Oxalate and root exudates enhance the desorption of *p,p'*-DDT from soils

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Abstract

The abiotic desorption of *p,p'*-DDT from seven Chinese soils spiked with *p,p'*-DDT and the effects of oxalate at 0.001–0.1 M and the root exudates of maize, wheat, and ryegrass were evaluated using batch experiments. Soil organic carbon played a predominant role in the retention of DDT. Oxalate significantly increased the desorption of *p,p'*-DDT, with the largest increments ranging from 11% to 54% for different soils. Oxalate addition also resulted in the increased release of dissolved organic carbon and inorganic ions from soils. Root exudates had similar effects to those of oxalate. Root exudates significantly increased DDT desorption from the soils, and the general trend was similar among the plant species studied for all the soils ($p > 0.05$). Low molecular weight dissolved organic carbon amendments caused partial dissolution of the soil structure, such as the organo-mineral linkages, resulting in the release of organic carbon and metal ions and thus the subsequent enhanced desorption of DDT from the soils. The enhancing effects of oxalate and root exudates on DDT desorption were influenced by the contents of soil organic carbon and dissolved organic carbon in soils.

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1. Introduction

The organochlorine pesticide dichlorodiphenyltrichloroethane (DDT) and its metabolites are of great concern as typical persistent organic pollutants (POPs) due to their long half-life, bioaccumulative nature and chronic adverse effects on humans and animals. DDT has been widely used throughout the world to control arthropod disease—vectors and agricultural pests. As a

result of its wide application, the residues of DDT and its metabolites are widely distributed and are persistent environmental contaminants. Although DDT is banned in developed nations, it is still being used in developing nations (Kunisue et al., 2003; Nakata et al., 2005). Additional release of DDT into the soil environment occurs due to the impurity of some other pesticides being used, such as dicofol (Qiu et al., 2004; Tao et al., 2004a; Nakata et al., 2005). The DDT in soil may be taken up by plants or degraded or transported to ground and surface waters, and thus its environmental fate still needs much attention.

The retention and mobility of DDT in soil are the primary determinants of its environmental fate and

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behavior, including bioavailability, persistence, and leaching potential. These processes are related to the adsorption and desorption characteristics of DDT. Enhancing the desorption of DDT would increase its bioavailability to plants and soil organisms, and its transportation to ground and surface water. Desorption of organic contaminants varies according to the differences in the physicochemical properties of soil. Owing to the high lipophilic nature of DDT, soil organic matter is the dominant sorptive phase. However, the roles of soil inorganic fractions and soil clay content should also be considered (Pavlostathis and Jaglal, 1991; Sheng et al., 2001). A better understanding of the factors affecting DDT adsorption and desorption is a prerequisite to elucidate the fate of DDT in soils and to reduce the potential environmental pollution due to the pesticide usage (Futch and Singh, 1999).

Since oxalate is abundant in the rhizosphere of many plant species, and is highly reactive with some soil fractions such as metal oxides and clay minerals (Stumm, 1986; Bhatti et al., 1998a,b), oxalate will have a profound effect on the fate of organic contaminants in soils. For example, organic acids have been shown to increase the desorption and bioavailability of weathered *p,p'*-DDE in soil (White et al., 2003). However the relative importance of soil properties in determining DDT desorption by oxalate is not fully understood. In addition, plant roots exude large amounts of carboxyl-containing compounds (root exudates). Approximately 28–59% of the photosynthetic products in a plant are translocated underground, of which up to 70% is excreted into soil (Lynch and Whipps, 1990). Such quantities of organic material released into the soil are likely to produce significant chemical changes, particularly in the rhizosphere, which in turn influence the desorption of organic pesticides from soils. However, to date, there is no direct evidence to support such a hypothesis.

The present study was therefore aimed: (1) to examine the desorption of *p,p'*-DDT from soils in relation to soil properties; (2) to address the effects of oxalate and plant root exudates on the desorption of DDT in soils. Seven Chinese soils with various soil properties and artificially spiked with *p,p'*-DDT were used.

