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Chemosphere 65 (2006) 707–715

CHEMOSPHERE

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P and trace metal contents in biomaterials, soils, sediments and plants in colony of red-footed booby (*Sula sula*) in the Dongdao Island of South China Sea

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Received 25 July 2005; received in revised form 22 December 2005; accepted 16 January 2006
Available online 10 March 2006

Abstract

Concentrations of P and trace metals Zn, Cu, Cd, Pb and Hg in the faeces, bones, eggshells and feathers of seabirds and in the plants, soils and sediments with and without seabird influence on Dongdao Island, South China Sea, were determined and analyzed. Among the seabird biomaterials, the levels of P, Zn, Cu and Cd are the highest in the droppings and several times those in other materials; the Hg concentration is the highest in the feathers; and the Pb content is comparable among these biomaterials. These marked differences indicate different intake-bioaccumulation–elimination pathways for different trace metals. The levels of P, Zn, Cu, Cd and Hg in the plant, soil and sediment samples with the influence of seabird droppings are significantly higher than those in the samples without, and they are significantly correlated with each other. Thus, P, Zn, Cu, Cd and Hg are very likely to have a common source—predominantly bird guano—and the faeces of red-footed booby is an important vector for the flux of nutrient phosphorus and trace metals Zn, Cu, Cd and Hg from marine to island ecosystems on Dongdao Island.

Keywords: Dongdao Island of South China Sea; Trace metals; Phosphorus; Red-footed booby droppings; Plants; Soils; Sediments

1. Introduction

Seabirds play an important role in the transport of nitrogen and phosphorus of marine origin to terrestrial ecosystem (Smith and Tearle, 1985; Cocks et al., 1998; Anderson and Polis, 1999); but their role in the movement of trace metals from marine to terrestrial ecosystems remains less studied and unclear, although seabird dropping has been recognized as a significant source for the trace metals in the Arctic flora and mire, in the soils with high gull density, and in the polar ornithogenic lake sediments (Godzik, 1991; Zale, 1994; Headley, 1996; Bargagli et al., 1998; Otero, 1998; Sun et al., 2000, 2004; Sun and Xie, 2001; Wager and Melles, 2001; Blais et al., 2005).

Xisha atoll consists of many small islands of coral sand and rock (Fig. 1), and among these islands only about 40 have been named and approximately 10 have a few residents (Hainan Ocean Administration, 1999). The nearby ambient sea, with thousands of reefs, atolls, submerged reefs and banks, is probably one of the most biologically diverse bodies of water on the planet (Morton and Blackmore, 2001). Due to the distance from mainland China and the restriction on the travel to these islands, the research work performed on the Xisha Islands are largely incomplete and unknown to the international scientific community, only some research reports in Chinese are available (Exploration Group of Xisha Islands of Institute of Soil Science of CAS, 1977; Hainan Ocean Administration, 1999). Because only Chinese troops and a few fishermen are allowed to reside in some islands, on the other hand, the Xisha region is at a relatively pristine condition

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doi:10.1016/j.chemosphere.2006.01.043

