The earthworm gastrointestinal effect on the release of organic bound residues in soils

J H Du1,2
1 State Key Laboratory of Pollution Control and Resources Reuse, College of Environmental Science and Engineering, Tongji University, Shanghai 200092, China
E-mail: hjkxdjh@163.com

Abstract. Earthworm activities promote the release of bound residues and the digestive activities of earthworms contribute to the process. Earthworm digestive effects on bound residues can be divided into physical and chemical effects. Physical effects include gastrointestinal abrasion and mixing. The abrasion of soil and litter residues in earthworm gizzards and intestine can grind the food into fine particles, which increase the contact surface with microbial and promote the desorption of bound residues. Chemical effects are attributed to the secreted surfactant substances and digestive enzymes. The surfactants, especially at levels that lead to micellization, can enhance the desorption process of the organic contaminants that sored in the soil. The enzymes in earthworm digestive tracts can decompose the humus in soil, which may promote the release of organic residues that bind with humus.

1. Introduction
As a result of coal combustion, industrial production, agricultural activity, and atmospheric deposition, organic contaminants are now ubiquitous in soils [1-5]. Due to their strong hydrophobicity and persistence, the concentrations of organic contaminants can reach up to thousands of µg/kg levels in soils[1, 2, 4]. After entering into soils, a significant proportion of organic contaminants become nonextractable residues[6, 7], which are considered to be less available for plant uptake or microbial degradation [8]. And the fraction of nonextractable residues in soils has been shown to increase with increasing contact time [8-12].

The bound residues which are adsorbed strongly, may take a longer time to desorb, because of the energy step to overcome. However, the bound residues are not entirely excluded from environment interaction, because of natural weathering and biological effects. These processes influence the adsorption sites, which promote the formation or release bound residues[13-17].

As soil ecosystem engineers, earthworms can directly or indirectly influence soil physical, chemical and biological properties [18-20]. The release of bound residues can be promoted by earthworms via two mechanism, digestive function and changing in binding status between residues and soil. The main purpose of this review is to explain the effect of earthworm digestion on bound residues release and degradation.

2. Feeding habits of earthworm
Earthworms can be divided into three ecological groups: epigeics, endogeics, and anecics. Different species of earthworm have different feeding strategies and digestive enzymes. Epigeics feed on litter...
and/or the attached microflora and ingest little or no soil[21]. They can fragment organic wastes into much finer particles by passing them through a grinding gizzard inside their mouth that all earthworms possess. Due to their feeding habits, the activity of cellulose is much higher in epigeics than other species. Endogeics primarily consume soil and associated humified organic matter in the upper layer of mineral[22]. They are the only species that feed on large quantity of soil, and are thus often called geophagous[21]. Geophagous endogeic earthworms have a poor digestive enzymatic capacity, while the mutualistic relationship between soil microflora and earthworms can promote the digestion of organic compounds[23]. Anecics feed at the soil surface by dragging leaves, manure, and other partially decomposed organic matter into soil, some soil is also ingested[21]. Anecic earthworms incorporate litter material into the mineral soil. Since earthworms of different ecological groups likely affect nutrient mineralization differently.

3. Transformation of SOM in earthworm gut

3.1. Physical processes

The physical stress such as abrasion is likely to promote the release of desorption-resistant contaminants in worm guts [24, 25]. Physical digestion mainly takes place in the grinding gizzard and intestine, and it can strongly increases the exposed surface area and enhanced the beneficial action of aerobic microorganisms [26]. The gizzard is a highly muscular organ, which is oval, hard, and thick walled, and it can moisten and actively churn the food. With the contraction of circular muscles, mastication can take place in gizzard, assisted by some grits or gravels [26]. Previous study has suggested that earthworms are more likely to digest organic matter that mixed with mineral soil, especially sand grains, which will promote the crushing of organic matter [22]. Moreover, small longitudinal folds and one larger fold (namely the typhlosole) on earthworm intestine walls can enhance the desorption of organic contaminants from the ingested soils, due to intensive abrasion processes [24].

