Characterization and speciation of mercury in mosses and lichens from the high-altitude Tibetan Plateau

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Abstract The accumulation and species of mercury (Hg) in mosses and lichens collected from high-altitude Tibetan Plateau were studied. The altitudes of the sampling sites spanned from 1983 to 5147 m, and a total of 130 mosses and 52 lichens were analyzed. The total mercury (THg) contents in mosses and lichens were in the ranges of 13.1–273.0 and 20.2–345.9 ng/g, respectively. The average ratios of methylmercury (MeHg) in THg in mosses and lichens were 2.4 % (0.3–11.1 %) and 2.7 % (0.4–9.6 %), respectively, which were higher than those values reported in other regions. The contents of THg in both mosses and lichens were not correlated with the THg in soils ($p > 0.05$). The lipid contents displayed a significantly positive correlation with concentrations of MeHg in mosses ($r = 0.461$, $p < 0.01$, $n = 90$), but not in lichens. The correlations between Hg contents in

mosses and the altitudes, latitudes and longitudes of sampling sites indicated the mountain trapping and spatial deposition of Hg in the Tibetan Plateau.

Keywords Moss · Lichen · Mercury · Methylmercury · Tibetan Plateau

Introduction

As a global pollutant, mercury (Hg) has the characteristics of persistence, bioaccumulation and toxicity (PBT). Elemental Hg has low vapor pressure and long residence time (0.5–2 years) in the atmosphere. Once emitted in the environment, Hg can undergo long-range transport and deposit to remote ecosystem (Fitzgerald et al. 1998; Miller et al. 2005) even in polar regions (Bargagli et al. 2005, 2007; Negri et al. 2006; Poissant et al. 2008) and high mountain areas. Due to their special geographic positions and environmental conditions, studying the cycling of Hg in remote or high-altitude regions is indispensable for understanding the global transport of Hg.

The Tibetan Plateau, located in the north of the Himalayas, is one of the most remote and high-altitude regions in the world. It is also called the “roof of the world” (with an average elevation of 4000 m above sea level) and one of the “three polar regions” (together with the Arctic and the Antarctic). Although

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there is little industry, relatively high levels of persistent organic pollutants (POPs) and heavy metals have been detected in various environmental matrices due to the mountain trapping effect in this high-altitude region (Sheng et al. 2013; Wang et al. 2014; Yang, et al. 2007, 2013). Therefore, Tibetan is an ideal site for studying the long-range atmospheric transport of semi-volatile pollutants (Cong et al. 2007).

Recently, unexpectedly high concentrations of Hg were also found in fish collected from Tibetan Plateau (Shao et al. 2016; Yang et al. 2011; Zhang et al. 2014). However, the studies are still limited, and fish can only reflect the contamination status in several specific aquatic ecosystems. For water and atmosphere, the low contents of Hg and the difficulties in sampling, preservation and detection make them not appropriate for a large-scale study. Up to now, neither accumulation nor Hg species in other biological samples from the Tibetan Plateau have been reported, which are imperative for further understanding the biogeochemical cycle of Hg in this typical region.

Mosses and lichens are geographically widespread and can grow even in cold and high-altitude mountain regions including the Tibetan Plateau. Because they have enough abundance and wide distribution for repetitive sampling and comparison and can accumulate high levels of pollutants exceeding their metabolic requirements (Backor and Loppi 2009), mosses and lichens are ideal samples to study the contamination in typical regions, where large-scale sampling is difficult and expensive. As mosses and lichens do not have roots, they absorb most nutrients from the atmosphere and take up negligible amounts of water and minerals from soil. This makes both biota more suitable for indicating the source and sink of atmospheric pollutants, including Hg (Bargagli et al. 2002; Bergamaschi et al. 2002; Onianwa 2001; Sardans and Penuelas 2005; Schintu et al. 2005; Vannini et al. 2014; Zechmeister et al. 2003).

The aims of this work were to study the accumulation and species of Hg in mosses and lichens collected from the Tibetan Plateau and their implications for indicating related deposition of Hg. The altitude of the sampling sites spanned from 1983 to 5147 m, and corresponding soil samples were also investigated. To our knowledge, this is the first large-scale studying Hg accumulation in vegetation samples from Tibet and provides a basis for further study of Hg contamination in this high-altitude region.