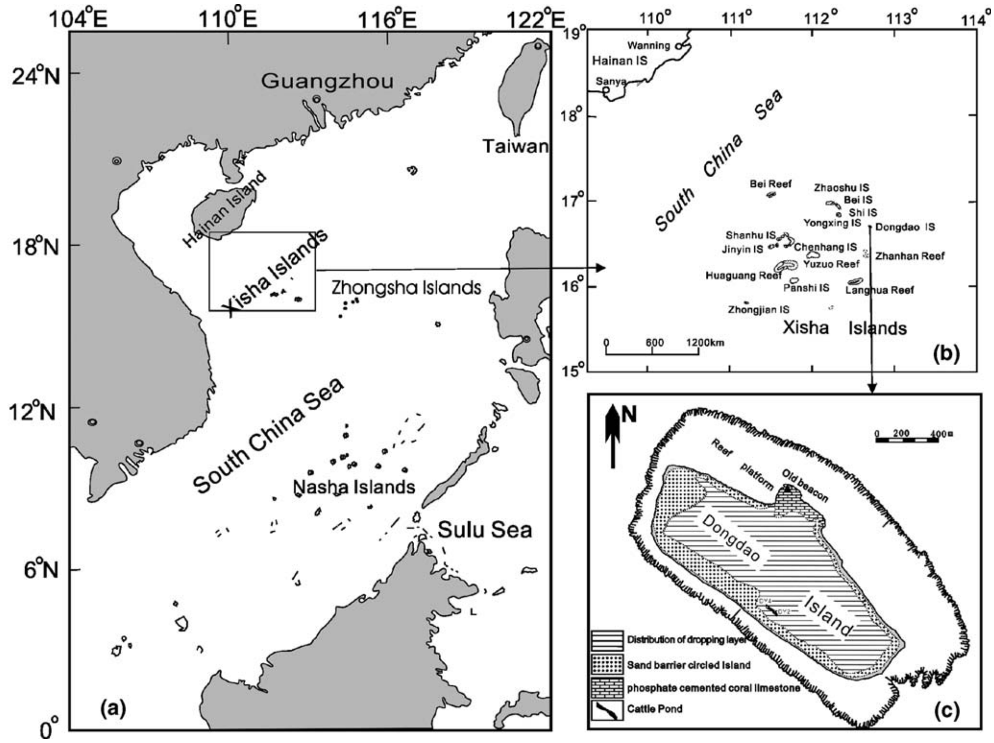

Fig. 1. Maps showing the geographical locations of (a) the Xisha Islands and (b) the Dongdao Island, as well as (c) the distribution of morphological zones of the Dongdao Island.

and thus provides an ideal site for investigating the geochemical characteristics of trace metals and seabirds' role in the movement of trace metals from marine to terrestrial ecosystems.

The Dongdao Island of Xisha atoll is located in the center of South China Sea (Fig. 1). From March 10 to April 11, 2003, we performed a systematic field investigation in this island and collected numerous samples of biological materials (such as faeces, bones, eggshells and feathers of red-footed booby), plants, soils and sediments. In this study, we determined and analyzed the levels of element P and trace metals Zn, Cu, Cd, Pb and Hg in these samples with the aim of examining seabirds' role in the flux of nutrients and trace metals from marine to terrestrial ecosystems.

2. Materials and methods

2.1. Study area

Dongdao Island (16°39′–16°41′N, 112°43′–112°45′E) is located in the east of Xisha Islands of South China Sea, about 33 km from Yongxin Island, the largest one of Xisha Islands. It is a tropic reef island with an elliptical shape and a northwest–southeast orientation (Fig. 1). Dongdao Island is developed on an individual reef flat, and was formed in the period of mid-late Holocene, the primary formation time of Xisha Islands (Lu et al., 1979; Hainan Ocean Administration, 1999). It has a land area of 1.55 km^2 and an elevation of about 3–6 m above sea level (a.s.l.).

The eastern, southern and western shores of Dongdao Island are surrounded by 5–6 m high sand barriers. The sand barrier on the southeastern shore is slightly higher than that on the northwestern shore. These sand barriers are covered by thriving vegetations, mainly shrubs such as *Scaevola sericea*, *Guettarda speciosa*, and *Aporosa villosa*. A wide and continuous area of beach rock and unconsolidated bioclasts of tridacna shells crop out along the northern shore. Along the northwestern shore is a sandy beach of coral and shell. In the interior is an up to 3 m high flat. In the middle, about half area of the island is covered by *Pisonia grandis* woodland, providing a good and shaded nesting place for numerous seabirds. Under the *P. grandis* woodland is black guano phosphatic soils enriched with organic matter. This area has a distinct smell of seabird droppings. At present, the Dongdao Island is occupied by approximately 25 000 breeding pairs of red-footed booby (*Sula sula*) (Xie et al., 2005), and has been identified as the natural protection area for this seabird species.

According to the Yongxin Island Observatory (Hainan Ocean Administration, 1999), the annual rainfall and average relative humidity of this island are about 1500 mm and 81%, respectively. The dry and wet seasons are very clear. Eighty-seven percent of total precipitation occurs from June to November due to the effect of southwest monsoon. From December to May is the dry season due to the influence of northeast monsoon.

Cattle Pond is a crescent-shaped fresh lake, located within the southeastern sand barrier. It is about 150 m long and has a maximum width of 15 m. It gets its name by providing the only fresh water supply for the cattle flocks on the island. The water depth is usually less than 0.5 m, and varies with the alternation of dry and wet seasons; in the dry season, the lake surface area becomes small, even drying out due to strong evaporation.

2.2. Sample collection

Samples of biomaterials, plants, soils, and sediments were collected during March 10–April 11, 2003. To avoid trace metal contamination, only steel, plastic or bamboo tools (knife, spade and shovel) were used for sampling, and after sampling samples were immediately placed in plastic bag, identified and sealed.

Non-destructive methods were used to obtain faeces, eggshells and feathers of the red-footed booby (*S. sula*). Fecal samples, including three fresh dropping samples, were taken from four different sites with breeding colonies. Three eggshell samples were randomly collected under the tree *P. grandis*. Primary feather samples were collected from two individual red-footed boobies. Wing bone samples were collected from a dead red-footed booby.

