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ORIGINAL ARTICLE

A review of POPs in the fragile critical zone of the Tibetan Plateau: transport and transformation

Jun Li[1,2] · **Guoli Yuan**[1,2]

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Abstract The near-surface environment of the Tibetan Plateau is a fragile critical zone. Our understanding of the transport and transformation of persistent organic pollutants (POPs) in the ecosystem has significantly improved with research conducted in recent decades. In the current study, POP concentrations in soils logarithmically decreased and fractionated with increasing distance from the source area, patterns attributed to air–soil exchange. Transport from soils resulted in the enrichment of POP concentrations in plants and sediments. The enantiomeric fraction indicated that transformation of POPs in soils was significantly correlated with altitude. At the same time, the chiral signature of POPs in soils was maintained from soils to sediments, while the chiral transformation from soils to plants was found to be complex.

Keywords Tibetan Plateau · Critical zone · Transport · Transformation · POPs

1 Introduction

Extensive and increasing human activity produce chemical pollutants that have long-lasting effects on the near-surface environment, which was recently termed Earth's "critical zone" (CZ) (Brantley et al. 2007). These persistent pollutants are transported between media of plant–soil–sediment by aqueous and biological dynamics, which drive cycling of chemicals across the CZ (Mobley 2009). As "the third pole" of the earth, with elevations above 4000 m, the Tibetan Plateau (TP) includes unique geographical conditions and vast frozen ground, which combine to form an isolated groundwater system lacking hydraulic connections with other water sources (Cheng and Jin 2013). The surface ecosystems of the TP are especially sensitive and vulnerable to anthropogenic disturbance. Environmental pollution in the fragile CZ of the TP merits focused study, owing to its differences from karst or loess systems.

Persistent organic pollutants (POPs) are semi-volatile, bioaccumulative, and toxic. Due to long-range atmospheric transport (LRAT) and cold condense, they can reach and affect the CZ of the TP (Yuan et al. 2014c, 2015a). Soils, especially surface soils in which air–soil exchange occurs, are the major reservoirs of POPs in the terrestrial environment (Yuan et al. 2015b). Measurement of POPs in soils of the TP provides a signature to trace their source and pathways in the CZ (Yuan et al. 2015b). POP sinking in soils have been found to be a secondary source (Yuan et al. 2014c), leading researchers to investigate the POP contribution of the soil–plant or soil–sediment system and its transformation in the CZ of the TP (Yuan et al. 2014c, 2015c). Herein, much attention is paid to the environmental processes of POPs, such as transport and transformation. Study of POPs in the fragile CZ helps improve understanding of the behavior of pollutants in the global cycle.

2 Results and discussion

The sampling sites of 44 surficial soils across the TP, five surficial sediments, and eight associated catchment soils are shown in Fig. 1. The sampling and analytical methods

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✉ Guoli Yuan
yuangl@cugb.edu.cn