3.2. Surfactants in earthworm gut

Surfactant like substances in earthworm gut can enhance the desorption process of organic contaminants by increasing surface areas and their aqueous concentrations [25, 27, 28]. Surfactants have both the polar groups and nonpolar groups, therefore they can function as emulsifiers and solubilizes [29, 30]. Surfactant like substances can also increase the instantaneous sorption rate and alter the sorption intensity, rather than its extent, especially at low concentrations. According to [31]. In earthworm digestive fluids, surfactant micelles can lead to micellization, which are great solubilizes for lipophilic contaminants [32]. Furthermore, according to [33], higher desorption rates of organic contaminants are often accompanied by greater gut-fluid surfactancy and higher micelle concentration, and solubilized contaminants that are excreted by earthworms can more available for physical transport, chemical reactions, and metabolism by other organisms [32].

3.3. Digestive enzymes

Earthworms have a comprehensive digestive enzyme system, in which polyphenol oxidase, catalase, protease, polysaccharides, glycosidase, phosphatase, and some other high activity enzymes may decompose humus, while humus plays a central role in adsorption and desorption behaviors of organic contaminants in soils. Enzymes in earthworm are mainly from microorganism in the digested soil or digestive tract secretion, and their species varies a lot in different ecological categories and niches [34].

Studies founded that the average molecular mass of the humic acids decreased incubation with gut fluid, which promoted the release of bound residues. It is generally considered that humic acids consist of aromatic and aliphatic moieties. Compared to an aromatic component, earthworm digestive enzymes break down peptidic component preferentially, which obviously change the composition of humics. When the digested soil transit in digestive tract, enzymes break down the “peripheral” part of humics, such as peptides and polysaccharides.

Conflicting results have shown that digestive tract of earthworm accelerate the formation of bound
residues. There are two reasons for the promotion of the formation process: one reason is that earthworm digestion promotes the process of soil humification, which enhance physical trapping or adsorption of residues into humus; another is that enzymes in earthworm can degrade organic residues, and the degradation products are more likely to be adsorbed onto the organic matter in soil.

Earthworms, especially epigeics, can decompose organic waste, such as fallen leaves, which accelerate organic wastes humification process. During this process, the organic residues retained on the surface of organic wastes transformed into bound residues. The mixing of organic residues with minerals and organic matter in digestive system can enhance the transformation process. As mentioned in the previous section, geophagous earthworms can decompose humus by digesting soil organic matter. However, new humus molecules can also be synthesized while decomposing humus in soil. The synthesis of new humus can be explained in the following way. Highly active oxidases in the gastrointestinal tract of earthworms, such as polyphenol oxidase and catalase, re-polymerize polyphenols and proteinaceous substance[35, 36].

The metabolites such as hydroxyl derivatives of organic contaminants through digestive enzymes may be relatively more strongly adsorbed to soil than original forms. Wondi and Cathy suggested that hydroxyatrazine is more likely to bound to soil organic matter than atrazine because the replacement of the chlorine atom by a hydroxyl group permits additional hydrogen bonding[37].

The effect of the earthworm digestive tract on the binding residue is a complex process that is related to the earthworm species, the properties of the compounds, and the type of soil.

3.4. The mutualism between earthworm gut and soil microbial

Many studies suggested that there was mutualism between earthworm gut and soil microflora [35, 38, 39], especially for geophagous endogeic, which have poor digestive enzymes [23]. In earthworm gut various conditions are suitable for microbial to survive, including high moisture, neutral pH, and high content of mucus, which is produced in the foregut and becomes adsorbed afterwards. The mucus in earthworm gut is a mixture of bioavailable organic matters with low molecular weights, and it has a “priming effect” on microbial in soils [39]. The mucus can. During transport in earthworm gut, microbial gradually recover their initial metabolic status [39], and begin to decompose complex macromolecular organic matters like humus. At the same time, microbial in the guts can also provide protein, essential amino acids, fatty acids and other substances for earthworms. Important microbial in earthworm gut include Bacillus, Pseudomonas, Klebsiella, Azotobacter, Serratia, Aeromonas, Morganella and Enterobacter, and they can decompose a wide variety of organic substances such as cellulose, hemicellulose, humus and other natural polymers such as Bacillus, Pseudomonas, Klebsiella, Azotobacter, Serratia, Aeromonas, Morganella and Enterobacter[40].

4. Conclusion

The release of bound residues is mainly due to the change of organic matter in the soil, and the process is complex. It is clear that the composition of organic matter in earthworms casts is different from the surrounding soil, and the differences can also affect the release of bound residues. The impact of casts also needs further discussion.