Soil, plant and sediment samples were collected from known breeding sites as well as from control area without nesting birds, and the sampling sites were selected based on the distribution of seabird breeding colonies and on-the-spot investigations. Five common perennial plant species in the Dongdao Island were chosen for this study and they are *S. sericea*, *G. speciosa*, and *A. villosa*, *P. grandis* and *Sesuvium portulacastrum*. Soil samples were collected at a depth of 5 cm from the surface along with the corresponding surface plants. Ten plant and eight surface soil samples were randomly selected from the central and shaded woodland, where a large number of birds, predominantly red-footed boobies, nest in the tree, and these samples are apparently influenced by the birds. Additional four plant and four surface soil samples were randomly collected from on or outside the sand barriers, where we could not find any nesting birds during field investigations. In addition to the surface soils, three pits of 50–70 cm depth within the breeding colonies were excavated in order to expose the soil profiles. In these pits, a ~40 cm thick brownish horizon significantly influenced by seabird droppings has a sharp boundary with the underlying horizon predominantly composed of white coral sand. From these pits, 3–5 kg soil samples were collected at 5 cm interval to a depth of 50–70 cm. Together with the surface soil samples, a total of 52 soil samples were collected, 34 from ornithogenic soil layers and 18 from the soil layers not influenced by seabird faeces.

Sediment cores DY2 and DY4 of 126 cm and 117 cm long, respectively, were collected from Cattle Pond during the field investigations, and sediment core ZY was retrieved from a lagoon in the adjacent Zhongjian Island, which is presently not occupied by seabirds. During sampling, PVC plastic gravity pipes of 12 cm in diameter were pushed down into the soft substrate of the lake floor and then quickly retrieved. These sediment cores were transported directly to laboratory without slicing, and preserved in cold storage prior to analysis. In the laboratory, the sediment cores were opened, photographed and described. According to the field observations as well as sampling documents, DY2 and DY4 cores have similar lithological characters. Gray-white coral, shell and sandy gravel sediments, apparently not influenced by seabird droppings, form the bottom sediment layers of both cores. In contrast, the top 96 cm of DY2 and 87 cm of DY4 are apparently influenced by guano with the exception of the well-sorted fine coral sand interval between 84 and 88 cm in DY2 and between 58 and 69 cm in DY4. Gray-white coral sands and gravels are observed throughout the sediment core ZY, indicating the lack of guano influence. Detailed descriptions on the sedimentary patterns of these cores are given by Liu et al. (2005). These sediment cores were segmented at 1–2 cm intervals in the laboratory to give a total of 141 and 54 sediment sub-samples with and without guano influence, respectively.

2.3. Sample preparation and analysis

For the wing bone of red-footed booby, about 0.5–2.0 g samples were dipped in boiling water to remove soft tissues, dried at 60 °C for 12 h, and then powdered. The pulverized sample was kept in clean polyethylene bottles. Following the method of Burger and Gochfeld (2000) and Dauwe et al. (2000), the feather samples were washed alternately with deionized water and acetone to remove loosely adherent external contamination, dried in open air, and then powdered. For these powder samples, 0.1 mg was digested in 1:1 mixture of HNO_3 (70%) and H_2O_2 (30%) in a microwave vessel for 10 min and then diluted by deionized water.

The plant samples were analyzed according to the procedure by Xie and Sun (2003). They were cleaned from soil deposits, washed separately and thoroughly with tap and deionized water, and dried at 60 °C for 12 h. Root tissues of these plant samples were discarded to avoid possible soil contamination, and only the above ground plant parts (stems, leaves) were analyzed. These dried tissues were blended and powdered. The powder sample (0.5 g) was fused with NaOH and Na_2O_2 at 650 °C in a covered nickel crucible. The residue was extracted by 50 ml deionized water at 90 °C, and the filtrate was diluted to 100 ml using deionized water.

For the faeces, soil, and sediment samples, after air-drying in the clean laboratory, they were ground and passed through a 120-mesh screen, and then dried at 60 °C for 12 h. About 3 g of each dried powder sample was taken, precisely weighed, and then digested by multi-acid in a Pt crucible with electric heating.

We measured copper, zinc, cadmium and lead levels using atomic absorption spectrophotometry (AAS) equipped with high temperature graphite tube furnace (Model Vario 6 made by Analytik Jena AG, Germany).