1 State Key Laboratory of Biogeology and Environmental Geology, China University of Geosciences, Beijing 100083, China

2 School of the Earth Sciences and Resources, China University of Geosciences, Beijing 100083, China

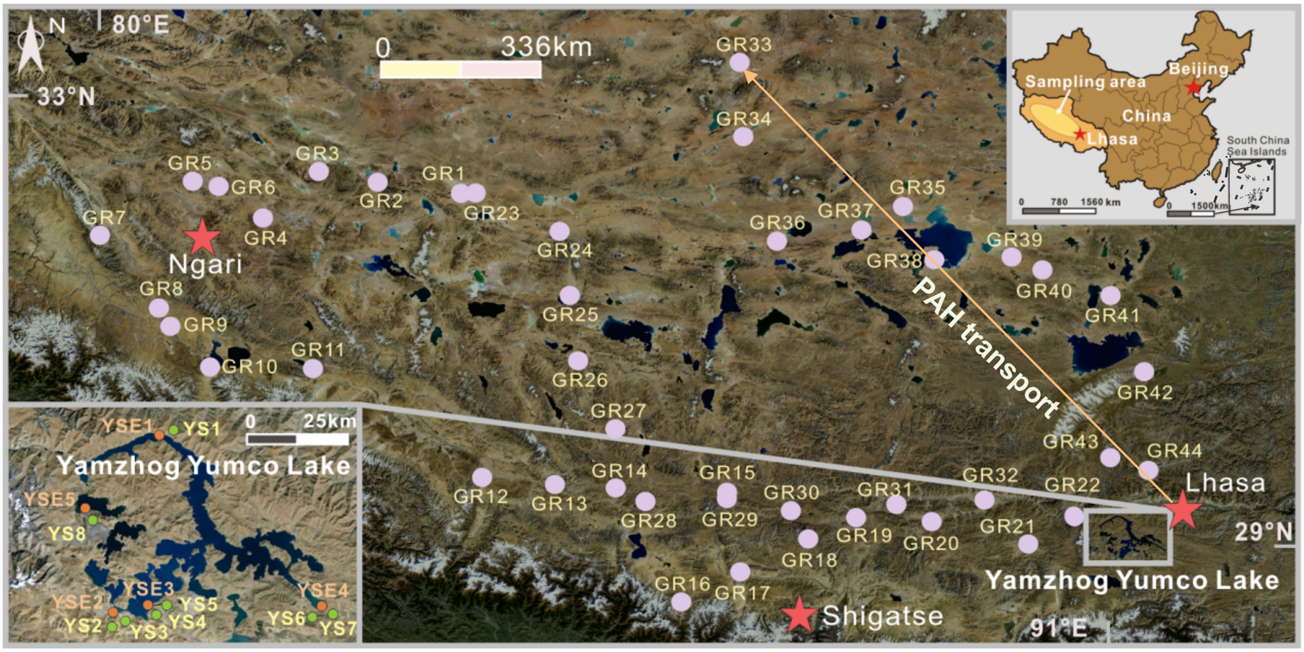

Fig. 1 Map showing sampling sites

are described in our previous reports (Yuan et al. 2014a, 2015c).

2.1 Transport pattern by air–soil exchange

In the TP, 10 samples were selected along a trajectory starting at the local source of Lhasa to study the transport of polycyclic aromatic hydrocarbons (PAHs; Fig. 1). As shown in Fig. 2, with increasing distance from Lhasa, total concentrations of PAHs logarithmically decreased and they were gradually fractionated. It could be concluded that the locally sourced PAHs migrated within the TP, but few were transported outside the TP in global cycling (Yuan et al. 2015b). A similar occurrence has been observed in a smaller area of the TP (Li et al. 2017a). Soil properties and altitude are important factors influencing the transport of pollutants (Yuan et al. 2012a, b, 2014a, b).

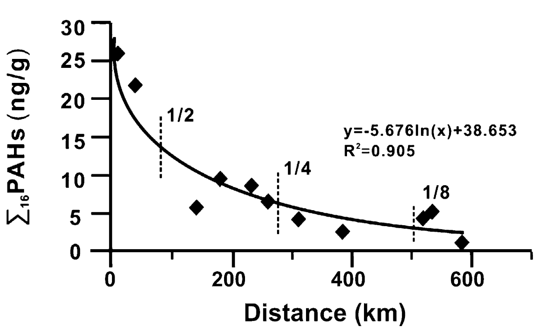

Fig. 2 The relationship between PAH concentration and distance from the source area

2.2 Transport from soils to plants

Investigations of POP levels in soils and plants can provide critical information for assessing transport from soil to plant (Yuan et al. 2015b). Compared to the concentrations in soils, an enrichment of organochlorine pesticides (OCPs) was observed in plants (Fig. 3). This result suggests the possible bioaccumulation of POPs in the food chain of the TP.

