Deriving Site-Specific 2,2-Bis(chlorophenyl)-1,1-dichloroethylene Quality Criteria of Water and Sediment for Protection of Common Tern Populations in Bohai Bay, North China

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In this paper we first present a method of deriving site-specific water and sediment quality criteria of chemicals for protecting wildlife populations. The method has two steps: (1) identification of the threshold concentration in specific tissue corresponding to a population benchmark response and (2) extrapolating quality criteria on the basis of the bioaccumulation in tissue from the water or sediment (e.g., the bioaccumulation factor (BAF) and biota/sediment accumulation factor (BSAF)). The method was applied to derive 2,2-bis(chlorophenyl)-1,1-dichloroethylene (*p*,*p*′-DDE) quality criteria of water and sediment of Bohai Bay, China, for common tern populations. The benchmark concentration in eggs of the common tern was determined to be 663 ng/g wet weight from the relationship curve between concentration (biotic burden in eggs) and the intrinsic rate of population increase (*r*) calculated by an age-structured matrix approach. The *p*,*p*′-DDE concentrations (mean 58.79 and ranging from 13.14 to 326.60 ng/g wet weight) measured in common tern eggs ($n = 35$), collected from the Beidagang wetland on the coast of Bohai Bay in China, and those in surface water or sediment from literature values were combined to estimate the probability distribution of BAF and BSAF using the Monte Carlo method. Finally, the marine water and sediment quality criteria of *p*,*p*′-DDE in Bohai Bay were estimated to be 4 ng/L and 1.9 ng/g dry weight, respectively.

Introduction

Water and sediment quality criteria are the basis of water and sediment quality standards, which protect humans from contaminants, sustain the productivity of natural resources, and ensure the aesthetic quality of the environment (*1*). Prior development of water quality criteria (WQC) from the 1900s to the 1970s consisted of reviewing all data available concerning the toxicity of a pollutant to aquatic life and then using the data as deemed best to derive the criteria for that pollutant (*2*). In these approaches, the median lethal concentration (LC50) or no-observed-effect concentration (NOEC) for the most sensitive species often was selected as the assessment end point (*3*, *4*). Beginning in the 1980s, quality criteria were derived on the basis of ecological risk assessment to protect 95% of aquatic life species, and other measures of response, especially chronic toxicity including survival, fecundity, growth rate, and so on, were applied as assessment end points (*2*, *5*, *6*). The sediment quality criterion (SQC) was derived from the WQC multiplied by the equilibrium-partitioning coefficient (*7*) or biological effects-based assessments (*8*, *9*). Chronic toxicity of chemicals often severely affects the species population rather than the individual because of the individuals' multigenerational accumulation and interspecific competition (*5*). In addition, the risk at the population level is more relevant to the aims of managers or regulators, since it can provide a more relevant measure of ecological impact (*10*). Recently, the improvement of the criteria to protect water resources based on the risk of the piscivorous bird population has raised the concern of governments and was listed in research plans for multiple years (*11*).

Several methods, such as field surveys of organism abundance and model extrapolation for estimating extinction probability, biomass, and intrinsic rate of increase, have been proposed for population assessment (*10*, *12*−*15*). While data such as the population size and population fluctuation coefficients, which are necessary for estimation of the extinction risk, are scarce (*15*), the intrinsic rate of increase (*r*) is another important possible end point (*13*, *14*). *r* is a comprehensive summary index that measures the population-level effects, which indicate the potential persistence of a species population (*16*, *17*), and is listed as an assessment end point of population-level effects in the reports of the Ecological Committee on Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) Risk Assessment Methods (*18*).

The pollutant 2,2-bis(chlorophenyl)-1,1-dichloroethylene (*p*,*p*′-DDE), one of the persistent lipophilic metabolites from dichlorodiphenyltrichloroethane (DDT), can cause eggshell thinning in birds and decrease the size of bird populations (*19*, *20*). The concentrations of *p*,*p*′-DDE in birds, particularly waterfowl and raptors, are greatly enhanced by bioaccumulation to concentrations that pose a significant hazard (*19*, *21*−*23*). DDT was widely used in China from 1950, and the total production of DDT was 270000 tons, accounting for 20% of the total world production (*24*). Although DDT was banned at the beginning of the 1980s in China, there are still *p*,*p*′-DDE residues in the water and sediment in Bohai Bay (*25*). Several papers have reported that the common tern is susceptible to *p*,*p*′-DDE, and its reproductive success decreased even at low concentrations of *p*,*p*′-DDE (*25*−*28*). Common terns are not listed as an endangered species in China. They breed in northern China and fly to southern China or Australia in the winter (*29*).