The total mercury concentration was determined by atomic fluorescence spectrometry (AFS-930, Beijing Vital Co., Beijing, China), and its detection limit is 0.1 μg kg^{-1}. Phosphorus concentration was measured using ultraviolet visible spectrophotometer (UV–VIS 8500). All elemental concentrations are expressed in mg kg^{-1}, except for Hg in μg kg^{-1} and P in percentage (%), based on dry weight. Quality assurance procedures included the analysis of replicate samples, and appropriately certified reference materials (CRMs, supplied by National Research Center for CRM's of China, Beijing), which were used as the internal standards and analyzed with each set of samples in 20% proportion. The recovery efficiency was $100 \pm 5\%$ for most elements, and the reading was accepted when reference samples were within 10% range of the expected concentration. Operational blanks consisted of 2 ml of the acids reacted without any sample material.

2.4. Data analysis

In this study, plant, soil and sediment samples were separated into two groups (A and B) (Table 1): with or without the influence of bird faeces. After testing the data for normality, a statistical comparison of mean levels for both group samples was performed with one-way analysis of variance (ANOVA) followed by Turkey test. Pearson correlation coefficients were used to examine the relationship between different trace metals and P in the bird-influenced samples. All analyses were performed with the aid of ORIGIN 6.1 package. We accepted p-values of <0.05 as statistically significant.

3. Results and discussion

3.1. Comparative concentrations of P and trace metals in the biological materials

The levels of five trace metals (Cu, Zn, Cd, Hg, Pb) and nutrient element P in the faeces, bones, eggshells and feathers of red-footed booby are shown in Fig. 2.

P has the highest level of up to approximately 16% in the red-footed booby droppings, and this could be attributed to two factors. First, according to Wang et al. (1987), the seawater, the primary producers (such as diatoms and green algae), and the second consumers (such as fish) around the Dongdao Island have phosphorus concentrations of <0.09 mg kg^{-1}, 0.31–3.3% and 4.3–16%, respectively, characteristic of evident bioaccumulation trend. Thus, as seabird of higher tropic level, the red-footed booby is expected to have higher P levels. Second, most of the phosphate consumed by seabirds (about 70%) is contained in the unassimilated faeces (Ayliffe et al., 1992; Schreiber et al., 1996).

Zn also has the highest concentration of up to 419.4 mg kg^{-1} in the seabird droppings (Table 1). This level is comparable with the results of Nyholm (1995) and Otero (1998) although it is difficult to compare species

Table 1
Mean concentrations and variation ranges of trace metals and P_2O_5 in soils, plants and sediments with and without the influence of seabird droppings in the Dongdao Island

Description	Oxides/elements	P_2O_5 (%)		Cu (mg kg^{-1})		Zn (mg kg^{-1})		Cd (mg kg^{-1})		Pb (mg kg^{-1})		Hg (μg kg^{-1})	
		Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range
Red-footed booby	Faeces ($n = 12$)	36.27	33.02–38.40	21.1	16.5–25.4	419.4	350–514	6.34	5.15–7.34	1.60	0.86–3.71	107.8	83–120
Group A[a]	Soils ($n = 34$)	2.61	0.79–8.91	10.23	3.87–47.5	63.34	14.24–300	3.58	0.91–10.8	2.06	0.48–6.57	17.78	4–41
	Plants ($n = 10$)	0.92	0.47–1.70	12.25	5.5–16.5	79.07	22.5–198	1.67	0.17–8.45	1.98	0.81–2.69	11.3	5–25
	Sediments ($n = 141$)[b]	1.51	0.66–5.60	9.88	4.06–23.3	40.77	16–179	2.17	0.50–6.43	2.74	0.10–8.90	28.20	4–88
Group B[a]	Soils ($n = 18$)	0.34	0.10–0.75	3.23	1.46–8.50	7.78	2.78–27.5	0.27	0.05–0.70	1.94	0.34–3.4	4.44	1–15
	Plants ($n = 4$)	0.43	0.40–0.46	9	7–11	17.5	14–21.5	0.16	0.02–0.29	1.4	0.49–2.05	7.1	5–10
	Sediments ($n = 54$)[c]	0.33	0.03–1.42	3.65	1.73–6	12.95	5.46–35	1.15	0.31–2.00	2.31	0.18–8.07	5.07	0.33–15

[a] Group A and B indicate samples with and without bird influence, respectively.
[b] The sample number for the Cu concentration analysis is 134.
[c] The sample number for the Cd concentration analysis is 31.