2.3 Transport from soils to sediments

As shown in Table 1, the concentrations of *trans*-chlordane (TC) and *cis*-chlordane (CC) in sediments were higher than those in soils of the catchment area. We attribute this to chlordane being preferentially adsorbed

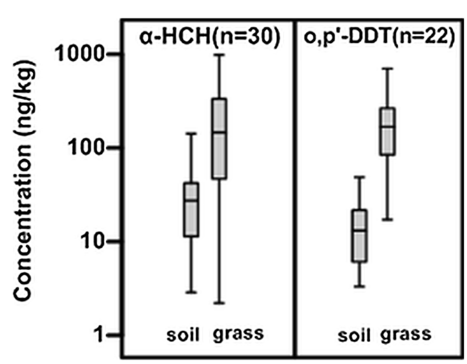

Fig. 3 Box plot distribution of α-HCH and *o,p*′-DDT concentrations in soil and grass samples

Table 1 Concentration (pg/g) and EF for samples of Yamzho Yumco lake

	Min	Max	Median	Mean	SD
Soil (n = 8)					
Conc.					
TC	16.8	23.7	19.3	19.7	2.3
CC	20.9	35.7	30.5	29.8	4.6
TC + CC	40.3	56.9	49.9	49.5	6.6
F_{TC}	0.350	0.481	0.405	0.400	0.042
EF					
TC	0.331	0.413	0.372	0.371	0.031
CC	0.498	0.599	0.552	0.549	0.039
Sediment (n = 5)					
Conc.					
TC	28.4	39.4	31.5	32.6	4.2
CC	43.7	60.3	45.4	48.7	6.9
TC + CC	75.0	93.4	77.9	81.3	6.6
F_{TC}	0.354	0.474	0.408	0.402	0.047
EF					
TC	0.357	0.378	0.369	0.368	0.008
CC	0.534	0.555	0.547	0.545	0.009

onto fine particles prior to being transported into the lake sediments (Yuan et al. 2015c). Since the fine particles from catchment soils are preferentially deposited as surficial sediments, POPs would certainly be found in higher concentrations in sediments compared to their source soils, similar to patterns resulting from a melting glacier (Li et al. 2017b). Nevertheless, the close values of TC/(TC + CC) between the soils and sediments indicate that the composition of chlordane did not vary greatly during surficial transport.

2.4 Transformation in soils

Enantiomeric fractions (EFs) of POPs have been used as a powerful tool to investigate POPs' environmental and biological transformation (Yuan et al. 2015a, c). In the TP, EFs of α-HCH and *o,p′*-DDT have been found to approach a racemic mixture as sampling altitude increases, up to approximately 4900 m (Yuan et al. 2014c). This observation is explained by microbial transformation weakening with decreasing air temperature (Li et al. 2017b). The relationship between EF and altitude has been observed for polychlorinated biphenyl as well (Yuan et al. 2015a). The study of chemical transformation in soils of the TP have found that clay serve as a catalyst for the transformation of polybrominated diphenyl ether (Sun et al. 2015).

2.5 Transformation in aquatic media and plants

For the soil–sediment system, the similar EF values (Table 1) show that the chiral signature in soils was maintained for TC and CC during the surficial transformation process from soils to sediments. This result suggests that the chiral signature coming from soils or other environmental media might be recorded in TP sediments, a finding that is quite different from that in the non-background regions (Ulrich et al. 2009) and that would be significant for further work since the sedimentary profile in the TP provides unique information to trace the sources and discuss the historical record of POPs (Yuan et al. 2015c).

For the soil–plant system, the predominant enantiomeric excess in grass was different from that in soils, either α-HCH or *o,p′*-DDT (Yuan et al. 2014c). Moreover, the EFs in grass were seldom associated with concentration, altitude, or soil properties (Yuan et al. 2014c). This suggests that the biological transformation of POPs in plants is complex and differs from that in soils.

3 Perspective

Although a series of POP researches have been conducted in the TP in recent decades, the fundamental processes influencing the transport and transformation of POPs in the fragile CZ are still not fully understood. For example, mobilization and degradation in the vertical distribution of POPs in the soils have not been determined in the TP, and POPs' response to intense climate change is still unclear. Further work is necessary to investigate the environmental and geochemical process of POPs in the TP CZ.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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