In this paper, the marine water and sediment quality criteria (MWQC and MSQC) of Bohai Bay were determined using the threshold (e.g., benchmark concentration lower bound (BMCLB)) in eggs of the common tern calculated by the benchmark approach (*30*) and the bioaccumulation factor (BAF) and biota/sediment accumulation factor (BSAF) based on field data, respectively. The threshold was calculated using a hazard relationship between the *p*,*p*′-DDE dose (biotic burdens in eggs) and the response (*r*). To estimate BAF and BSAF, 35 common tern eggs were collected from the Beidagang wetland on the coast of Bohai Bay for analysis of

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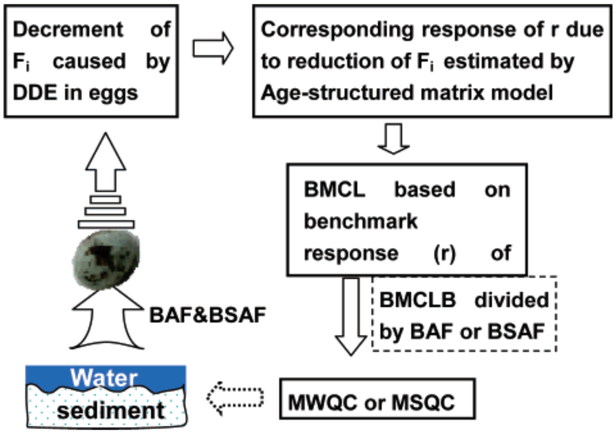

FIGURE 1. Process of deriving dichlorodiphenyltrichloroethane (DDE) marine water and sediment quality criteria (MWQC and MSQC) using the benchmark concentration lower bound (BMCLB) and the bioaccumulation in tissue from the water (BAF) and sediment (BSAF), respectively. F_i = fertility parameter, and r = the intrinsic rate of population increase.

DDTr's. Finally, probability distributions of *p,p′*-DDE MWQC and MSQC for protection of the common tern population in Bohai Bay were analyzed using the Monte Carlo method.

Materials and Methods

Process of Estimating MWQC and MSQC for Protection of the Common Tern Population. The method for determining the appropriate MWQC and MSQC of *p,p′*-DDE in this study is shown in Figure 1. The available data on the effect of *p,p′*-DDE fertility success were incorporated into the fertility parameter (F_i) in an age-structured matrix to calculate r at specific concentrations. A decrease in r of 10% from r_0, the intrinsic rate of population increase without *p,p′*-DDE exposure, was regarded as the benchmark response (*30*), and then the BMCLB was calculated on the basis of the relationship curve fitted by a power function. Finally, the MWQC and MSQC of *p,p′*-DDE in Bohai Bay were calculated using the BMCLB, BAF, and BSAF measurements based on field data.

Calculation of the Intrinsic Rate of Population Increase (*r*). An age structured matrix model was used to calculate r (*31*). The following age-structured matrix model was applied to describe the dynamics of the common tern population over time:

$$\vec{N}_{t+1} = \mathbf{M} \times \vec{N}_t \qquad (1)$$

where $\vec{N}_t$ and $\vec{N}_{t+1}$ are the vectors of age structure at times t and $t + 1$ and $\mathbf{M}$ is the population projection matrix. Equation 1 can be expanded as