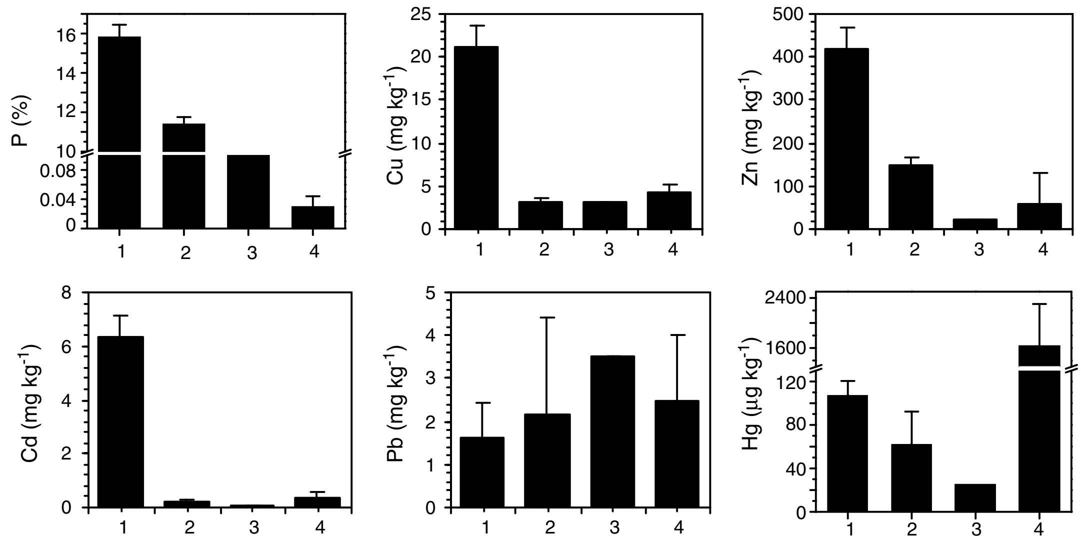

Fig. 2. Concentrations of P, Cu, Zn, Cd, Pb and Hg in seabird droppings (1), wing bone (2), eggshell (3) and feather (4) from red-footed booby. Their analytical sample numbers are twelve, three, one and two, respectively.

with different feeding habits, life spans and moulting cycles (Ancora et al., 2002). The concentrations of Cu and Cd in the seabird droppings are significantly lower at 21.1 and 6.34 mg kg^{-1}, respectively (Table 1), but they are still several times higher than those in the bones, eggs and feathers; and this indicates that they could be readily eliminated in excreta as observed by Otero (1998), Dauwe et al. (2000) and Ancora et al. (2002). Hg has the highest level in the feathers, about 20–30-fold higher than those in the droppings (Fig. 2), and this is consistent with the results by Burger and Gochfeld (2000). One likely explanation for this is that red-footed boobies (*S. sula*) have large fish as its main diet, they thus accumulate Hg through biomagnification in the food chain (Burger and Gochfeld, 2000), and the feathers play the primary role in the elimination of Hg. Pb has comparable levels in all the determined biomaterials, indicating a lack of biomagnification in the food chain, and this is consistent with the previous report (Ancora et al., 2002).

Our above results for red-footed booby are consistent with those for other seabird species. Otero (1998) observed positive correlations between Cd, Zn and Cu in the faeces of yellow-legged gull. Dauwe et al. (2000) detected considerably lower levels of Cu, Cd, and Zn levels in the feathers of songbirds than those in excrements. Ancora et al. (2002) reported higher Cd level in excreta of Adélie penguins than that in feathers due to the poor absorption by the gastrointestinal tract and the ability of kidneys and liver to eliminate this element. Seabird droppings contain diet-derived and non-biologically available trace metals; these metals are accumulated in different body organs and excreted via different physiological routes (Rainbow, 1990), and the concentrations of these trace metals in the seabird excreta closely reflect those in their diets (Norheim, 1967). Although it is difficult to compare results from different seabird species, these consistent findings suggest the existence of a common intake-excretion model as proposed by Ancora et al. (2002): most trace metals such as Cu, Zn and Cd may form metallothionein complexes, which are directed to lysosomes, immobilized there and later excreted, and thus reduce the accumulation in the feathers.

3.2. Comparative concentrations of P and trace metals in plants, soils and sediments

The concentrations and concentration ranges of P_2O_5 and trace metals (Cu, Zn, Cd, Hg, Pb) in the plant, soil and sediment samples from Dongdao Island with and without notable influence of red-footed booby are given in Table 1 and plotted in Fig. 3, respectively. As can be seen from Fig. 3 and Table 1, the concentration ranges of P_2O_5, Cu, Zn, Cd and Hg with bird influence are clearly different from those without; and the ANOVA test results, given in Table 2, confirm that these differences are statistically significant ($p < 0.05$). For the plant samples, the significance levels (p value) are only slightly lower than 0.05 (Table 2), and this seems to be caused by small sample number of the determined plants.