Materials and methods

Sample collection

A map of the study area and the sampling sites are shown in Fig. 1. A total of 130 mosses (*Bryopsida*), 52 lichens (*Usnealongissima* Ach.) and 146 soil samples were collected from 160 sites of the Tibetan Plateau in June of 2010, 2011 and 2012. At each site, samples were collected using a stainless steel spade. Surface soil samples were collected in the depth of 0–5 cm. All samples were sealed in clean polyethylene bags and carried back to the laboratory immediately. The green shoots of mosses and the outermost portion of the lichens were kept and rinsed with deionized water before pretreatment. All samples were freeze-dried, ground and then kept at -20°C until analysis. In addition, the soil samples were passed through a 100-mesh sieve.

Determination of total mercury (THg), methylmercury (MeHg) and lipid contents

Using a Hydra II-C atomic absorption spectrometer (Teledyne Leeman Labs, Hudson, USA), the contents of THg in solid samples could be automatically burned and determined without further pretreatment. For soil samples, about 0.25 g ground sample was weighed in a nickel boat and then analyzed directly. For mosses and lichens, about 0.05 g sample was weighed because the relatively high lipid content may cause matrix effects.

For MeHg analysis, about 0.2 g sample was weighed into an 8-mL brown glass tube and 2 mL 25 % (m/v) KOH/CH₃OH solution was added. The mixture was mechanically shaken for 4 h at 37 °C and 240 rpm. After cooling down, the solution was centrifuged at 3000 rpm for 20 min. Then, 0.15 mL of solution was transferred into the autosampler vial and ethylated by sodium tetraethyl borate (NaBET₄). The concentration of MeHg was determined by purge and trap gas chromatography-atomic fluorescence spectrometry (GC-AFS) method with a MERX Automatic Methylmercury System (Brooks Rand Laboratories, Seattle, WA). The concentrations of inorganic mercury (IHg) were calculated by subtracting the contents of MeHg from THg.

The lipid contents of mosses and lichens were determined gravimetrically. Two grams mosses or lichens and 10 g anhydrous sodium sulfate were

Fig. 1 Map of the study area **Table 1** Results of THg and MeHg in certified reference materials (CRMs) (ng/g, $n = 5$)

CRMs	THg			MeHg		
	Certified	Determined	Recovery (%)	Certified	Determined	Recovery (%)
GBW07312 (sediment)	56 ± 6	54.7 ± 1.8	97.7 ± 3.2	—	—	—
GBW10020 (citrus leaf)	150 ± 20	149.8 ± 2.8	99.9 ± 1.9	—	—	—
TORT-2 (lobster)	270 ± 60	263.0 ± 15.0	97.4 ± 5.6	152 ± 13	169.9 ± 4.2	111.8 ± 2.8
DORM-4 (fish)	410 ± 55	373.2 ± 2.0	91.0 ± 0.5	354 ± 31	335.3 ± 11.7	94.7 ± 3.3

extracted using mixed solvents of hexane and dichloromethane (1:1, v/v) by accelerated solvent extraction (Dionex ASE 300, USA) at a temperature of 120 °C and a pressure of 1200 psi. The equilibration time was 10 min, and the extractions were performed for 3 cycles. The extraction was transferred into a clean and dry round-bottom flask (m_1) and subsequently concentrated on a rotary evaporator and with a high-purity nitrogen stream. The round-bottom flask was left overnight until constant weight and then weighted (m_2). The lipid content was calculated with the following equation (Staël and Ronald 1994):

$$\text{The lipid content} = (m_2 - m_1) / m_{\text{sample}}$$

Quality assurance/quality control (QA/QC)

For the analytical quality control, reagent blanks, certified reference materials (CRMs) and samples replicates were inserted in the analysis at set intervals. The analyzed values were in good agreement with the certified values (Table 1). Due to lack of plant CRMs for MeHg, 0.2 mL of 1 ng/mL MeHg standard solutions was spiked into the moss and lichen samples before extraction and the spiked recoveries of the entire method were between 85 and 107 %, indicating the accuracy of the method. The reproducibility of the spiked recoveries was also satisfied.

Statistical analysis

In order to extract information from the chemical analysis, multiple statistical analyses were performed with SPSS 20.0. A test of normality was executed to check the normal distribution of the analytical data. Under the premise of lacking of normality, Spearman's correlation was used for correlation analysis. Independent samples test and paired samples test were applied to assess the significant difference in comparisons.