2. Materials and methods

2.1. Materials

Seven surface (0–20 cm) soils from different parts of China were used. Sample sites, soil order and textures are shown in Table 1. Soil samples were air-dried, homogenized and ground to pass through a 0.5 mm diameter mesh and maintained at 4 °C prior to the chemical analysis and experiments. Soils were analyzed for pH, using a soil to water ratio of 1:1 (w/v), soil organic carbon

Table 1
Physicochemical properties of the soils studied

Soil	Sampling site	Order	pH (1:1)	Organic carbon (%)	DOC (mg kg ⁻¹)	P (mg kg ⁻¹)	Fe (mg kg ⁻¹)		Al (mg kg ⁻¹)		Clay (%)	Texture
							Crystalline	Amorphous	Crystalline	Amorphous		
1	Heilongjiang	Mollisol	6.3	3.94	852	26	5392	2729	1265	1485	39.6	Silt clay loam
2	Inner Mongolia	Mollisol	8.2	2.74	570	5.1	3239	638	478	777	28.4	Silt loam
3	Yunnan	Ultisol	7.4	1.27	383	17	18148	3207	1676	1258	30.9	Clay loam
4	Liaoning	Alfisol	6.4	1.06	361	13	5959	1762	670	841	29.8	Clay loam
5	Beijing	Alfisol	7.4	0.82	548	6.2	3176	919	820	590	24.1	Loam
6	Jiangxi	Ultisol	5.3	0.66	298	3.0	15541	3087	2374	1346	42.6	Clay
7	Gansu	Aridisol	7.8	0.51	218	5.4	3559	626	416	449	14.7	Sand loam

(SOC) content (Nelson and Sommers, 1982), dissolved organic carbon (DOC), particle size distribution, available phosphorus, amorphous/crystalline iron and aluminum (Manning and Goldberg, 1997). The contents of DDT and its metabolites in the original samples were extracted as follows: 20 g of soil were mixed with 10 g anhydrous Na_2SO_4 in paper extraction thimbles and then extracted with 100 ml hexane/acetone (1:1 v/v) for 24 h at a rate of six cycles per hour in a Soxhlet extraction apparatus. The extract was concentrated to 2 ml in a rotary evaporator. The residue was transferred to a column (1 cm internal diameter $\times$ 5 cm length) prepared by packing silica gel (60–80 mesh), covered by a 2 cm layer of Na_2SO_4 , and then washed with 30 ml hexane and 30 ml acetone. The eluate was reduced to 1 ml volume for analysis by a gas chromatograph (Agilent model 6890 plus) equipped with an electron-capture detector (GC- μ ECD).

The soils were artificially contaminated with *p,p'*-DDT. A concentration of 2 mg kg^{-1} soil of *p,p'*-DDT was dissolved in acetone and thoroughly mixed with soil samples. The spiked soil samples were stored in an open container under a sterile fume hood for five weeks, to ensure no acetone remained in the sample, and subsequently stored in brown glass containers at 4 °C for a further five weeks prior to the use in the following experiments. The actual concentrations of DDT and its metabolites in the spiked soils were measured to determine if any degradation had occurred.

Root exudates were collected from solution cultures of maize (*Zea mays* L.), wheat (*Triticum aestivum* L.) and ryegrass (*Lolium rigidum* L.). Seeds were obtained from the Chinese Academy of Agricultural Sciences, and surface-sterilized by soaking in a solution of H_2O_2 (3%) for 15 min and then Ca (NO_3)₂ (3.0 mM) for 4 h prior to cultivation. The seedlings were grown under growth chamber conditions at a day:night cycle of 16:8 h at 22:15 °C. The plants were grown for two weeks in nutrient solution. The solution in the culture dishes was replaced daily. The composition of the nutrient solution was: KNO_3 1.5 mM; Ca (NO_3)₂ 1 mM; MgSO_4 0.5 mM; $\text{NH}_4\text{H}_2\text{PO}_4$ 0.25 mM; EDTA-Fe 11.9 μM ; H_3BO_3 11.5 μM ; MnSO_4 1.25 μM ; ZnSO_4 0.2 μM ; CuSO_4 0.075 μM and $(\text{NH}_4)_6\text{Mo}_7\text{O}_{24}$ 0.025 μM . The solution was buffered at pH 5.8 with 2 mM Mes-Tris. Fifteen days following germination, the solution in the culture dishes (30 ml per seedling) was replaced twice daily with distilled and sterilized water in the morning and fresh nutrient solution in the evening. The culture-solution collected in the evening from each culture dish was used as the source of root exudates.

p,p'-DDT (98%) was obtained from Sigma–Aldrich Inc. (St. Louis, USA). The standards for *p,p'*-DDT, *p,p'*-DDE and *p,p'*-DDD were purchased from National Research Center for Certified Reference Materials (Beijing, China). Oxalate was of reagent grade in sodium salt (Beijing Chemical Reagent Co.).