The differences in the mean P_2O_5 concentrations among the soil, plant and sediment samples with and without bird influence are approximately 8-fold, 2-fold and 5-fold, respectively (Table 1). The elevated P_2O_5 content in the bird-influenced materials is very likely related to guano input as the red-footed booby droppings have the highest P levels among the determined biological materials (Fig. 2). Seabird-derived guano provides a major nutrient source for plant growth and soil development at atolls (Hutchinson, 1950; Woodroffe and Morrison, 2001) and for the ecosystems of Dondao Island (Exploration Group of Xisha Islands of Institute of Soil Science of CAS, 1977; Gong and Huang, 1995; Gong et al., 1997). Seabird-derived guano also plays a substantial role in the

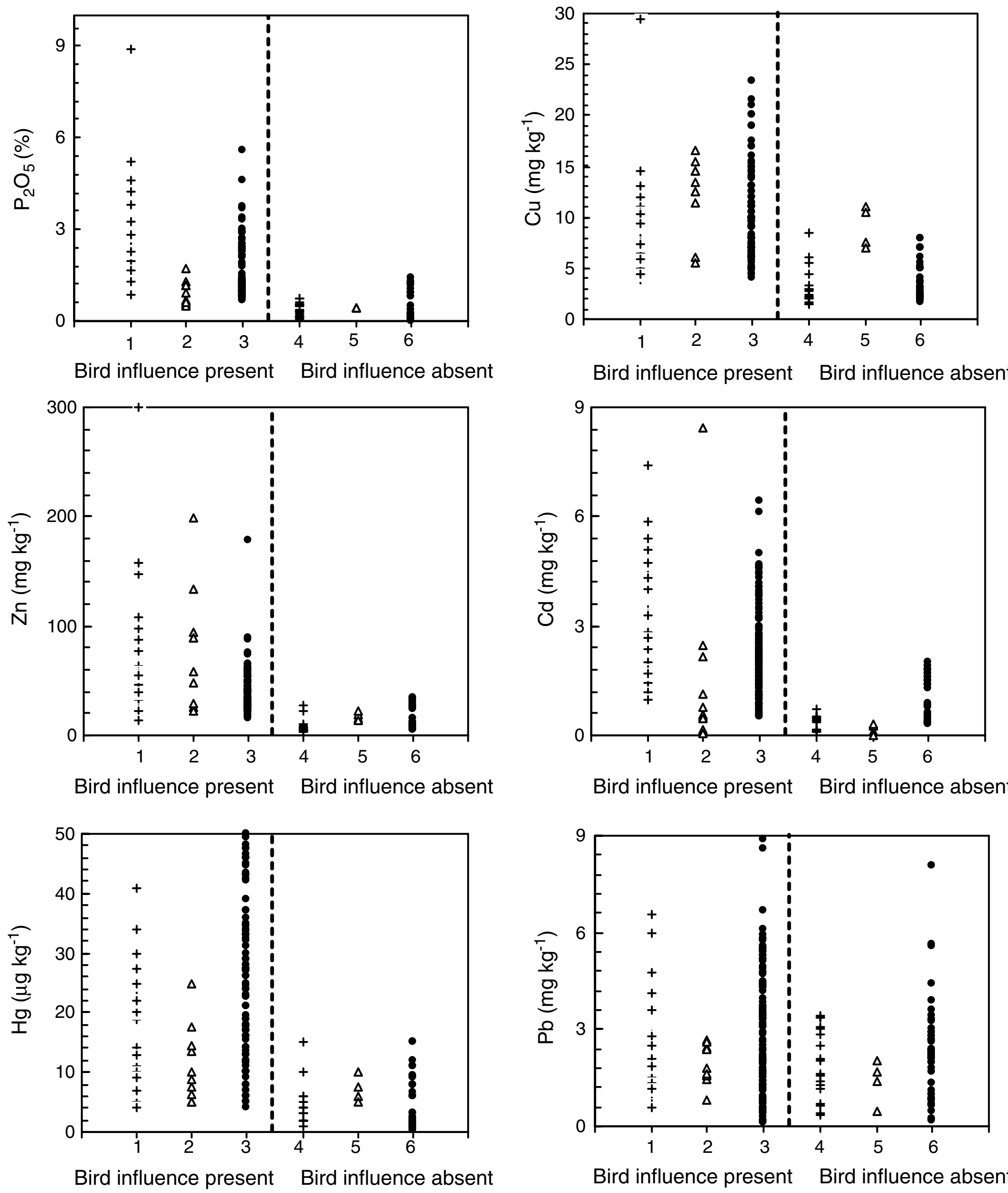

Fig. 3. Concentration comparisons of P_2O_5, Cu, Zn, Cd, Hg and Pb in the soils (1, 4), plants (2, 5) and sediments (3, 6) with and without influence from seabird droppings.