$$\begin{vmatrix} N_{\mathrm{egg},t+1} \\ N_{1,t+1} \\ N_{2,t+1} \\ N_{3,t+1} \\ N_{4,t+1} \\ N_{5,t+1} \\ \ldots \\ N_{25,t+1} \end{vmatrix} = \begin{vmatrix} 0 & F_1 & F_2 & F_3 & F_4 & F_5 & \ldots & F_{25} \\ P_1 & 0 & 0 & 0 & 0 & 0 & \ldots & 0 \\ 0 & P_2 & 0 & 0 & 0 & 0 & \ldots & 0 \\ 0 & 0 & P_3 & 0 & 0 & 0 & \ldots & 0 \\ 0 & 0 & 0 & P_4 & 0 & 0 & \ldots & 0 \\ 0 & 0 & 0 & 0 & P_5 & 0 & \ldots & 0 \\ \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\ 0 & 0 & 0 & 0 & 0 & 0 & \ldots & 0 \end{vmatrix} \times \begin{vmatrix} N_{\mathrm{egg},t} \\ N_{1,t} \\ N_{2,t} \\ N_{3,t} \\ N_{4,t} \\ N_{5,t} \\ \ldots \\ N_{25,t} \end{vmatrix}$$

where $N_{i,t}$ is the number of common terns in age group i at time t, P_i is the probability of individual survival at age group i, and F_i is the mean number of female neonatal offspring produced by one female at age i. F_i can be calculated as follows (*32*):

$$F_i = \psi_i \theta_i c_i \delta_i \sigma \qquad (2)$$

where ψ_i is the breeding probability, θ_i is the nest success for nest attempts, defined as the proportion of nests that hatch at least one egg, c_i is the clutch size for nesting attempts and is defined as the number of eggs laid per nest, δ_i is survival of the young and is defined as the fledging success from eggs, and σ represents the ratio of female neonatal offspring in the total eggs produced by one female at age i. The maximum eigenvalue of matrix $\mathbf{M}$ was regarded as the population growth rate (λ) per year, which is the exponent of r ($\lambda = e^r$) (*31*).

Review of Demographic Data for the Common Tern. To our knowledge, no data about life-cycle parameters of common terns in Bohai Bay have been reported. In this paper, the life-cycle parameters from other geographical regions were used to estimate the intrinsic rate of increase in the common tern population in Bohai Bay. Because differences between locations, including starvation, predators, and disease, could confound demographic data (*33*), the life-cycle parameters used in this study were estimated by averaging those from several geographical regions. The oldest known individuals bred successfully at 26 years of age (*34*), but about 90% of the breeding population was between 3 and 10 years of age (*35*). Some females (12%) started breeding at 2 years of age, most (77%) at an age of 3−4 years, and others (11%) at an age of 5 years or older (*33*). Nisbet reported that 3% of the eggs were abandoned in Bird Island, MA (*36*). The range of the annual mean clutch size (c_i) for the common tern was from 2.55 to 3.00 (*34*, *36*, *37*) with a mean of 2.77. Four papers have reported young survival: 71% (n = 103) (*38*), 69% (n = 420) (*39*), 57% (n = 468)(*40*), and 59% (n = 152) (*41*). Thus, the mean young survival was estimated to be 64%. Subadult survival from fledging to 2 years of age was 0.47, from 2 to 3 years 0.85, and from 3 to 4 years 0.90 (*42*, *43*). Adult survival was estimated to be 0.90 (*44*). However, Dicostanzo (*44*) reported a total survival value of 0.143 for fledging 4 year olds and an annual adult mortality of about 8% (*45*). That is, the annual subadult (fledging 4 year olds) and adult (5−26 years) survivals were 0.62 and 0.92, respectively. Thus, the mean survivals for 2 year olds, 3 year olds, 4 year olds, and older birds were calculated to be 0.545, 0.735, 0.76, and 0.91, respectively. All life-cycle parameters are listed in Supporting Information Table 1.

Decrease of *r* Caused by *p,p′*-DDE. *p,p′*-DDE is a degradation product of DDT, contributing 80−95% of the total DDTr in organisms (*25*, *50*). The available data on the relationship between the occurrence of *p,p′*-DDE in common tern eggs and the fledging success rate of the young are listed in Supporting Information Table 2 (*26*, *27*). The toxicity data replacing δ_i in eq 2 and other life-cycle parameters were combined to calculate the intrinsic rate of common tern population increase (r) under specific *p,p′*-DDE concentrations. The relationship of concentration (C_{egg}, biotic burden in eggs) to the response (r) was developed by a power function (*16*) as follows:

$$r = r_0(1 - (\log(C_{\mathrm{egg}})/\alpha)^{\beta}) \qquad (3)$$

where α is the concentration of toxic chemicals (log-normal scale) when $r = 0$ and β is a power indicating nonlinearity.