Results and discussion

THg and MeHg in mosses, lichens and soils

The concentrations of THg in moss, lichen and soil samples were in the range of 13.1–273.0 ng/g (average: 53.5 ng/g), 20.2–345.9 ng/g (average: 77.7 ng/g) and 5.6–388.2 ng/g (average: 42.3 ng/g), respectively. As a whole, the contents of THg in mosses and soils from Tibet were in the same order of magnitude with those from the Antarctica and the Arctic, while the THg in lichens were much lower than those from the Antarctic (Table 2). The average content of Hg in the Earth's crust was about 50 ng/g dry wt (Bargagli et al. 2005, 2007). According to the results investigated by the China National Environmental Monitoring Center in 1980s, the China national average concentration of Hg in topsoil was 0.065 mg/kg (range 0.001–45.9 mg/kg) (Wei et al. 1991). Several recent studies showed that the average concentration of Hg in soils from the Tibetan Plateau was 26 ng/g (Table 2) (Zhang 1994; Zhang et al. 2002; Zhu et al. 2014). Compared with these results, the average concentration of Hg in soils collected in this work was still in a relatively low level.

The concentrations of MeHg in mosses and lichens were in the range of 0.1–6.1 ng/g (average: 1.1 ng/g) and 0.3–5.5 ng/g (average: 1.5 ng/g), respectively. The MeHg contents were positively correlated with THg concentrations both in mosses ($r = 0.505$, $p < 0.01$, $n = 130$) and in lichens ($r = 0.342$, $p < 0.05$, $n = 52$). The mean ratios of MeHg in THg in mosses and lichens were 2.4 % (0.3–11.1 %) and 2.7 % (0.4–9.6 %), respectively, which were higher than those reported values in mosses and lichens from other regions (Hall and Louis 2004; Lupsina et al. 1992). This is probably because ultraviolet (UV)

Table 2 Comparison of THg and MeHg in soils, mosses and lichens from different regions (ng/g, dw)

Region	Soil	Moss		Lichen		References
		THg	MeHg	THg	MeHg/THg	
Antarctic	–	68 (27–570)	–	358 (90–1661)	–	Bargagli et al. (2005)
Antarctic	24.6	31.3	–	–	–	Dos Santos (2006)
Antarctic	12.7	–	–	–	–	Bargagli et al. (2007)
Arctic	–	130	–	–	–	Bargagli et al. (1995)
Arctic	–	55–156	–	–	–	Bargagli et al. (1998)
Ontario, Canada	–	64.6–93.9	0.4–1.43	33.17	0.56	Hall and Louis (2004)
Tibetan Plateau	26 (6–73)	–	–	–	–	Zhang (1994)
Tibetan Plateau	26	–	–	–	–	Zhang et al. (2002)
Tibetan Plateau	26 (15–563)	–	–	–	–	Zhu et al. (2014)
Tibetan Plateau	42.3 (5.6–388.2)	53.5 (13.1–273.0)	1.1 (0.1–6.1)	77.7 (20.2–345.9)	1.5 (0.3–5.5)	This study

radiation increases with altitudes (Dahlback et al. 2007) and the UV radiation in the high-altitude Tibet is relatively strong (Ren et al. 1997), which can oxidize gaseous elemental Hg to divalent reactive gaseous mercury more easily and accelerate the methylation of gaseous elemental Hg (Lalonde et al. 2001). This has been demonstrated in surface water of lakes in Kejimikujik, Canada, where the concentration of MeHg was the highest in the early afternoon because the UV light was the strongest at that time (Siciliano et al. 2005). As a result, the mosses and lichens in Tibet may accumulate relatively high ratio of MeHg.

Factors affecting Hg accumulation in mosses and lichens

In order to find the factors affecting Hg accumulation in mosses and lichens, soil samples from the same sites were also collected and analyzed. As shown in Table 2, the concentrations of THg in soils ranged from 5.6 ng/g to 388.2. However, the THg contents in mosses and lichens were not correlated with the THg in soils ($p > 0.05$), demonstrating that the soil is not the main source of Hg in mosses and lichens. This could be explained by mosses and lichens absorbing most nutrients from the atmosphere instead of the soils and agrees with previous studies (Bargagli et al. 2002; Onianwa 2001; Sardans and Penuelas 2005; Schintu et al. 2005; Zechmeister et al. 2003).