Table 2
Significant levels (p value) of one-way ANOVA analysis for the differences between the mean levels of P_2O_5 and trace metals in the soils, plants and sediments with and without bird influence

	P_2O_5	Cu	Zn	Cd	Pb	Hg
Soils	<0.001	0.0013	0.01	<0.001	0.87[a]	<0.001
Plants	0.032	0.013	0.05	0.046	0.15[a]	0.047
Sediments	<0.001	<0.001	<0.001	<0.001	0.65[a]	<0.001

[a] There were no significant differences between the mean level of Pb in the soils, plants, sediments with and without bird influence.

development of insular phosphorites in islands (Rodgers, 1994; Trichet and Fikri, 1997; Baker et al., 1998). In Dongdao Island, tropic climatic conditions with high temperature and abundant precipitation would lead to decomposition of red-footed booby guano, and a great deal of released phosphates would move downward in the form of organic compounds and subsequently re-precipitated in underlying calcareous sands to form ''guano phosphatic soils or rocks'' within the seabird colonies (Exploration Group of Xisha Islands of Institute of Soil Science of CAS, 1977; Gong et al., 1997).

The substantially higher contents of trace metals Hg, Cu, Zn and Cd in the plant, soil and sediment samples of the Dongdao Island with influence from bird droppings are also apparently caused by seabird droppings. First, as shown in Table 1, these elements are greatly enriched in seabird droppings. With respect to Hg, although the feathers of red-

Table 3
Correlation coefficients between trace metals and P_2O_5 for all the analyzed samples influenced by seabird droppings

	P_2O_5	Cu	Zn	Cd	Pb	Hg
P_2O_5	1					
Cu	0.494[a]	1				
Zn	0.683[a]	0.712[a]	1			
Cd	0.815[a]	0.378[a]	0.508[a]	1		
Pb	−0.130	0.182[b]	0.063	−0.105	1	
Hg	0.184[a]	0.122	0.1968[a]	0.154[b]	0.194[a]	1

The total number of analytical samples is 185.
[a] Correlation is significant at the 0.01 level (2-tailed).
[b] Correlation is significant at the 0.05 level (2-tailed).

footed booby have the highest concentration, its levels in the excrement samples are still very high (up to 107.8 μg kg^{-1}) and exceed those in the soil, plant and sediment samples (Table 1). Second, the descending order of Zn, Cu and Cd levels in these bird-influenced materials is consistent with the one in the bird droppings. Third, we performed correlation analyses on the concentration data in the bird-influenced materials. The results are given in Table 3 and show significant and positive correlations among Cu, Zn, Cd, Hg and P_2O_5 at the level of 0.05, suggesting that Cu, Zn, Cd and Hg have a common source with P_2O_5, mainly from seabird droppings. And last, seabirds generally play an important role in the trace metal input for island ecosystems. Headley (1996) reported considerable levels of trace metals in the seabird faeces of an Arctic region, and suggested that the faeces of nesting seabirds constituted the primary input of trace metals into the soils. Otero (1998) and Otero and Fernández-Sanjurjo (2000) observed significantly higher levels of Cd, Cu, Zn and Hg in the soils with high gull density than those without, and proposed that the gull faeces be an important vector of trace metal input, except for lead. Godzik (1991) and Grodzinska and Godzik (1991) detected notably higher levels of trace metals in the mosses occupied by nesting seabirds than those in the adjacent tundra without any seabird colonies. Hawke et al. (1999) suggested that the Cd concentration can reflect the presence or absence of seabird breeding, and its contributions from pre-European seabird breeding may match anthropogenic sources of Cd (e.g. superphosphate fertilizers) in many New Zealand locations.

In contrast with P and trace metals Cu, Zn, Cd and Hg, Pb is an exception. As illustrated in Fig. 2, the varying ranges of Pb concentration in the samples with and without bird influence have large overlaps; and the mean contents in the bird-influenced plants, soils and sediments are close to those without bird influence (Table 1). This hypothesis is confirmed by the statistical analysis. As shown in Table 2, all the significance levels (p value) of ANOVA test for Pb concentrations are much higher than 0.05, indicating that the differences are not significant. Furthermore, the droppings are not notably enriched with Pb as compared with bones, feathers and eggshells (Fig. 2); the average Pb level in the droppings (1.60 mg kg^{-1}, $n = 12$) is even lower than those in the bird-influenced soils (2.06 mg kg^{-1}, $n = 34$) and sediments (2.74 mg kg^{-1}, $n = 141$) (Table 1). These suggest that the effect of faeces of red-footed booby on the Pb content in the pants, sediments and soils is insignificant in the Dongdao Island. This inference is also supported by correlation analysis. As shown in Table 3, all the determined P and trace metals, with the exception of Pb, showed significant and positive correlations.