Benchmark Concentration of *p,p′*-DDE. The benchmark concentration approach was recommended to estimate MWQC and MSQC (*30*, *46*), which uses the concentration−response curve fitted by Benchmark software version 1.32 (United States Environmental Protection Agency, Washington, DC), to obtain the benchmark concentration lower bound (95% confidence interval bound) corresponding to a default response (10%) from the reference, i.e., a decrease in r of 10% from r_0 in this study.

Collection of Common Tern Eggs. Common terns feed largely on small fish and shrimp. Nests are simple depressions

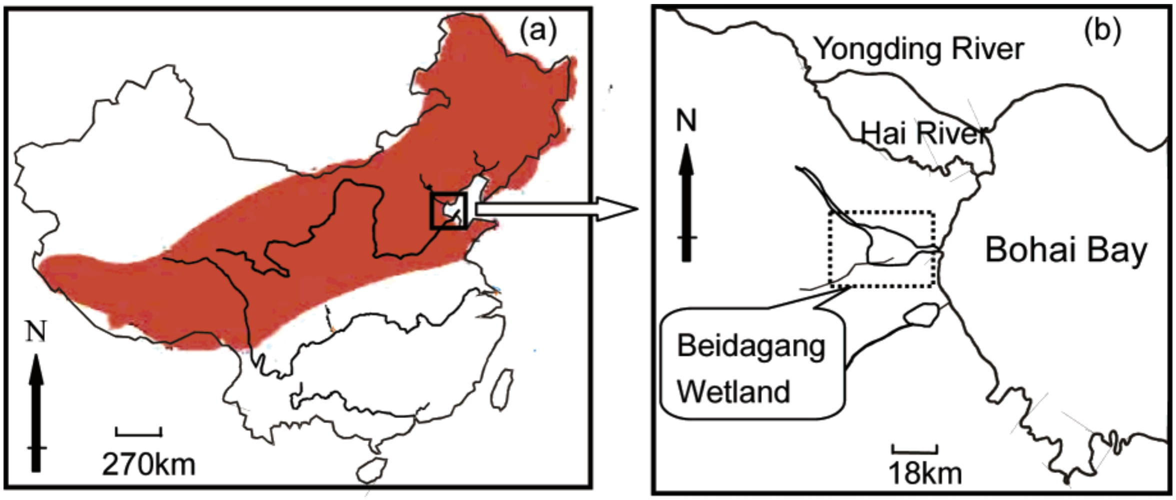

FIGURE 2. Map of the sampling site for common tern eggs: (a) the red shaded area represents the distribution of common tern colonies in China; (b) map for western coastal Bohai Bay, China, and the sampling site in the Beidagang wetland.

in the sand or shallow cups of dead grass formed on beaches or open rocky areas. Most of their colonies are along the beach, salt-marsh islands, lakes, ponds, and rivers (*47*). They are widely distributed along the coasts of eastern China and lakes in southwestern, northwestern, and northeastern China (as shown in Figure 2a) (*29*). The 35 eggs from common terns were provided by the Beidagang wetland conservation office in Tianjin in May 2003. The reserve is located on the western coast of Bohai Bay, as shown in Figure 2b. The eggs were individually wrapped in rice husks and immediately transported back to the laboratory, arriving within 5 h. Upon arrival at the laboratory, the samples were cleaned with pure water (18.2 MΩ cm) and stored at −80 °C for the analysis of DDT-related chemicals.

