory (gadwall [*A. strepera*] and northern pintails) and resident (black-bellied [*Dendrocygna autumnalis*] and fulvous [*D. bicolor*] whistling ducks) waterfowl (Tables 1 and 2), suggesting that the residues in migratory birds had been picked up in the same region or in the same feeding areas of resident whistling ducks [40].

A more comprehensive study was conducted from 1986 to 1988 to document acquisition of POPs in resident and migratory birds of northwest Mexico [42,43]. The study areas included Mexicali Valley in Baja California, Yaqui Valley in Sonora, and Culiacán Valley in Sinaloa (Fig. 1). Yaqui and Culiacán Valleys were sampled in summer (July–August), and Mexicali Valley was sampled in summer (July) and winter (December). Eight species, from fish-eating to granivorous birds, were sampled in the three regions. Overall, DDE residues varied from 0.009 to 26 μg/g ww (Table 3). In each region concentrations of DDE were significantly higher in fish-eating than in granivorous birds. During the summer DDE concentrations were higher in double-crested and neotropic cormorants (*Phalacrocorax brasilianus*) from Culiacán, Sinaloa,

Table 2. Mean DDE and DDT (μg/g ww) concentrations in carcasses of gadwalls and whistling ducks from Culiacan, Sinaloa, Mexico, 1981–1982[a]

Species	*p,p′*-DDE	*p,p′*-DDT
Gadwall	0.207 (14)	0.034 (3)
Black-bellied whistling duck	0.075 (14)	0.086 (5)
Fulvous whistling duck	0.132 (4)	0.026 (1)

[a] Data compiled from Mora et al. [40]. The numbers in parentheses indicate the number of samples with detectable residues.

Table 3. Levels of DDE and DDT (μg/g ww) in carcasses of birds from northwest Mexico, 1986[a]

	Mexicali				Yaqui		Culiacan	
	Summer		Winter		Summer		Summer	
Species	DDE	DDT	DDE	DDT	DDE	DDT	DDE	DDT
Pied-billed grebe	1.2 (2)							
Double-crested cormorant	11.46 (1)	0.018 (1)	1.79 (8)	0.024 (8)	0.82 (5)	0.007 (4)	5.05 (6)	0.023 (6)
Neotropic cormorant							3.77 (6)	0.02 (6)
Cattle egret[b]	1.99 (7)	0.016 (7)	0.99 (8)	0.015 (8)	0.75 (6)	0.02 (5)	0.27 (7)	0.008 (6)
Great-tailed grackle	3.06 (6)	0.009 (2)	4.06 (8)	0.025 (6)	1.93 (6)	0.012 (1)	0.46 (9)	ND
Red-winged blackbird	1.68 (4)	0.008 (2)	0.96 (4)	0.007 (1)				
Mourning dove	0.04 (6)	0.019 (1)	0.03 (9)	ND	0.03 (7)	ND	0.06 (6)	ND
White-winged dove					0.02 (2)	ND	0.04 (6)	ND

[a] Data compiled from Mora and Anderson [42] and Mora [43]. The numbers in parentheses indicate the number of samples with detectable residues.
[b] Eggs of cattle egrets from Mexicali had mean DDE levels of 3.22 ($n = 40$) and 3.49 μg/g during 1987 and 1988, respectively. Levels of DDT were 0.033 and 0.017 μg/g ww for the same period.
ND = Not detected.

than in cormorants from Yaqui Valley, Sonora. Of the species collected in the three regions, cattle egrets (*Bubulcus ibis*) and great-tailed grackles from Mexicali had significantly higher residues ($p < 0.05$) than those from Sonora and Sinaloa. At Mexicali DDE concentrations were not significantly different between summer and winter for any species; however, hexachlorocyclohexane concentrations increased significantly in mourning doves (*Zenaida macroura*) and grackles during the winter. Residues of DDE in eggs of cattle egrets collected during 1987 and 1988 at Mexicali averaged 3.2 and 3.5 μg/g ww, respectively, and were higher than in carcasses [43]. Overall, DDE concentrations in birds from northwest Mexico were similar to, and in some cases lower than, those found during the same period in the southwestern United States [14,25–29]. It is important to note, however, that about 40% of the samples had DDE levels above 1 μg/g ww, a level that has been determined as critical, particularly when present in small birds, which are common prey of raptors [7]. The DDE/DDT ratios were high in all cases, indicating no recent use of DDT in these areas (however, see discussion of the use of DDE/DDT ratios below). Of the three areas sampled in Mexico, the northernmost region (Mexicali) represented the greatest source of DDE and other POPs to birds than the other two areas farther south. In Mexico, as in many other countries, most pesticides have been applied to cotton. During the 1980s cotton was one of the primary crops at Mexicali, with approx. 52,000 ha planted each year.