Because of the lipophilicity of MeHg, it accumulates generally easier in higher lipid organisms. The contents of lipid in mosses and lichens were in the range of 0.48–7.21 % (average: 2.90 %) and 3.33–32.74 % (average: 14.49 %). Unexpectedly, the concentrations of MeHg in lichens were not correlated with the lipid contents ($r = -0.084$, $p > 0.05$, $n = 48$), although they contained more lipid than mosses. On the contrary, the concentrations of MeHg displayed a significantly positive correlation with lipid contents in mosses ($r = 0.461$, $p < 0.01$, $n = 90$). In addition, the THg and IHg contents in both mosses and lichens showed no significant correlation with the lipid contents ($p > 0.05$).

The spatial distribution of THg, MeHg and IHg in mosses

Because the collected lichens were anchored on barks or twigs, the spatial distribution of lichens and available sampling sites in the Tibet are limited.

Therefore, correlations between THg, MeHg and IHg in lichens and altitudes, longitudes and latitudes of the sampling sites were not statistically analyzed. Only the correlations between these parameters of sampling sites and Hg in mosses were further investigated.

In high mountain regions, altitude is an important factor influencing the distribution of Hg due to the mountain trapping (Zhang et al. 2013). In this work, all the concentrations of THg ($r = 0.362$, $p < 0.01$, $n = 130$), MeHg ($r = 0.281$, $p < 0.01$, $n = 130$) and IHg ($r = 0.378$, $p < 0.01$, $n = 130$) in mosses showed significantly positive correlations with the altitudes of sampling sites (Table 3; Fig. 2). The increasing rates of concentrations along with altitudes were 1.52, 1.07 and 1.49 ng/g per 100 m for THg, MeHg and IHg in mosses. This could be attributed to the mountain trapping effect of Hg and was in agreement with other studies (Zhang et al. 2013). Normally, Hg can undergo long-range atmospheric transport and be deposited to remote places and high-altitude mountainous areas. The more frequent precipitation in higher elevations would result in greater Hg wet deposition. Thus, the concentrations of THg, MeHg and IHg in mosses increased with the increasing altitudes of the sampling sites.

The concentrations of THg, MeHg and IHg in mosses displayed a significantly negative correlation with the longitudes of the sampling sites (for THg, $r = -0.489$, $p < 0.01$, $n = 130$; for MeHg, $r = -0.495$, $p < 0.01$, $n = 130$; for IHg, $r = -0.479$, $p < 0.01$, $n = 130$) (Table 3). This suggested that the contents of THg, MeHg and IHg in mosses decreased from west to east, which were consistent with the distribution pattern of organochlorine pesticides (OCPs) (Yang et al. 2013) and heavy metals (Cong et al. 2007), indicating the atmospheric transport of Hg to Tibet.

The correlations between the latitudes of the sampling sites and the concentrations of THg, MeHg and IHg in mosses were also investigated. The latitudes showed little effects on the THg and IHg concentrations in mosses ($p > 0.05$), probably because of the relatively smaller range of latitudes of the sampling sites (N28.5160°–31.1409°). We also noticed that the MeHg contents in mosses showed a significantly negative correlation with the latitudes of the sampling sites ($r = -0.308$, $p < 0.01$, $n = 130$). Because the factors regulating the distribution of MeHg in mosses are complex, further studies are needed to explain this correlation.

Table 3 Correlations of THg, MeHg and IHg contents in mosses with the lipid, altitude, longitude and latitude

	THg	MeHg	IHg
Lipid	−0.09 ($n = 90$)	0.392** ($n = 90$)	−0.109 ($n = 90$)
Altitude	0.362** ($n = 130$)	0.281** ($n = 130$)	0.378** ($n = 130$)
Longitude	−0.489** ($n = 130$)	−0.495** ($n = 130$)	−0.479** ($n = 130$)
Latitude	−0.124 ($n = 130$)	−0.308** ($n = 130$)	−0.116 ($n = 130$)

** Correlation is significant at the 0.01 level (two-tailed)

* Correlation is significant at the 0.05 level (two-tailed)

Fig. 2 Spatial distributions of THg, MeHg and IHg in mosses

Environmental implications

As the “roof of the world,” Tibet is an ideal and indispensable area for studying the long-range atmospheric transport of Hg. However, due to the extremely harsh environmental conditions and the

difficulties in sampling, the large-scale study about the biogeochemical cycle of Hg in this high-altitude and mountainous region is difficult.