2.2. Desorption experiment

To measure the desorption of *p,p'*-DDT from the soils, 0.5 g samples of the original soils or the *p,p'*-DDT spiked soils were added to centrifuge tubes, 30 ml of distilled water was added, and the suspension adjusted to pH 6.5 with NaOH or HCl. To each tube, 1 μg of 2,4,5,6-tetrachlor-*m*-xylene (internal standard) and 200 mg of TenaxTM beads (60/80 mesh, Scientific Instrument Services, Inc. NJ, USA), which served as an infinite sink for dissolved hydrophobic organic compounds, were added. The tubes were capped and placed on a shaker at 25 °C for 7 d. The tubes were then centrifuged at $800 \times g$ and the TenaxTM beads were removed. The TenaxTM beads were transferred to a capped vial containing 5 ml hexanes and 0.5 g anhydrous Na_2SO_4 , and the vials were placed on a shaker at 25 °C for 24 h. A portion of the hexanes was then analyzed by GC- μ ECD.

To study the influence of oxalate or root exudates on desorption, the desorption solution was displaced by either oxalate solution at one of the following concentrations: 0, 0.0005, 0.001, 0.005, 0.01, 0.05 and 0.10 M, or root exudates at pH 6.5. In order to avoid the disturbance of microorganism from soils and root exudates, all extraction solutions contained NaN_3 (0.02%) to inhibit microbial activity.

To determine the effect of oxalate and root exudates on the aqueous concentration of inorganic soil constituents, the same treatments were used but in the absence of TenaxTM beads. After a 7 d equilibration period, the tubes were centrifuged at $800 \times g$ for 20 min and a portion of the supernatant was analyzed for the aqueous concentrations of the extracted inorganic ions (Fe, Al, Ca, Mg and P). The supernatant of the samples treated with oxalate were analyzed for oxalate and DOC.

2.3. Analysis and statistics

The concentrations of DDT and its metabolites (*p,p'*-DDT, *p,p'*-DDE, and *p,p'*-DDD) in the extracts were analyzed using an Agilent Gas Chromatograph 6890 equipped with a ⁶³Ni electron capture detector (μ ECD) and a HP-5 capillary column (30 m, 0.32 mm i.d., 0.25 μm film thickness). Separation was achieved according to the following program: 50 °C initial temperature; ramped at 15 °C min^{-1} to 180 °C, held for 3 min; then at 10 °C min^{-1} to 260 °C, held for 3.5 min. Nitrogen was used as the carrier gas (1 ml min^{-1}) and make-up gas (60 ml min^{-1}). A 1.0 μl aliquot of the extract was injected in splitless mode. The injector was held at 210 °C, and the detector at 300 °C. *p,p'*-DDT and its metabolites quantification were carried out using five-point calibration plots. Each calibration level contained 40 ng ml^{-1} 2,4,5,6-tetrachlor-*m*-xylene as an internal standard. The analytical detection limits were 6 ng g^{-1}

for p,p' -DDT and 4 ng g^{-1} for p,p' -DDE and p,p' -DDD compounds. Recovery of the internal standard was $92.3\% (\pm 1.7\%)$.

Inorganic ions in the final solutions were determined by inductively coupled plasma atomic emission spectrometry (ICP-AES, OPTIMA2000DV, Perkin Elmer). Oxalate was analyzed by a P/ACE MDQ capillary electrophoresis system from Beckman (Fullerton, CA, USA). DOC was determined by a Phoenix 8000 TOC analyzer. DOC released in the presence of oxalate was calculated by detracting oxalate from the DOC assayed in solution.

All extractions were performed in triplicate. The results were analyzed using an analysis of variance (ANOVA); the least significant difference (LSD) test was used to determine the significance of the differences between treatments. Statistical analyses were conducted in SPSS (Statistical Package for Social Science) v. 10.0.