Chemical Analysis. Dichloromethane, methanol, and hexane were high-performance liquid chromatography grade or pesticide grade and were obtained from Fisher Scientific (New Jersey). 2,2-Bis(chlorophenyl)-1,1-dichloroethane (*p,p′*-DDD (purity 99.5%)), *o,p′*-DDD (99.5%), *o,p′*-DDT (99.5%), *p,p′*-DDT (99%), *o,p′*-DDE (99.5%), and *p,p′*-DDE (99.4%) were all purchased from Chemservice (Chester, England), and 2,2-bis(chlorophenyl)-1-chloroethylene (*p,p′*-DDMU (99.9%)) was from Sigma (St. Louis, MO). Polychlorinated biphenyl (PCB) 121 (99%) and PCB 189 (100%) (International Union of Pure and Applied Chemistry (IUPAC)) were purchased from Accu Standard (Connecticut), and standard stock solutions were prepared in acetonitrile.

Whole egg samples (approximately 10 g wet weight each, excluding the shell) were mixed with 20 g of Na_2SO_4 and spiked with PCB 121 (140 ng) and PCB 189 (140 ng) as internal standards. The spiked samples were Soxhlet extracted for 24 h using 200 mL of a dichloromethane/methanol (7:3, v/v) mixture solution. The extracts were rotoevaporated to 50 mL and divided into two portions. The first 40 mL of extract was rotoevaporated and reconstituted with 30 mL of hexane. The hexane solution was mixed with 5 mL of sulfuric acid (98%) in a separatory funnel and shaken for 5 min. After the solution was partitioned, the hexane layer was collected and rinsed twice with 30 mL of pure water (18.2 MΩ cm). Then the solution was dried by passing it through about 20 g of anhydrous sodium sulfate and concentrated to about 1 mL. It was then passed through a glass column (10 mm i.d.) packed with 12 g of 5% H_2O deactivated neutral Al_2O_3 (200 mesh size, Shanghai Ludu Chemicals, China) for further cleanup. DDTr's were eluted with 30 mL of high-purity hexane and 30 mL of hexane/dichloromethane (3:1, v/v). The eluant was rotoevaporated to about 3 mL, then dried under a gentle stream of nitrogen at room temperature, and dissolved in 0.5 mL of hexane for gas chromatography−mass spectrometry (GC−MS) analysis. A detailed description of the instrumental conditions of GC−MS analysis is provided in the Supporting Information.

The second portion of the extract (10 mL) was used to determine the lipid percentage. The extracts were rotoevaporated to dryness and heated at 65 °C for about 30 min, and the lipid amount was determined gravimetrically. The lipid content was calculated on a wet weight basis.

Quality Control. A total of 35 egg samples were divided into two batches, i.e., 10 samples and 25 samples, for DDTr determination. A standard mixture containing DDTr's and internal standards was used to determine the general recovery of the compounds throughout the analytical procedure. The procedure described above was validated for recovery on the basis of triplicate analyses. For analyzing the first 10 samples, the recoveries of PCB 121 and PCB 189 were 90.6 ± 8.4% and 97.8 ± 8.3%, respectively, and those of DDTr's ranged from 99% to 113%; for analyzing the other 25 samples, the recoveries of PCB 121 and PCB 189 were 84 ± 11% and 84 ± 15%, respectively, and those of DDTr's ranged from 95% to 115%. The concentrations of DDTr's were quantified using mean relative response factors determined from calibration standard runs. All equipment rinses were done with methanol to avoid sample contamination, and a laboratory blank was analyzed with every set of seven samples. The method detection limits for two sample batches were both 0.05 ng/g wet weight for all the DDTr's.

Marine Water and Sediment Quality Criteria. Considering the bioaccumulation of chemicals through food chains, the MWQC can be calculated using the bioaccumulation factor (BAF) between water and eggs based on the BMCLB as follows:

$$\mathrm{MWQC} = (\mathrm{BMCL})/(\mathrm{BAF}) \tag{4}$$

Similarly, the MSQC was estimated using the BSAF as follows:

$$\mathrm{MSQC} = (\mathrm{BMCL})/(\mathrm{BSAF}) \tag{5}$$

The bioaccumulation factor from water to eggs was estimated by the following equation:

$$\mathrm{BAF} = [C_{\mathrm{egg}}]/[C_{\mathrm{water}}] \tag{6}$$

where C_{egg} (ng/g wet weight) and C_{water} (ng/L) are the *p,p′*-DDE concentrations in eggs and water, respectively.