References
[1] Hou H, Zhao L, Zhang J, Xu Y F, Yan Z G, Bai L P and Li F S 2013 Organochlorine pesticides and polychlorinated biphenyls in soils surrounding the Tanggu Chemical Industrial District of Tianjin, China Environ. Sci. Pollut. Res. 20 3366-80
[2] Kumar B, Verma V K, Mishra M, Kumar S, Sharma C S and Akolkar A B 2014 Persistent organic pollutants in residential soils of North India and assessment of human health hazard and risks Toxicol Environ. Chem. 96 255-72
[3] Perez-Vazquez F J, Flores-Ramirez R, Ochoa-Martinez A C, Orta-Garcia S T, Hernandez-Castro B, Carrizalez-Yañez L and Pérez-Maldonado I N 2014 Concentrations of persistent organic pollutants (POPs) and heavy metals in soil from San Luis Potosí, México Environ. Monit.
Vácha R, Skála J, Čechmánková J, Horváthová V and Hladík J 2015 Toxic elements and persistent organic pollutants derived from industrial emissions in agricultural soils of the Northern Czech Republic J. Soils Sed. 15 1813-24

Yuan G L, Wu H Z, Fu S, Han P and Lang X X 2014 Persistent organic pollutants (POPs) in the topsoil of typical urban renewal area in Beijing, China: Status, sources and potential risk J. Geochem. Explor. 138 94-103

Liu X, Xu X, Li C, Zhang H, Fu Q, Shao X, Ye Q and Li Z 2015 Assessment of the environmental fate of cycloxaiprid in flooded and anaerobic soils by radioisotopic tracing Sci. Total Environ. 543 116

Ambrosi D, Kearney P C and Macchia J A 2002 Persistence and metabolism of oxadiazon in soils Journal of Agricultural & Food Chemistry 25 868-72

Gao Y, Zeng Y, Shen Q, Ling W and Han J 2009 Fractionation of polycyclic aromatic hydrocarbon residues in soils J. Hazard. Mater. 172 897-903

Macleod C J A and Semple K T 2000 Influence of Contact Time on Extractability and Degradation of Pyrene in Soils Environ. Sci. Technol. 34 4952-57

Macleod C J A and Semple K T 2003 Sequential extraction of low concentrations of pyrene and formation of non-extractable residues in sterile and non-sterile soils Soil Biol Biochem 35 1443-50

Ncibi M C, Mahjoub B and Gourdon R 2007 Effects of aging on the extractability of naphthalene and phenanthrene from Mediterranean soils J. Hazard. Mater. 146 378-84

Zhang J J, Wen B, Shan X Q, Zhang S and Khan S U 2007 Temporal change in the distribution patterns of hexachlorobenzene and dichlorodiphenyltrichloroethane among various soil organic matter fractions Environ. Pollut. 150 234-42

Xing B S and Pignatello J J 1997 Dual-Mode Sorption of Low-Polarity Compounds in Glassy Poly(Vinyl Chloride) and Soil Organic Matter Environ. Sci. Technol. 31 792-99

Lebeuf E J and Weber W J J 2000 Macromolecular Characteristics of Natural Organic Matter. 2. Sorption and Desorption Behavior Environ. Sci. Technol. 34 3632-40

Cornelissen G, Rigterink H, Ferdinandy M M A and Noort P C M V 1998 Rapidly desorbinding fractions of PAHs in contaminated sediments as a predictor of the extent of bioremediation Environ. Sci. Technol. 32 966-70

Cornelissen G, Noort P C M V, Govers H A J 1998 Mechanism of Slow Desorption of Organic Compounds from Sediments: A Study Using Model Sorbents Environ Sci Technol 32

Xing B S and Pignatello J J 2010 Time-dependent isotherm shape of organic compounds in soil organic matter: Implications for sorption mechanism Environ. Toxicol. Chem. 15 1282-88

Hickman Z A and Reid B J 2008 Earthworm assisted bioremediation of organic contaminants Environ. Int. 34 1072-81

Mougin C, Chevrier N, Repincay C, Hedde M and Hernandez-Raquet G 2013 Earthworms highly increase ciprofloxacin mineralization in soils Environmental Chemistry Letters 11 127-33