3. Results and discussion

3.1. Abiotic p,p' -DDT desorption and its relationship with soil properties

The seven soils investigated belong to four types of representative Chinese soils. The soil properties are given in Table 1. No DDT or its metabolites was detected in six of the soils, however, the Beijing soil contained $32 \text{ } \mu\text{g kg}^{-1}$ p,p' -DDE (dry weight).

The amounts of p,p' -DDT desorption from the soils are shown in Fig. 1. After ten weeks of equilibrium, no DDT degradation was found by Soxhlet extraction. The desorption ratios ranged from 30.1% to 51.8%, and the Mollisol soil from Heilongjiang desorbed the least amount of p,p' -DDT while the Aridisol soil from Gansu desorbed the most. A significant negative correlation

Fig. 1. Desorption percentage of p,p' -DDT in spiked soils and its relation with soil organic carbon (SOC). Data based on three replicates are presented as mean $\pm$ SD for p,p' -DDT desorption.

was observed between the amounts of p,p' -DDT desorption and the soil organic carbon (SOC) contents with R of 0.853 ($p < 0.01$), indicating that SOC played a predominant role in DDT desorption from soils (Nakata et al., 2005). The mechanisms involved are likely to be due to hydrophobic adsorption and partitioning (Senesi, 1992). DDT is a highly lipophilic compound which will bind with SOC and thus make it less mobile (Tao et al., 2004a). SOC includes both soluble and insoluble fractions of organic carbon, and the proportion of dissolved organic carbon (DOC) in a soil is usually very small. Both solid organic carbon and dissolved organic carbon have to be taken into account for a proper description of the distribution of hydrophobic compounds in sediment or soil/water system (Chiou et al., 1986; Ben-Hur et al., 2003; Tao et al., 2004a). A negative correlation was also observed between the DOC contents and the amounts of p,p' -DDT desorption ($R = 0.805$, $p < 0.05$). The DOC in soil can enhance the dissolution of organic compounds in soil (Chiou et al., 1986; Seol and Lee, 2000; Tao et al., 2004a). The most likely reason for this negative relationship between the DOC and the DDT desorption is due to the dynamic equilibrium between SOC and DOC in soils (Antoniadis and Alloway, 2002; Ben-Hur et al., 2003), indeed, a positive correlation between SOC and DOC was found in this study ($R = 0.895$, $p < 0.01$).

The influence of other soil properties was also examined. Clay content, available P and amorphous (crystalline) Fe and Al showed negligible effects on DDT desorption from the soils (Ouyang et al., 2003) with a correlation coefficient of 0.63 or lower.

3.2. Effect of oxalate on abiotic p,p' -DDT desorption

Desorption of p,p' -DDT in soils in the presence of oxalate is shown in Fig. 2. Oxalate amendment enhanced

Fig. 2. Desorption of p,p' -DDT in spiked soils in the presence of oxalate. Data based on three replicates are presented as mean $\pm$ SD for p,p' -DDT desorption.

the DDT desorption for all the soils. It is noteworthy that a significant increase in desorption occurred at very low oxalate concentration ($p < 0.01$). With increasing oxalate concentrations, the increase in desorption became less pronounced and then reached equilibrium. The Alfisol soil from Liaoning and the Aridisol soil from Gansu reached the highest desorption at 0.01 M; Jiangxi and Beijing soils reached at 0.05 M, and the other soils at 0.1 M of oxalate. Although the different soils reached the highest desorption at different oxalate concentrations, the general trend was consistent, and there were no statistical differences in desorption between the soils at an oxalate concentration of 0.01 M or higher. The highest increase in DDT desorption was from 11% to 54% in the presence of oxalate. The lower increases in DDT desorption at higher oxalate concentrations possibly due to large quantities of sorbing oxalate restricting the diffusion of resident p,p' -DDT in soils (White et al., 2003).

The extractable inorganic elements and DOC in the soils were quantified at all oxalate concentrations. Fe, Al, Ca, Mg, and P were selected as the representative inorganic elements. The concentrations of the ions were increased substantially at the low oxalate concentrations except Ca^{2+} because of low K_{sp} of calcium oxalate. The released inorganic ions, especially Mg and P, correlated with the desorption of p,p' -DDT in the presence of oxalate (Table 2). A significant correlation ($p < 0.01$) also existed between the release of DOC and the desorption of p,p' -DDT in six of the soils ($p < 0.05$), although not in the Gansu soil which possessed the lowest content of SOC (Table 2).