As a scientific and effective approach, bioindication has been widely applied for assessing the contamination and toxic effects of Hg and other

pollutants in the environment (Vannini et al. 2014; Zhou et al. 2008). By analyzing appropriate bioindicators, the high cost and difficulties in sampling could be avoided for studying Hg pollution in harsh environments. Some organisms have been successfully used for Hg bioindication, such as macroalgae (Cairrao et al. 2007), oyster (Vaisman et al. 2005), *Halimione portulacoides* (Válega et al. 2008) and mussel (Blackwell et al. 2013). However, the use of these indicators is impracticable for studying the environmental behavior of Hg in Tibet.

Mosses and lichens are geographically widespread and can grow even in cold and high-altitude regions including Tibetan Plateau. They have also been suggested to be used as bioindicators of Hg (Bargagli et al. 2005, 2007; Bergamaschi et al. 2002). In this work, the contents of THg, MeHg and IHg in mosses reflected the geographic variations and the mountain trapping of Hg in the high-altitude Tibetan Plateau, indicating the potential application of moss as bioindicator of Hg in the Tibetan Plateau. However, the species is an important factor influencing the accumulation of Hg in moss due to the different metabolic and morphological characteristics of various moss species (Bargagli et al. 2002; Onianwa 2001; Vannini et al. 2014). In this work, the altitude of the sampling sites spanned from 1983 to 5147 m and it is difficult to ensure a single species in all sampling sites. Thus, the collected mosses were not differentiated at the species level. In addition, the mechanism and processes of Hg accumulation in moss are complicated and much still remain unknown. Further studies are necessary to be done in the future.

Conclusions

Due to the special geographic position and the environmental conditions, the accumulation and biogeochemical cycling of Hg in Tibetan Plateau may differ from other regions, which is indispensable for understanding the long-range transport of Hg. The contents of THg in both mosses and lichens were not correlated with the THg in soils ($p > 0.05$). The lipid contents displayed a significantly positive correlation with concentrations of MeHg in mosses ($r = 0.461$, $p < 0.01$, $n = 90$), but not in lichens. Meanwhile, the contents of THg, MeHg and IHg in mosses reflected the geographic

variations and the mountain trapping of Hg in the high-altitude Tibetan Plateau.

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References

- Backor, M., & Loppi, S. (2009). Interactions of lichens with heavy metals. *Biologia Plantarum*, 53(2), 214–222.
- Bargagli, R., Brown, D. H., & Nelli, L. (1995). Metal biomonitoring with mosses: Procedures for correcting for soil contamination. *Environmental Pollution*, 89(2), 169–175.
- Bargagli, R., Sanchez-Hernandez, J. C., Martella, L., & Monaci, F. (1998). Mercury, cadmium and lead accumulation in Antarctic mosses growing along nutrient and moisture gradients. *Polar Biology*, 19(5), 316–322.
- Bargagli, R., Agnorelli, C., Borghini, F., & Monaci, F. (2005). Enhanced deposition and bioaccumulation of mercury in Antarctic terrestrial ecosystems facing a coastal polynya. *Environmental Science and Technology*, 39(21), 8150–8155.
- Bargagli, R., Monaci, F., Borghini, F., Bravi, F., & Agnorelli, C. (2002). Mosses and lichens as biomonitors of trace metals. A comparison study on *Hypnum cupressiforme* and *Parmelia caperata* in a former mining district in Italy. *Environmental Pollution*, 116(2), 279–287.
- Bargagli, R., Monaci, F., & Bucci, C. (2007). Environmental biogeochemistry of mercury in Antarctic ecosystems. *Soil Biology & Biochemistry*, 39(1), 352–360.
- Bergamaschi, L., Rizzio, E., Valcuvia, M. G., Verza, G., Profumo, A., & Gallorini, M. (2002). Determination of trace elements and evaluation of their enrichment factors in Himalayan lichens. *Environmental Pollution*, 120(1), 137–144.
- Blackwell, B. D., Driscoll, C. T., Spada, M. E., Todorova, S. G., & Montesdeoca, M. R. (2013). Evaluation of zebra mussels (*Dreissena polymorpha*) as biomonitors of mercury contamination in aquatic ecosystems. *Environmental Toxicology and Chemistry*, 32(3), 638–643.
- Cairrao, E., Pereira, M. J., Pastorinho, M. R., Morgado, F., Soares, A. M. V. M., & Guilhermino, L. (2007). *Fucus* spp. as a mercury contamination bioindicator in coastal areas (Northwestern Portugal). *Bulletin of Environmental Contamination and Toxicology*, 79(4), 388–395.
- Cong, Z. Y., Kang, S. C., Liu, X. D., & Wang, G. F. (2007). Elemental composition of aerosol in the Nam Co region, Tibetan Plateau, during summer monsoon season. *Atmospheric Environment*, 41(6), 1180–1187.
- Dahlback, A., Gelsor, N., Stamnes, J. J., & Gjessing, Y. (2007). UV measurements in the 3000–5000 m altitude region in Tibet. *Journal of Geophysical Research-Atmospheres*, 112(D9).
- dos Santos, I. R., Silva-Filho, E. V., Schaefer, C., Maria Sella, S., Silva, C. A., Gomes, V., Passos, M. J., & Van Ngan, P. (2006). Baseline mercury and zinc concentrations in terrestrial and coastal organisms of Admiralty Bay, Antarctica. *Environmental Pollution*, 140(2), 304–311.