Organochlorine residues in prey of the peregrine falcon were studied during 1978 in Baja California [44]. Concentrations of DDE in breast muscle of marine birds (petrels, phalaropes, gulls, and murrelets) from the central region of Baja California varied and were high in only a few cases. One black storm petrel (*Oceanodroma melania*) had a concentration of 5.2 μg/g ww, and one Heermann's gull (*Larus heermanni*) had a concentration of 6.1 μg/g ww. Only about 4% (three of 74) of the samples collected had DDE residues high enough to adversely affect the reproductive success of peregrine falcons [44]. Levels of DDE and 2,2-bis(*p*-chlorophenyl)-1,1-dichloroethane (DDD) were mostly either not detected or were detected at very low concentrations, suggesting that little parent DDT was available in the areas where samples were collected.

A few studies on sediments and aquatic organisms have also reported relatively low levels of POPs in parts of northwest Mexico. Total DDT concentrations were relatively low (<20 ng/g ww) in clams, shrimp, and fish(*Mugil spp.*) collected in 1980 and 1981 at Yavaros, Sonora, and Caimanero, Sinaloa, lagoons. Concentrations in fish ranged from 0.4 to 12 ng/g ww, and those in shrimp and clams ranged from 0.2 to 7 ng/g ww [45]. The highest total DDT value in sediments collected in both areas during the same period was 16.4 ng/g dry weight (dw) [46], about three times less of what was reported for sediments off the San Diego coast in 1971 [47]. Total DDT (85% *p,p′*-DDE) concentrations were also low (range = 11–58 ng/g ww) in mussels collected during 1984 at the Punta Banda estuary near Ensenada, Baja California [48].

Analyses of bat guano collected during 1991 in nine caves in northern Mexico indicated that the highest DDE residues (0.99 μg/g dw) were at the Ojuela cave in the state of Durango (Fig. 1) [49]. Based on the DDE concentrations in guano, it was estimated that the DDE body burdens were not harmful to the bats. Because the rest of the guano from other Mexican colonies was relatively uncontaminated with POPs and there were no agricultural sources near the Ojuela cave, it was argued that one possible source of DDE could have been the Carlsbad area in New Mexico rather than Latin America. This explanation assumed that bats wintering at the Ojuela cave might have come from Carlsbad Cavern, New Mexico [49].

Eastern Mexico

Residues of DDE in carcasses of black skimmers wintering in Texas and the eastern coast in Mexico were measured during 1983 [16]. Mean DDE residues in carcasses of skimmers from Texas (2.5 μg/g ww) were not different from mean residues in skimmers from Chachalacas, Veracruz, in eastern Mexico

(2.0 μg/g ww) [16]. The results suggested no accumulation of DDE at these wintering sites, particularly in Mexico. Elevated DDE concentrations in black skimmers in Texas have been observed throughout the years. Thirty-six percent of black skimmer eggs collected in Texas during 1978 to 1981 had DDE concentrations above 10 μg/g ww [50]. Mean DDE levels in black skimmer eggs from the Texas coast collected in 1984 were 3.1 μg/g ww [51], a value still considerably higher than levels in other fish-eating birds from the same areas [52].

Brown pelican addled eggs were collected from Pelican Island (n = 14) on the Texas Gulf Coast and from Isla Contoy, Quintana Roo, and Laguna del Carmen, Tabasco (n = 13), in southeastern Mexico [53]. Geometric mean DDE concentrations were very low and similar for the Texas and Mexican colonies (0.16 and 0.14 μg/g ww, respectively). Both DDD and DDT were detected in eggs from both colonies, although at much lower levels than DDE. Residues of DDE in eggs of brown pelicans from the Gulf Coast decreased from over 3 μg/g ww in 1970 to less than 1 μg/g ww in 1981 [52,54]. Thus, DDE residues in 1986 were approx. one-sixth of those reported in 1981.

Two similar studies were conducted throughout several Latin American countries from 1979 to 1988 to determine whether major accumulation of POPs in peregrine falcon prey occurred during the winter [11,12]. Shorebirds were collected during the fall of 1987 and the spring of 1988 from the beaches of Veracruz, Tabasco, and Campeche in southeastern Mexico [12]. Residues of DDE in migrants during the fall ranged from 0.05 to 4.83 (mean = 0.68) μg/g ww in carcass, and those in the spring ranged from 0.13 to 2.99 (mean = 1.12) μg/g ww, levels that are not significantly different from those measured during the fall. Thus, these results favored the alternative hypothesis of no accumulation of POPs by migrant birds during the winter in southeastern Mexico. Concentrations of DDT were very low but present, so local recent use was suggested. Because of the high DDE residues in migrants during the fall, the presence of a source of DDE other than DDT in the breeding grounds was also suggested [12]. One-third of the migrants had residues above 1 μg/g ww, a level that could be of concern for raptors feeding on these prey.