The increased desorption of DDT and DOC in the presence of oxalate was expected, and the effect of oxalate on DDT desorption is under the influence of the SOC and DOC contents (Table 3). Soils with higher organic carbon retained more DDT. When oxalate is added to soils, chelation of the metal ions with oxalate will disrupt organo-mineral linkages, resulting in the mobilization of SOM and inorganic ions into the aque-

Table 3

Correlation coefficients between the SOC and DOC contents with the increase of p,p' -DDT desorption by oxalate amendments

Soil property	Oxalate concentration (M)				
	0.001	0.005	0.01	0.05	0.1
SOC	0.935**	0.758*	0.820*	0.774*	0.874**
DOC	0.946**	0.926**	0.918**	0.916**	0.889**

* Indicates significant correlation at level of $p < 0.05$, and ** at $p < 0.01$.

ous phase, and/or reduce the degree of the linkages in soil organic matter (Bhatti et al., 1998a,b; Yang et al., 2001). Part of the solid organic carbon complexed with soil minerals will thus be released into soil solution and the p,p' -DDT, once complexed with this fraction of organic carbon, will desorb into the soil solution. Thus the higher SOC in the soils, the more DDT was released when oxalate was added.

3.3. Effects of root exudates on abiotic p,p' -DDT desorption

Low molecular weight root exudates usually include organic acids, amino acids and saccharides (Baudoin et al., 2003). The concentration of organic carbon in the root exudates collected from the solution culture was 42.3, 31.5 and 25.8 mg C kg⁻¹ and the pH of the exudates was 6.58, 7.44 and 7.12 for maize, wheat and ryegrass, respectively. The largest amount of organic carbon was detected in the maize sample, and it appeared that the amount of the exudates was related to the plant biomass.

Significant increase in p,p' -DDT desorption occurred in the presence of root exudates, with $p < 0.01$ for maize and wheat and $p < 0.05$ for ryegrass (Fig. 3). Compared

Table 2

Correlation coefficients between the inorganic ions and DOC released with the desorption of p,p' -DDT in the presence of oxalate

Soil	DOC ^a	Fe	Al	Mg	P
1	0.899**	0.566	0.567	0.836*	0.872*
2	0.951**	0.561	0.395	0.874**	0.907**
3	0.959**	0.949**	0.914**	0.818*	0.911**
4	0.937**	0.831*	0.781*	0.975**	0.944**
5	0.908**	0.903**	0.815*	0.939**	0.819*
6	0.975**	0.976**	0.940**	0.897**	0.909**
7	0.788*	0.811*	0.820*	0.573	0.885**

* Indicates significant correlation at level of $p < 0.05$, and ** at $p < 0.01$.

^a Oxalate is detracted from DOC released in soil solution.

Fig. 3. Desorption of p,p' -DDT in spiked soils by maize, wheat and ryegrass root exudates. Data based on three replicates are presented as mean $\pm$ SD for p,p' -DDT desorption.

with water, maize, wheat and ryegrass roots increased the *p,p'*-DDT desorption from 8.4% to 35.8%, 9.7% to 36.8% and 3.1% to 23.7%, respectively, for different soils. Amongst the three species, ryegrass exudates had the least effect on *p,p'*-DDT desorption, which could be related to the relative low biomass of the ryegrass root (Fig. 3).

The release of inorganic elements also increased significantly in the presence of root exudates (Table 4). For example, the concentration of Ca^{2+} was increased in the presence of root exudates, in contrast to its behavior in the presence of oxalate. Since Ca^{2+} is a major component of soil minerals, the organic ligands in the exudates may interact with and dissolve soil minerals and soil organic matter through the formation of organo-metal complexes (Nardi et al., 1997; Jones, 1998; Tao et al., 2004b), and subsequently release the organic compounds, such as DDT, which was previously sequestered within the solid phase (White, 2002). Significant correlations between soil organic carbon and increases in *p,p'*-DDT desorption in the presence of root exudates

were obtained ($p < 0.01$) with correlation coefficients (R) of 0.933 for maize, 0.891 for wheat, and 0.929 for ryegrass.