Lavelle P 1997 Faunal activities and soil processes: adaptive strategies that determine ecosystem function Adv. Ecol. Res. 27 93-132

Römcke J, Jänsch S and Didden W 2005 The use of earthworms in ecological soil classification and assessment concepts Ecotoxicol. Environ. Saf. 62 249-65

Butenschoen O, Marhan S, Langel R and Scheu S 2009 Carbon and nitrogen mobilisation by earthworms of different functional groups as affected by soil sand content Pedobiologia 52 263-72

Lavelle P 1983 The structure of earthworm communities (Netherlands: Springer)

Qi Y C and Wei C 2010 Comparison of earthworm bioaccumulation between readily desorbable and desorption-resistant naphthalene: implications for biouptake routes Environ. Sci. Technol. 44 323-28

Assess. 187 4119

[4] Vácha R, Skála J, Čechmánková J, Horváthová V and Hladík J 2015 Toxic elements and persistent organic pollutants derived from industrial emissions in agricultural soils of the Northern Czech Republic J. Soils Sed. 15 1813-24

[5] Yuan G L, Wu H Z, Fu S, Han P and Lang X X 2014 Persistent organic pollutants (POPs) in the topsoil of typical urban renewal area in Beijing, China: Status, sources and potential risk J. Geochem. Explor. 138 94-103

[6] Liu X, Xu X, Li C, Zhang H, Fu Q, Shao X, Ye Q and Li Z 2015 Assessment of the environmental fate of cycloxaiprid in flooded and anaerobic soils by radioisotopic tracing Sci. Total Environ. 543 116

[7] Ambrosi D, Kearney P C and Macchia J A 2002 Persistence and metabolism of oxadiazon in soils Journal of Agricultural & Food Chemistry 25 868-72

[8] Gao Y, Zeng Y, Shen Q, Ling W and Han J 2009 Fractionation of polycyclic aromatic hydrocarbon residues in soils J. Hazard. Mater. 172 897-903

[9] Macleod C J A and Semple K T 2000 Influence of Contact Time on Extractability and Degradation of Pyrene in Soils Environ. Sci. Technol. 34 4952-57

[10] Macleod C J A and Semple K T 2003 Sequential extraction of low concentrations of pyrene and formation of non-extractable residues in sterile and non-sterile soils Soil Biol Biochem 35 1443-50

[11] Ncibi M C, Mahjoub B and Gourdon R 2007 Effects of aging on the extractability of naphthalene and phenanthrene from Mediterranean soils J. Hazard. Mater. 146 378-84

[12] Zhang J J, Wen B, Shan X Q, Zhang S and Khan S U 2007 Temporal change in the distribution patterns of hexachlorobenzene and dichlorodiphenyltrichloroethane among various soil organic matter fractions Environ. Pollut. 150 234-42

[13] Xing B S and Pignatello J J 1997 Dual-Mode Sorption of Low-Polarity Compounds in Glassy Poly(Vinyl Chloride) and Soil Organic Matter Environ. Sci. Technol. 31 792-99

[14] Lebeuf E J and Weber W J J 2000 Macromolecular Characteristics of Natural Organic Matter. 2. Sorption and Desorption Behavior Environ. Sci. Technol. 34 3632-40

[15] Cornelissen G, Rigterink H, Ferdinandy M M A and Noort P C M V 1998 Rapidly desorbinding fractions of PAHs in contaminated sediments as a predictor of the extent of bioremediation Environ. Sci. Technol. 32 966-70

[16] Cornelissen G, Noort P C M V, Govers H A J 1998 Mechanism of Slow Desorption of Organic Compounds from Sediments: A Study Using Model Sorbents Environ Sci Technol 32

[17] Xing B S and Pignatello J J 2010 Time-dependent isotherm shape of organic compounds in soil organic matter: Implications for sorption mechanism Environ. Toxicol. Chem. 15 1282-88

[18] Hickman Z A and Reid B J 2008 Earthworm assisted bioremediation of organic contaminants Environ. Int. 34 1072-81

[19] Mougin C, Chevrier N, Repincay C, Hedde M and Hernandez-Raquet G 2013 Earthworms highly increase ciprofloxacin mineralization in soils Environmental Chemistry Letters 11 127-33

[20] Lavelle P 1997 Faunal activities and soil processes: adaptive strategies that determine ecosystem function Adv. Ecol. Res. 27 93-132