The BSAF was estimated as

$$\mathrm{BSAF} = [C_{\mathrm{egg}}]/[C_{\mathrm{sediment}}] \tag{7}$$

where C_{sediment} (ng/g dry weight) is the *p,p′*-DDE concentration in sediment. In general, concentrations measured in the field have a specific probability distribution. The concentration probability distribution functions were identified using a hypothesis test (Matlab version 6.5, Natick, MA). Probability distributions of the BAF and BSAF were analyzed using a Monte Carlo simulation based on the specific probability distribution of the exposure concentration (Crystal Ball 2000 Pro, Decisioneering, Denver, CO).

Results and Discussion

Concentrations of DDTr's in the Eggs of Common Terns. Although DDT was also banned at the beginning of the 1980s in China, one of its metabolite residues, DDE, is still detected in aquatic environments due to its environmental persistence and the emergence of other sources such as the usage of dicofol, which contains DDT-related chemicals (*25*).

The concentrations of DDTr's measured in the eggs of the common tern inhabiting Bohai Bay are summarized in Supporting Information Table 3. Of the seven DDTr metabolites, only *p,p′*-DDMU and *p,p′*-DDE were detected in all samples, which differed from the DDTr composition profiles reported by Nisbet (1984) (*23*), in which DDE, DDD, and DDT were all detected in the eggs of common terns from Massachusetts. Similar to other investigations (*48*, *49*), *p,p′*-DDE was the major DDT metabolite, comprising 96.8−99.5% of the total DDTr concentration. Concentrations of *p,p′*-DDE ranged from 13.14 to 326.60 ng/g wet weight, lower than those reported in the eggs of the little egret and the night heron (*50*). The concentration range of *p,p′*-DDMU, a compound rarely included in studies of DDTr's in the environment, was 0.33−6.53 ng/g wet weight, indicating a large biomagnification potential for *p,p′*-DDMU compared with DDD and DDT. It is not known if DDMU can affect the reproduction and survival of the common tern; the mouse oral LD_{50} for DDMU is 2700 mg/kg, which is greater than that of *p,p′*-DDE (880.9 mg/kg) (*51*). It has been reported that *p,p′*-DDE is the main contributor to the reduction of the fertility success of common terns (*26*, *27*). The exposure concentrations of *p,p′*-DDE in common tern eggs transformed by a logarithm fitted a normal probability distribution using the hypothesis test of the "jbtest" function in Matlab version 6.5 software ($p = 0.3951$). The mean and standard deviation (SD) were 58.79 ng/g wet weight and 36.39, respectively. The concentration data in Supporting Information Table 3 were plotted as cumulative probability distributions on a log-normal basis (Figure 3).

BMCLB. The fledging success rate of the young under the condition of *p,p′*-DDE exposure was incorporated into F_i in the age-structured matrix using eq 2. Then r at specific concentrations of *p,p′*-DDE was calculated with the life-cycle demographic parameters shown in Supporting Information Table 1. The dose (C_e)−response (r) curve shown in Figure 4 was fitted on the basis of eq 3 using nonlinear regression, and r_0 was estimated to be 0.09 using the life-cycle parameters without *p,p′*-DDE exposure. α (95% confidence interval (CI)) and β (CI) were 3.67 (3.65−3.70) and 10.02 (8.65−11.39), respectively, as determined by

$$r(C_e) = 0.09(1 - (\log(C_{\mathrm{egg}})/3.65)^{10.02}) \tag{8}$$

Using the curve shown in Figure 4, the benchmark response, r, which decreased 10% from r_0, was estimated to be 0.08, and the corresponding benchmark concentration (BMC) and BMCLB were 830 and 663 ng/g wet weight. C_{egg} was equal to 4467 ng/g wet weight when $r = 0$.