4. Conclusions

This study reports that oxalate enhanced the desorption of *p, p'*-DDT in several contrasting soils. Similar, increases in the desorption of *p,p'*-DDT from these soils occurred in the presence of root exudates from maize, wheat and ryegrass. The effects of oxalate and root exudates on the desorption of *p,p'*-DDT were influenced by SOC and DOC contents of soils. Oxalate and root exudates increased the desorption of *p,p'*-DDT through a partial dissolution of the soil structure, including desorption of organic carbon from soils, and the formation of dissolved complexes with inorganic metal ions. Since oxalate and root exudates are ubiquitous composition of rhizosphere soils, the presence of these dissolved carbon sources will clearly have a profound effect on the mobility and fate of DDT in soils.

Table 4

Contents of the major inorganic ions (mg kg^{-1}) released from soils in the presence of root exudates

Soil	Treatment	Fe	Al	Ca	Mg	P
1	Water	400	528	142	93	4.4
	Maize	1052	1394	336	330	5.2
	Wheat	896	1393	182	349	6.0
	Ryegrass	705	1210	238	153	5.8
2	Water	3.8	5.2	2940	185	0.1
	Maize	24	42	6135	479	0.3
	Wheat	7.7	16	11911	646	0.2
	Ryegrass	13	22	7757	349	0.1
3	Water	84	114	1717	223	6.2
	Maize	109	171	2014	387	7.0
	Wheat	159	229	2609	337	6.2
	Ryegrass	125	174	2018	332	6.5
4	Water	344	575	102	72	2.5
	Maize	685	822	829	167	2.7
	Wheat	403	774	683	185	2.6
	Ryegrass	436	645	717	199	2.7
5	Water	44	58	1081	174	6.3
	Maize	406	494	1243	229	7.0
	Wheat	385	520	1458	298	7.0
	Ryegrass	103	174	1383	285	6.6
6	Water	925	1718	55	83	0.6
	Maize	1084	1774	66	104	0.7
	Wheat	1179	1865	62	98	0.8
	Ryegrass	981	1823	66	71	0.8
7	Water	2.5	5.5	3011	214	0.1
	Maize	22	38	6646	542	0.1
	Wheat	12	25	8162	570	0.1
	Ryegrass	11	9	7055	497	0.1

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References

- Antoniadis, V., Alloway, B.J., 2002. The role of dissolved organic carbon in the mobility of Cd, Ni and Zn in sewage sludge-amended soils. *Environ. Pollut.* 117, 515–521.
- Baudoin, E., Benizri, E., Guckert, A., 2003. Impact of artificial root exudates on the bacterial community structure in bulk soil and maize rhizosphere. *Soil Biol. Biochem.* 35, 1183–1192.
- Ben-Hur, M., Letey, J., Farmer, W.J., Williams, C.F., Nelson, S.D., 2003. Soluble and solid organic matter effects on atrazine adsorption in cultivated soil. *Soil Sci. Soc. Am. J.* 67, 1140–1146.
- Bhatti, J.S., Comerford, N.B., Johnston, C.T., 1998a. Influence of oxalate and soil organic matter on sorption and desorption of phosphate onto a spodic horizon. *Soil Sci. Soc. Am. J.* 62, 1089–1095.
- Bhatti, J.S., Comerford, N.B., Johnston, C.T., 1998b. Influence of soil organic matter removal and pH on oxalate sorption onto a spodic horizon. *Soil Sci. Soc. Am. J.* 62, 152–158.
- Chiou, C.T., Malcolm, R.L., Brinton, T.I., Kile, D.E., 1986. Water solubility enhancement of some organic pollutants and pesticides by dissolved humic and fulvic acids. *Environ. Sci. Technol.* 20, 502–508.