- Fitzgerald, W. F., Engstrom, D. R., Mason, R. P., & Nater, E. A. (1998). The case for atmospheric mercury contamination in remote areas. *Environmental Science and Technology*, 32(1), 1–7.
- Hall, B. D., & Louis, V. L. S. (2004). Methylmercury and total mercury in plant litter decomposing in upland forests and flooded landscapes. *Environmental Science and Technology*, 38(19), 5010–5021.
- Lalonde, J. D., Amyot, M., Kraepiel, A. M. L., & Morel, F. M. M. (2001). Photooxidation of Hg(0) in artificial and natural waters. *Environmental Science and Technology*, 35(7), 1367–1372.
- Lupsina, V., Horvat, M., Jeran, Z., & Stegnar, P. (1992). Investigation of mercury speciation in lichens. *Analyst*, 117(3), 673–675.
- Miller, E., Vanarsdale, A., Keeler, G., Chalmers, A., Poissant, L., Kamman, N., & Brulotte, R. (2005). Estimation and mapping of wet and dry mercury deposition across north-eastern north America. *Ecotoxicology*, 14(1–2), 53–70.
- Negri, A., Burns, K., Boyle, S., Brinkman, D., & Webster, N. (2006). Contamination in sediments, bivalves and sponges of McMurdo Sound, Antarctica. *Environmental Pollution*, 143(3), 456–467.
- Onianwa, P. C. (2001). Monitoring atmospheric metal pollution: A review of the use of mosses as indicators. *Environmental Monitoring and Assessment*, 71(1), 13–50.
- Poissant, L., Zhang, H. H., Canário, J., & Constant, P. (2008). Critical review of mercury fates and contamination in the arctic tundra ecosystem. *Science of the Total Environment*, 400(1–3), 173–211.
- Ren, P. B. C., Sigernes, F., & Gjessing, Y. (1997). Ground-based measurements of solar ultraviolet radiation in Tibet: Preliminary results. *Geophysical Research Letters*, 24(11), 1359–1362.
- Sardans, J., & Penuelas, J. (2005). Trace element accumulation in the moss *Hypnum cupressiforme* Hedw. and the trees *Quercus ilex* L. and *Pinus halepensis* Mill. in Catalonia. *Chemosphere*, 60(9), 1293–1307.
- Schintu, M., Cogoni, A., Durante, L., Cantaluppi, C., & Contu, A. (2005). Moss (*Bryum radiculosum*) as a bioindicator of trace metal deposition around an industrialised area in Sardinia (Italy). *Chemosphere*, 60(5), 610–618.
- Shao, J. J., Shi, J. B., Duo, B., Liu, C. B., Gao, Y., Fu, J. J., et al. (2016). Mercury in alpine fish from four rivers in the Tibetan Plateau. *Journal of Environmental Sciences*, 39, 22–28.
- Sheng, J. J., Wang, X. P., Gong, P., Joswiak, D. R., Tian, L., Yao, T. D., & Jones, K. C. (2013). Monsoon-driven transport of organochlorine pesticides and Polychlorinated Biphenyls to the Tibetan Plateau: three year atmospheric monitoring study. *Environmental Science and Technology*, 47(7), 3199–3208.
- Siciliano, S. D., O'Driscoll, N. J., Tordon, R., Hill, J., Beauchamp, S., & Lean, D. R. S. (2005). Abiotic production of methylmercury by solar radiation. *Environmental Science and Technology*, 39(4), 1071–1077.
- Stacl, L. S., & Ronald, A. H. (1994). Vegetation-atmosphere partitioning of polycyclic aromatic hydrocarbons. *Environmental Science and Technology*, 28(5), 939–943.
- Vaisman, A. G., Marins, R. V., & Lacerda, L. D. (2005). Characterization of the mangrove oyster, *Crassostrea rhizophorae*, as a biomonitor for mercury in tropical estuarine systems, northeast Brazil. *Bulletin of Environmental Contamination and Toxicology*, 74(3), 582–588.