Based upon these results, we propose that the red-footed booby excrements are an important vector for the movement of trace metals Zn, Cu, Cd and Hg as well as nutrient phosphorus from the marine to island ecosystems in the South China Sea.

3.3. Preliminary evaluation of the trace metal contamination in the Dongdao Island

In the present study, it is difficult to accurately evaluate the contamination level of trace metals in the soils and sediments of Dongdao Island. First, few data about the historical trace metal levels in this island are available. Second, the guano-derived element concentrations are closely related to the degree of the influences by seabirds (Zale, 1994; Otero, 1998; Otero and Fernández-Sanjurjo, 2000; Sun et al., 2000; Blais et al., 2005). As shown in Table 1, the levels of P and trace metals in the plants, soils and sediments influenced by seabird droppings have large variation ranges; and the differences in seabirds' influence could play a substantial role in these variations besides factors such as texture, organic matter content, and weathering degree of these samples. Indeed, the concentrations of bio-element P and trace metals such as Hg, Cd, Cu and Zn in the ornithogenic sediments of polar region show remarkable variations versus depth, and these variation profiles have been used as reliable proxies for the variation of guano input and thus for the change of historical bird population (Zale, 1994; Sun et al., 2001; Wager and Melles, 2001).

Here we give a tentative estimation for the environment quality in the Dongdao Island using the determined mean levels of trace metals in the bird-influenced materials, the national environmental quality standards, and the published thresholds of trace metal levels that may affect wild animals and plants. For the soils in this island, the concentrations of Cu, Zn, Hg and Pb in the bird-influenced samples were lower than the critical levels given in Chinese Environmental Quality Standard (No. GB15618-1995) (threshold: Cu 100 mg kg^{-1}, Zn 300 mg kg^{-1}, Hg 1.0 mg kg^{-1}, Pb 350 mg kg^{-1}), but the concentration of Cd is above the critical level (0.6 mg kg^{-1}). For the lake sediments, the corresponding national standard is not available, so we used the marine sediment standard instead (No. GB181668-2002, threshold: Cu 35 mg kg^{-1}, Zn 150 mg kg^{-1}, Hg 0.2 mg kg^{-1}, Pb 60 mg kg^{-1}, Cd 0.5 mg kg^{-1}); and like in the soils, the concentrations of Cu, Zn, Hg and Pb in the sediments are below the critical levels and the concentration of Cd is above. We also compared the concentrations of Cd, Cu, Zn, Hg and Pb in the sediments of the Dongdao Island with the threshold effect level (TEL) from Canadian ecological database for sediment baseline (Cu 36 mg kg^{-1}, Zn 123 mg kg^{-1}, Hg 0.173 mg kg^{-1}, Pb 35 mg kg^{-1}, Cd 0.6 mg kg^{-1}) (Ni et al., 2005), and again Cd is the only element exceeding the TEL. We did not evaluate the contamination level of trace metals in the plants of Dongdao Island due to the limited quantity of samples.

In summary, as a whole, the contamination level of trace metals, except Cd, in the bird-influenced soils and sediments in the Dongdao Island seems to be relatively low.

4. Conclusions

The faeces of red-footed booby is an important vector for the flux of trace metals Zn, Cu, Cd and Hg as well as nutrient phosphorus from marine to island ecosystems in the South China Sea. Element P and trace metals Zn, Cu, Cd, Pb and Hg have significantly different concentrations in faeces, bones, eggshells and feathers of the red-footed boobies from the Dongdao Island of South China Sea, reflecting complex pathways in the seabird for the intake, bioaccumulation and elimination of these elements. The levels of P, Zn, Cu, Cd and Hg in the plant, soil and sediment samples with the influence of seabird droppings are significantly higher than those in the samples without; they are significantly correlated with each other, and thus these elements very likely have a common source: predominantly bird guano. Pb is an exception, it is not rich in the red-footed booby droppings, and its level does not show any significant changes between difference samples. The contamination level of trace metals in the Dongdao Island on the whole is low with the exception of Cd, which has an alarming concentration in the bird-influenced soils and sediments.

Acknowledgements

This research was supported by grants from the National Natural Science Foundation of China (Grant Nos. 40231002 and 40476001) and the Projects of Knowledge Innovation of CAS (No. KZCX3-SW-151). We are grateful to PR China Military for authorizing us to perform the research project in Xisha atoll and to PR China troops in Xisha atoll for their assistance. We especially appreciate two anonymous reviewers for their critical reviews and careful corrections on this manuscript. Dr. Otero is also gratefully acknowledged for providing some related references during the revision of this manuscript.

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