Eggs and nestlings of reddish egrets (*Egretta rufescens*) were collected in 1993 at nesting colonies in the lower Laguna Madre, Texas, and at Isla Pimienta in Laguna el Barril, Tamaulipas, Mexico [55]. One objective of this study was to determine whether differences in organochlorine concentrations in eggs and tissues of this endangered species could be explained by differences in nesting locations on both sides of the U.S.–Mexico border. Residues of DDE in eggs (n = 6) and chicks (n = 5) from the Isla Pimienta colony averaged 0.23 and 0.03 μg/g ww, respectively, whereas residues in eggs (n = 6) and chicks (n = 5) from the colony at lower Laguna Madre averaged 0.14 and 0.02 μg/g ww, respectively [55]. The DDE residues in tissues of reddish egrets from the two border colonies were not significantly different. In addition, two composite prey samples (fish) from the lower Laguna Madre had an average level of *p,p′*-DDE of 0.014 μg/g ww, however, DDE was not detected in similar composite fish samples from Laguna el Barril in Tamaulipas [55]. Overall, DDE residues in reddish egrets from both sides of the U.S.–Mexico border seemed to indicate no differences in environmental DDE patterns in the aquatic environments of both sides of the Laguna Madre.

To determine the accumulation of POPs in birds from Chiapas, eggshell fragments of three eggs and one whole egg of black vultures (*Coragyps atratus*) were collected in the Tuxtla Valley in 1985 [20]. Concentrations of DDE in egg fragments ranged from 0.17 to 1.0, and the concentration was 0.65 μg/g ww in the whole egg. Concentrations of DDE were less than expected, particularly since eggs were collected from an area in Chiapas where DDT was still authorized for use in agriculture. One conclusion from the study was that continued use of DDT in Chiapas had not resulted in the accumulation of high levels of DDE in local food webs [20].

Great-tailed grackles from several areas that are known to be or were former range habitat of the aplomado falcon were collected in the southwestern United States (Arizona and Texas) and eastern Mexico (Tamaulipas, Veracruz, Tabasco, Campeche, and Chiapas) in 1991 [39]. The DDE data for grackles from Arizona and Texas were discussed above. Residues of DDE in grackles from eastern Mexico varied by locations and were significantly higher for the Chiapas/Tabasco area than for Veracruz. The highest DDE level (6.3 μg/g ww) was found in grackles near the town of Zapata in Tabasco. The lowest mean DDE levels (0.70 μg/g. ww) were found in grackles from Veracruz. Overall, DDE residues were not significantly different among grackles from Arizona, Texas, and Chiapas and Tabasco, Mexico, but they were significantly lower in Veracruz than in the other regions. Veracruz had been previously pointed out as an area of serious DDT pollution in Mexico [1]. Samples from the border states of Tamaulipas and Texas also indicated that DDE residues in grackles from the Mexican side (Tamaulipas) were lower than in those collected on the Texas side [39]. No *p,p′*-DDT was detected in the U.S. samples but was detected in the samples from Veracruz, Chiapas, and Tabasco, suggesting more recent use of DDT in Mexico. However, one study of environmental contaminants in oysters, mussels, and shrimp collected in 1992 at the Rio Palizada, Campeche, reported low average concentrations of total DDT of 0.9 ng/g dw [56].

Migratory birds at the Presa Silva, central Mexico

Earlier I indicated that about 40,000 migratory birds died during the winter of 1994–1995 at the Presa Silva Reservoir in central Mexico. After detailed investigations of the incident, the International Silva Reservoir Panel (unpublished report) concluded that the major cause of mortality of birds at the Presa Silva was botulism. Waterfowl samples were collected, and tissues were analyzed for organochlorine and heavy metal contamination. Some organochlorines (endosulfan) and heavy metals (chromium) were elevated in some tissues, but not at concentrations that would have caused such mortality. Botulism is caused by the bacterium *Clostridium botulinum* and has been reported to occur frequently in waterfowl and other aquatic species throughout North America [57].

DDE SOURCES AND DDE/DDT RATIOS

One issue of concern in studies of accumulation of contaminants in migratory birds has been the identification of the possible sources of DDE. The occurrence of DDT or DDD in a sample is sometimes used as an indication that the compound came from an area where the parent compound DDT was recently used [4,12]. One assumption is that any residual DDT in a sample from an area where DDT is no longer used must have come from another area where the parent compound was recently used. Similarly, DDE/DDT (or the inverse) ratios are also used as indicators of recent exposure to DDT [13,29].