- Válega, M., Lillebø, A. I., Pereira, M. E., Caçador, I., Duarte, A. C., & Pardal, M. A. (2008). Mercury in salt marshes ecosystems: *Halimione portulacoides* as biomonitor. *Chemosphere*, 73(8), 1224–1229.
- Vannini, A., Nicolardi, V., Bargagli, R., & Loppi, S. (2014). Estimating atmospheric mercury concentrations with lichens. *Environmental Science and Technology*, 48(15), 8754–8759.
- Wang, X. P., Halsall, C., Codling, G., Xie, Z. Y., Xu, B. Q., Zhao, Z., et al. (2014). Accumulation of perfluoroalkyl compounds in Tibetan Mountain snow: Temporal patterns from 1980 to 2010. *Environmental Science and Technology*, 48(1), 173–181.
- Wei, F. S., Chen, J. S., Wu, Y. Y., & Zheng, C. J. (1991). Study on soil background values of China. *Environ Sci*, 12(4), 12–19. (in Chinese).
- Yang, R. Q., Jing, C. Y., Zhang, Q. H., Wang, Z. H., Wang, Y. W., Li, Y. M., & Jiang, G. B. (2011). Polybrominated diphenyl ethers (PBDEs) and mercury in fish from lakes of the Tibetan Plateau. *Chemosphere*, 83(6), 862–867.
- Yang, R. Q., Yao, T. D., Xu, B. Q., Jiang, G. B., & Xin, X. D. (2007). Accumulation features of organochlorine pesticides and heavy metals in fish from high mountain lakes and Lhasa River in the Tibetan Plateau. *Environment International*, 33(2), 151–156.
- Yang, R. Q., Zhang, S. J., Li, A., Jiang, G. B., & Jing, C. Y. (2013). Altitudinal and spatial signature of persistent organic pollutants in soil, lichen, conifer needles, and bark of the southeast Tibetan Plateau: Implications for sources and environmental cycling. *Environmental Science and Technology*, 47(22), 12736–12743.
- Zechmeister, H. G., Hohenwallner, D., Riss, A., & Hanus-Ilmar, A. (2003). Variations in heavy metal concentrations in the moss species *Abietinella abietina* (Hedw.) Fleisch according to sampling time, within site variability and increase in biomass. *Science of the Total Environment*, 301(1–3), 55–65.
- Zhang, X. P. (1994). Research on the environmental background values of soils in Xizang. *Scientia Geographica Sinica*, 14(1), 49–55.
- Zhang, X. P., Deng, W., & Yang, X. M. (2002). The background concentrations of 13 soil trace elements and their relationships to parent materials and vegetation in Xizang (Tibet), China. *Journal of Asian Earth Sciences*, 21, 167–174.
- Zhang, Q. G., Pan, K., Kang, S. C., Zhu, A., & Wang, W. X. (2014). Mercury in wild fish from high-altitude aquatic ecosystems in the Tibetan Plateau. *Environmental Science and Technology*, 48(9), 5220–5228.
- Zhang, H., Yin, R. S., Feng, X. B., Sommar, J., Anderson, C. W. N., Sapkota, A., et al. (2013). Atmospheric mercury inputs in montane soils increase with elevation: evidence from mercury isotope signatures. *Scientific Reports*, 3(3322), 1–8.
- Zhou, Q. F., Zhang, J. B., Fu, J. J., Shi, J. B., & Jiang, G. B. (2008). Biomonitoring: An appealing tool for assessment of metal pollution in the aquatic ecosystem. *Analytica Chimica Acta*, 606(2), 135–150.
- Zhu, Y. J., Zhang, Y. Q., Liu, M., Chen, L. G., He, Q. S., Ye, Z. X., & Sun, J. R. (2014). Distribution and pollution assessment of the mercury in soils of Tibet. *Ecology and Environmental Sciences*, 23(9), 1487–1491.