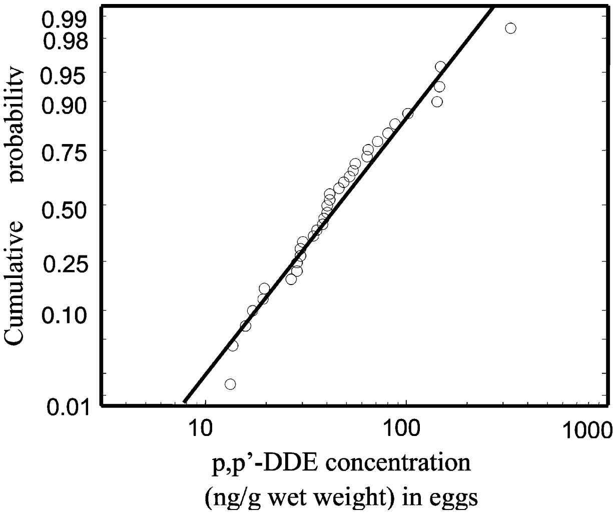

FIGURE 3. Cumulative probability distribution of DDE concentrations in common tern eggs. Symbols (○) correspond to the cumulative probability at a specific DDE concentration in the eggs.

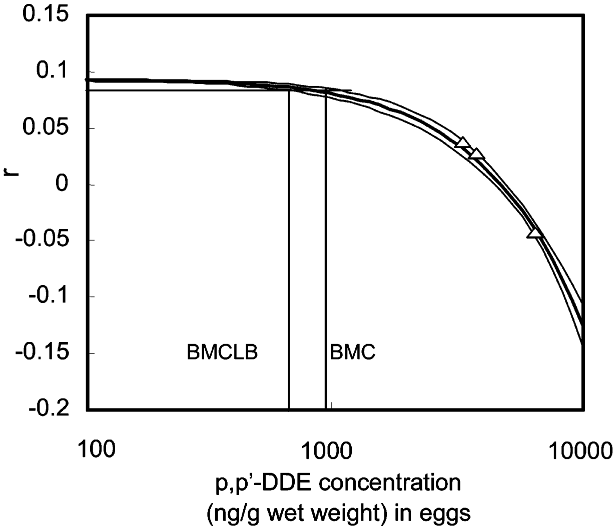

FIGURE 4. Relationship between the predicted *r* and *p,p′*-DDE concentration in the egg (solid curve). Dashed curves represent 95% prediction boundaries. Symbols (△) correspond to the predicted *r* at a specific DDE concentration. On the basis of the benchmark response (*r* = 0.08), BMC and BMCLB were estimated to be 830 and 663 ng/g wet weight. *r* = the intrinsic rate of increase, *p,p′*-DDE = 2,2-bis(chlorophenyl)-1,1-dichloroethylene, BMC = benchmark concentration, and BMCLB = benchmark concentration lower bound.

MWQC and MSQC in Bohai Bay. The concentrations of DDTr's in water and sediment from Bohai Bay have been reported in a previous paper (*25*). It is noteworthy that the DDT concentration was analyzed but not detected in water and sediment. Thus, *p,p′*-DDE in water and sediment is regarded as the source of *p,p′*-DDE in the eggs of common terns. The probability distribution of the *p,p′*-DDE concentration in the surface water of Bohai Bay was determined to have a log-normal distribution ($p = 0.5265$) using the data set reported by Wan et al. (*25*). The mean *p,p′*-DDE concentration and SD in water were calculated to be 1.19 ng/L and 0.62, respectively. Using the probability distributions of the *p,p′*-DDE concentration in water and eggs, the probability distributions of the *p,p′*-DDE BAF between eggs and water were obtained on the basis of eq 6 using the Monte Carlo method (Crystall Ball 2000 Pro) and then the mean BAF and its upper confidence bound (95%) estimated to be 13.8 L/g and 164, respectively. The *p,p′*-DDE BMCLB and probability distribution of the BAF were combined to calculate the probability distribution of MWQC on the basis of eq 4 by using the same simulation method (Supporting Information Figure 1a). The mean of MWQC was 31.7, with the range from 4 to 48.1 ng/L (95% confidence interval). Finally, 4 ng/L was recommended as the *p,p′*-DDE MWQC for Bohai Bay to protect the common tern population from the reproductive effects of DDTr's with 95% confidence.