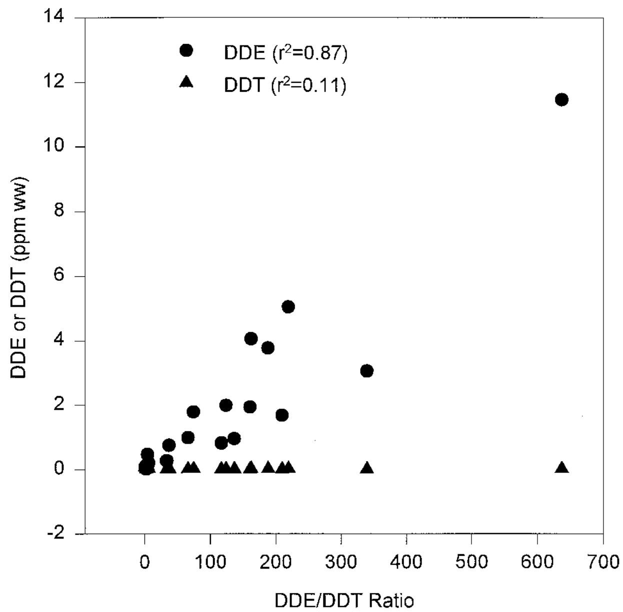

Fig. 2. Ratios of DDE to DDT in birds from northwest Mexico and California.

Small ratios (<1 to 50) are thought to indicate significant concentrations of DDT relative to DDE and therefore recent exposure to the parent compound. For example, DDE/DDT ratios ranged from 2 to 30 in bats collected 1 to 3 years after spraying with DDT in northeastern Oregon [58].

Nevertheless, under unknown exposure conditions, DDE/DDT ratios may not be indicative of recent DDT use but of long persistence and heavy use of DDT in the past. To determine whether DDE/DDT ratios could be used as indicators of recent exposure or of a strong association with DDT use, I analyzed DDE/DDT ratios with respect to mean DDE and DDT concentrations of approx. 10 avian species from fish-eating to granivorous birds (Fig. 2). The DDE/DDD ratios were not obtained since DDD is not often reported or detected. The ratios were obtained from samples from five regions in northwest Mexico and two regions in California, as previously described [40,42,43]. A significant association ($r^2 = 0.87$, $p < 0.05$) between the mean DDE concentration and the DDE/DDT ratio was observed (Fig. 2). The DDT values, however, were relatively low in all cases and almost uniform ($r^2 = 0.11$) for all ratio values. This result shows that the DDE/DDT ratios varied significantly with the amount of DDE but not DDT, which indicates that, under unknown environmental exposure conditions, the ratios predict the amount of DDE but are not reliable predictors of recent exposure to the parent compound DDT, except when they are relatively small. Additionally, DDE/DDT ratios varied among species from the same location, indicating only different accumulation of DDE in their diets. Also, DDE/DDT ratios were smaller in birds with lower DDE values (primarily herbivores and granivores) from areas of California and Mexico, again indicating lower exposure to DDE in the diet. In fact, the only species in which DDT was not detected were mourning and white-winged doves (*Zenaida asiatica*), which had some of the lowest DDE values of all species. Thus, the presence of small concentrations of DDT in a sample may not indicate recent DDT use.

DISCUSSION AND CONCLUSIONS

The use of organochlorine pesticides in agriculture in Mexico has decreased considerably, as indicated by the comparatively low residues in the samples discussed here, in favor of the use of less persistent, but highly toxic, organophosphorus and carbamate insecticides [59]. Studies of persistent organochlorine pesticides in resident and migratory birds of Mexico have been limited. However, a few studies, conducted mostly during the 1980s, have provided some information regarding the state of the environment in terms of environmental impact of pesticides on wildlife. The results for the most part seem to indicate that no major accumulation of DDE, the most persistent organochlorine compound, has occurred or been reported for almost 20 years. The majority of the data from these studies suggest that DDE concentrations in birds from Mexico are similar to those reported in birds from the southwestern United States. More work needs to be done, particularly in cotton-producing areas in Mexico, where DDT was applied heavily in the past (e.g., Chiapas and Michoacan). Because DDT is still sprayed in houses to control malaria outbreaks and may still be used in agriculture in Chiapas, this state is probably the one where most migrant species may still be at a significant risk of increased accumulation of DDE and DDT. Results from cotton-producing areas in northern Mexico (Tamaulipas and Baja California), however, indicate that residues in these areas are still comparable to those observed in birds from cotton-growing areas in the southwestern United States. Therefore, caution must be exercised when determining the source of POP, particularly DDE, residue acquisition in North American migrants collected on their breeding grounds.

In conclusion, the results from this review indicate that the available data do not show a clear pattern of increased accumulation of POPs (DDE) in migratory birds while in Mexico, at least in relation to residues observed in birds of the southwestern United States. Studies of contaminants in migrant birds must consider the possibility that migratory acquisition of DDE (and DDT) could also occur while birds winter or pass through some regions of the southwestern United States.

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