[21] Römcke J, Jänsch S and Didden W 2005 The use of earthworms in ecological soil classification and assessment concepts Ecotoxicol. Environ. Saf. 62 249-65

[22] Butenschoen O, Marhan S, Langel R and Scheu S 2009 Carbon and nitrogen mobilisation by earthworms of different functional groups as affected by soil sand content Pedobiologia 52 263-72

[23] Lavelle P 1983 The structure of earthworm communities (Netherlands: Springer)

[24] Qi Y C and Wei C 2010 Comparison of earthworm bioaccumulation between readily desorbable and desorption-resistant naphthalene: implications for biouptake routes Environ. Sci. Technol. 44 323-28
[25] Shan J, Wang T, Li C L, Klumpp E and Ji R 2010 Bioaccumulation and bound-residue formation of a branched 4-nonylphenol isomer in the geophagous earthworm Metaphire guillelmi in a rice paddy soil Envion. Sci. Technol. 44 4558-63
[26] Katheem K S and Ibrahim M H et al 2016 General Introduction to Earthworms, Their Classifications, and Biology
[27] Voparil I M and Mayer L M 2000 Dissolution of Sedimentary Polycyclic Aromatic Hydrocarbons into the Lugworm's (Arenicola marina) Digestive Fluids Environ. Sci. Technol. 34 307-53
[28] Wang F, Ji R, Jiang Z and Chen W 2014 Species-dependent effects of biochar amendment on bioaccumulation of atrazine in earthworms Environ. Pollut. 186C 241-47
[29] Rouse J D, Sabatini D A, Sulfia J M and Harwell J H 1994 Influence of surfactants on microbial degradation of organic compounds Crit. Rev. Environ. Sci. Technol. 24 325-70
[30] White J C, Peters R and Kelsey J W 2007 Surfactants differentially impact p,p'-DDE accumulation by plant and earthworm species Environ. Sci. Technol. 41 2922-29
[31] Aronstein B N, Calvillo Y M and Alexander M 1991 Effect of surfactants at low concentrations on the desorption and biodegradation of sorbed aromatic compounds in soil Environ. Sci. Technol. 25:10 1728-31
[32] Lawrence M M, Zhen C, Robert H F, Jia S F, Stephen S, Robert F L, Jumars P A, Christophe Q and Olivier F X D 1996 Bioavailability of Sedimentary Contaminants Subject to Deposit-Feeder Digestion Environ. Sci. Technol. 30 2641-45
[33] Ahrens M J, Hertz J, Lamoureux E M, Lopez G R, Mcelroy A E and Brownawell B J 2001 The role of digestive surfactants in determining bioavailability of sediment-bound hydrophobic organic contaminants to 2 deposit-feeding polychaetes Marine Ecology Progress 212 145-57
[34] Shan J, Brune A and Ji R 2010 Selective digestion of the proteinaceous component of humic substances by the geophagous earthworms Metaphire guillelmi and Amyntas corrugatus Soil Biol. Biochem. 42 1455-62
[35] Tikhonov V V, Byzo B A, Iua Z and Demin V V 2011 Earthworms as modifiers of the structure and biological activity of humic acids Biol. Bull. 38 24-32
[36] Frouz J, Li X, Brune A, Pizl V and Abakumov E V 2011 Effect of soil invertebrates on the formation of humic substances under laboratory conditions Eurasian Soil Sci 44 893-96
[37] Mersie W and Seybold C 1996 Adsorption and desorption of atrazine, deethylatrazine, desisopropylatrazine, and hydroxyatrazine on Levy wetland soil Journal of Agricultural & Food Chemistry 44 1925-29
[38] Byzo B A, Tikhonov V V, Nechitailo T Y and Demin V V 2015 Taxonomic composition and physiological and biochemical properties of bacteria in the digestive tracts of earthworms Eurasian Soil Sci 48 268-75
[39] Trigo D, Barois I, Garvin M H, Huerta E, Irisson S and Lavelle P 1999 Mutualism between earthworms and soil microflora Pedobiologia 43 866-73
[40] Byzo B A, Khomyakov N V, Kharin S A and Kurakov A V 2007 Fate of soil bacteria and fungi in the gut of earthworms Eur J Soil Biol 43 S149-56