The probability distribution of the *p,p′*-DDE concentration in the sediment of Bohai Bay was measured and found to have a log-normal distribution ($p = 0.9605$), and the mean (SD) was 0.58 (0.28) ng/g dry weight ($p = 0.9605$). Using a similar method, the probability distribution of MSQC was obtained as shown in Supporting Information Figure 1b. The mean of the MSQC was 15 ng/g dry weight, with the range from 1.90 to 22.5 ng/g dry weight (95% confidence interval). Thus, 1.90 ng/g dry weight was recommended as the *p,p′*-DDE MSQC for Bohai Bay with 95% confidence.

In fact, different species have distinct BMCLBs, which would influence the final MWQC and MSQC at the population level due to several factors. One is the sensitivity of species to *p,p′*-DDE, which controls the dose−response relationship. For example, with regard to reproductive success, the lowest observed effect concentrations of *p,p′*-DDE for night herons, brown pelicans, and mallard ducks are 1, 3, and 10 μg/g wet weight in eggs, respectively (*26*, *48*−*50*). The other causes are the population life-cycle parameters, which represent the potential of population persistence. For instance, when a population has a small r_0, the species could become endangered because it would take a long time for the population size to be restored from the effects of the contaminant (*52*), and vice versa for a species with a high r_0. Thus, the population dynamics for different species with a low r_0 would be more sensitive to a contaminant when the species are under a similar environmental stress. Other factors include the BAF and BSAF of a species, depending on their diet and behavior, which have a great effect on the MWQC and MSQC.

Guidelines for estimating quality criteria have recommended the species sensitivity distribution method to protect 95% of the aquatic species on the basis of acute and chronic toxicity data of animals and plants since the 1980s (*2*). Since the most endangered species frequently require protection through regulation or management decisions, in the future, the quality criteria of water and sediment should be improved considering these factors (e.g., individual toxicity, population persistence potential, site-specific BAF and BSAF).

However, it should be noted that the current marine water quality standard (MWQS) in China for DDT-related compounds (DDE, DDD, DDT) is 50 ng/L (*53*), which is higher than the MWQC recommended in this study. In the surface water of Bohai Bay, *p,p′*-DDE is a predominant metabolite in DDTr's; *p,p′*-DDE abundance in DDT-related compounds was 100% in 7 out of 15 seawater samples. At a concentration was 50 ng/L in the surface water, the probability distribution of *p,p′*-DDE residues in the eggs of common terns was predicted to exceed 4467 ng/g wet weight (as shown in Supporting Information Figure 2), suggesting that r would be negative and that the population would decrease. This suggests that the current MWQS in China would not protect the common tern population inhabiting Bohai Bay due to exposure to DDTr's.

This study's estimation of the MWQC and MSQC for the protection of the common tern population from exposure to DDE will help legislators make appropriate policy decisions to protect wildlife. Additionally, ecological risk assessment, which can predict the long-term influence of chemicals on wildlife, should be the basis for the formulation of China's two standards for judging the safety of wildlife. In addition, to protect the species with the most sensitive population, future research should focus on the following aspects: (1) The response of different species should be studied more thoroughly on the basis of concentrations of DDTr's in specific tissue. (2) Studies should be conducted to gather available data on life-cycle parameters of different species. (3) Field studies should be improved to obtain the BAF and BSAF in site-specific food webs.

Acknowledgments

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Note Added after ASAP Publication

The r values and reference citations in Table 2 of the Supporting Information were incorrect in the version published ASAP on March 15, 2006. The corrected version was published on March 22, 2006.

Supporting Information Available

Instrumental conditions for GC−MS analysis, life-cycle demographic parameters for the common tern population, exposure−effect relationship for a specific concentration of DDE on the survival of the young and predicted intrinsic rate of natural increase for the common tern, concentrations of DDT-related chemicals in common tern eggs, frequency charts of a Monte Carlo simulation for a log-normal distribution of MWQC and MSQC, a frequency chart of a Monte Carlo simulation for a probability distribution of predicted *p,p′*-DDE residues in common tern eggs based on MWQS, and the BAF probability distribution and the risk of common tern population shrinkage. This material is available free of charge via the Internet at http://pubs.acs.org.

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