- Futch, S.H., Singh, M., 1999. Herbicide mobility using soil leaching columns. *Bull. Environ. Contam. Toxicol.* 62, 520–529.
- Jones, D.L., 1998. Organic acid in the rhizosphere—a critical review. *Plant Soil* 205, 25–44.
- Kunisue, T., Watanabe, M., Subramannian, A., Sethuraman, A., Titenko, A.M., Qui, V., Prudente, M., Tanabe, S., 2003. Accumulation features of persistent organochlorines in resident and migratory birds from Asia. *Environ. Pollut.* 125, 157–172.
- Lynch, J.M., Whipps, J.M., 1990. Substrate flow in the rhizosphere. *Plant Soil* 129, 1–10.
- Manning, B.A., Goldberg, S., 1997. Arsenic(III) and arsenate(V) adsorption on three California soils. *Soil Sci.* 162, 886–895.
- Nakata, H., Hirakawa, Y., Kawazoe, M., Nakabo, T., Arizono, K., Abe, S.-I., Kitano, T., Shimada, H., Watanabe, I., Li, W., Ding, X., 2005. Concentrations and compositions of organochlorine contaminants in sediments, soils, crustaceans, fished and birds collected from Lake Tai, Hangzhou Bay and Shanghai city region, China. *Environ. Pollut.* 133, 415–429.
- Nardi, S., Reniero, F., Concheri, G., 1997. Soil organic matter mobilization by root exudates of three maize hybrids. *Chemosphere* 35, 2237–2244.
- Nelson, D.W., Sommers, L.E., 1982. Total carbon, organic carbon, and organic matter. In: Page, A.L. (Ed.), *Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties*. American Society of Agronomy, Madison, WI, pp. 539–579.
- Ouyang, Y., Nkedi-Kizza, P., Mansell, R.S., Ren, J.Y., 2003. Spatial distribution of DDT in sediments from estuarine rivers of central Florida. *J. Environ. Qual.* 32, 1710–1716.
- Pavlostathis, S.G., Jaglal, K., 1991. Desorptive behavior of trichloroethylene in contaminated soil. *Environ. Sci. Technol.* 25, 274–279.
- Qiu, X.H., Zhu, T., Li, J., Pan, H.S., Li, Q.L., Miao, G.F., Gong, J.C., 2004. Organochlorine pesticides in the air around the Taihu Lake, China. *Environ. Sci. Technol.* 38, 1368–1374.
- Senesi, N., 1992. Binding mechanisms of pesticides to soil humic substances. *Sci. Total Environ.* 123/124, 63–76.
- Seol, Y., Lee, L.S., 2000. Effect of dissolved organic matter in treated effluents on sorption of atrazine and prometryn by soils. *Soil Sci. Soc. Am. J.* 64, 1976–1983.
- Sheng, G., Johnston, C.T., Teppen, B.J., Boyd, S.A., 2001. Potential contribution of smectite clays and organic matter to pesticide retention in soils. *J. Agric. Food Chem.* 49, 2899–2907.
- Stumm, W., 1986. Coordinative interactions between soil solids and water—an aquatic chemicals point of view. *Geoderma* 38, 19–30.
- Tao, S., Guo, L.Q., Wang, X.J., Liu, W.X., Ju, T.Z., Dawson, R., Cao, J., Xu, F.L., Li, B.G., 2004a. Use of sequential ASE extraction to evaluate the bioavailability of DDT and its metabolites to wheat roots in soils with various organic carbon contents. *Sci. Total Environ.* 320, 1–9.
- Tao, S., Liu, W.X., Chen, Y.J., Xu, F.L., Dawson, R.W., Li, B.G., Cao, J., Wang, X.J., Hu, J.Y., Fang, J.Y., 2004b. Evaluation of factors influencing root-induced changes of copper fractionation in rhizosphere of a calcareous soil. *Environ. Pollut.* 129, 5–12.
- White, J.C., 2002. Differential bioavailability of field-weathered *p,p'*-DDE to plants of the *Cucurbita* and *Cucumis* genera. *Chemosphere* 49, 143–152.
- White, J.C., Mattina, M.I., Lee, W., Eitzer, B.D., Iannucci-Berger, W., 2003. Role of organic acids in enhancing the desorption and uptake of weathered *p,p'*-DDE by *Cucurbita pepo*. *Environ. Pollut.* 124, 71–80.
- Yang, Y., Ratté, D., Smets, B.F., Pignatello, J.J., Grasso, D., 2001. Mobilization of soil organic matter by complexing agents and implications for polycyclic aromatic hydrocarbon desorption. *Chemosphere* 43, 1013–1021.