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Low Level Mercury Uptake by Plants from Natural Environments —Mercury Distribution in *Solidago altissima* L.—

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In order to elucidate the participation of plants in the biogeochemical cycling of mercury in natural environments, total mercury contents in leaves, stems and roots of tall goldenrod (*Solidago altissima* L.), Compositae, were determined. The mercury content in stems was considerably lower than that in leaves and roots. A positive correlation of mercury content was observed between soil and roots. The leaves at the lower part of the plant tended to have a higher concentration of mercury than the upper leaves. However, the mercury content of the leaves was independent of that in the soil. These observations suggested that the leaves of the plant can accumulate environmental mercury, but the mercury does not come from the soil via the root and stems. The mercury in leaves might originate predominantly from ambient air. The mercury in the leaves accumulated from the air can be delivered to the soil when the leaves fall. The roots also can adsorb the mercury from the soil; however, the mercury does not move from the roots and is not released into the air via the plant body.

1. Introduction

Mercury released from anthropogenic and/or natural sources is widespread in nature, circulating among several media. Mercury taken into organisms will be accumulated through the food chain and causes serious damage to biological systems. Plants, on the lowest rung of the food chain ladder, might represent an important pathway for the intake

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of mercury into organisms.[1] Many studies have focused on environmental mercury and plants[2–7] in contaminated areas and have investigated factors such as the flux of mercury between air and vegetables,[2,3] plants as a biomonitors of air pollution,[4,5] and the remediation of contaminated soil (sediment) by plants,[6] among others. On the other hand, few studies have focused on the distribution of mercury in the plant body in the natural environment. In order to clarify the relationship between plants and mercury cycling in the environment, a basic investigation such as this one is important.

In this study, we selected *S. altissima* and measured mercury distribution in the plant body. *S. altissima* has a long straight stem (1–2 m height), and the leaves come out from the stem as the plant grows, which makes it easy to divide the leaves and stems based on age; the lower the part, the older the leaves. The plant is an annual herbaceous plant and is distributed worldwide, being found in North America, South America, Europe and Asia. The commonness of the plant is another advantage for our study. Thus, we measured the total mercury concentration in the leaves, stems and roots and discussed the uptake of mercury by the plant from the natural environment.

2. Materials and Methods

2.1 *Sampling*

S. altissima plants were collected at 15 sites around Kagoshima City from June to November in 2004. Kagoshima City is not industrialized, and airborne mercury measured continuously in the city showed little anthropogenic input:[8] the average concentration in the city, 10.8 ng m^{-3} throughout the year, was considerably lower than the guideline value of 40 ng m^{-3} (the Ministry of Environment, June 2003).

At the sampling site, the plants standing up straight were selected, taken with roots and brought back to the laboratory. After the worm-eaten leaves and withered leaves were removed, the leaves were collected every 10 cm from the top of the plant. The collected leaves were rinsed with water and wiped. The lengths of leaves were 2–13cm and the arithmetic mean of leaves in each plant was 7.7±1.5 cm. The long leaves were cut into 1–2 cm long pieces and all parts were put in the flask for acid digestion. The stems were rinsed with water and wiped and cut every 20 cm. A 0.5 g piece from the upper part of each section was used for the determination. The roots were washed with water to remove the soil completely and wiped. The root hair was collected and used for mercury determination. The soil around the roots was also taken with plants at every sampling site. The mercury concentration, based on wet weight, was converted to a dry weight value using the water content, which was measured separately by heating the sample at 40°C for three days.

2.2 *Treatment with mercury*

Two *S. altissima* plants taken at Kagoshima University were placed in a bucket with soil and brought back to the laboratory. To the soil, 200 ml of 1 mg l^{-1} mercury chloride solution (as Hg) was added every two days (2, 4, 6 and 8 days from the sampling). After 1 and 13 days from the last addition of mercury, the distribution of mercury in the plants was measured and compared with that in plants collected at Kagoshima University giving the background level.

2.3 *Mercury analysis*

The total mercury concentration was determined using the method proposed by Akagi *et al*.[9–11] A known amount of sample (<0.5 g) was placed in a 50-ml volumetric flask, to which 1 ml of water, 2 ml of 1:1 nitric acid-perchloric acid solution, and 5 ml of concentrated sulfuric acid were added, and the flask was heated on a hot plate at 230°C for 30 min. After cooling, the digested sample was made up to 50 ml with water and the mercury in a suitable aliquot of the resulting solution (<20 ml) was introduced into the semi-automated mercury analyzer Model-Hg 3500 (Sansou Seisakusho Co., Ltd., Tokyo, Japan) together with 1 ml of 10% stannous chloride solution. The atomic absorption of liberated mercury vapor was measured at 253.7 nm. The detection limit for Hg was 0.1 ng.

3. Results and Discussion

3.1 *Mercury concentration in S. altissima*

The analytical results are summarized in Table 1. The mercury concentration in the soil was in the range 7.9–529.2 ng g^{-1} (90.3±129.4 ng g^{-1}, arithmetic mean±S.D.), suggesting no serious pollution in this area. The mean value of mercury concentration in roots, 57.0±78.4 ng g^{-1}, is considerably higher than that of 2.9±1.5 ng g^{-1} in stems. The concentrations in leaves were in the range 15.1–43.0 ng g^{-1} (mean 28.3±8.3 ng g^{-1}), which is about ten times higher than that in stems. The typical distribution of mercury in *S. altissima* is shown in Fig. 1. The mercury concentration in leaves increased with an increase in the distance from the plant top with a high linear correlation (r=0.91±0.10). Since the distance from the top corresponds to the age, the mature leaves may contain a higher concentration of mercury. On the other hand, the mercury concentration in the stem is independent of the distance from the top.

3.2 *Correlations*

The correlations between soil mercury content and the mercury content of roots (a), stems (b) and leaves (c) are shown in Fig. 2: for the mercury in leaves and stems, arithmetic mean values in each sample were used. A high correlation was observed only in the plots of soils vs roots, but no correlation was found in the plots of soils vs leaves or stems. Moreover, no correlations were observed between the mercury concentrations in the leaves and stems, stems and roots, and leaves and roots with the correlation coefficients (r^2) of 0.00002, 0.044 and 0.0021, respectively. These results suggest that mercury in soil can be easily absorbed into the roots, but the mercury does not move from the root into the plant body.

3.3 *Uptake of mercury by S. altissima*

In order to confirm the lack of movement of mercury from the roots to the plant body of *S. altissima*, a mercury solution was added to the soil and the change in the mercury concentration in plant parts was investigated. The mercury concentrations in the mercury treated plant parts were measured after 1 and 13 days from the last mercury addition. Since no significant difference was observed between them, the mean values were used in the discussion (Table 2). A marked variation was observed in the roots: the mercury concen-

Table 1
Total mercury concentration in leaves, stems and roots of *Solidago altissima* L. (ng g^{-1})[a]

Sampling date	18.Jun	30.Jun	6.Jul	26.Jul	2.Aug	18.Aug	20.Aug	8.Sep	13.Sep	16.Sep	16.Sep	23.Sep	4.Oct	7.Oct	14.Oct	20.Oct	21.Oct	28.Oct	28.Oct	4.Nov	4.Nov	10.Nov	10.Nov	17.Nov		
height / cm	121	110	45	79	71	115	75	67	60	87	75	140	68	204	145	156	113	109	110	201	169	201	185	188		
leaves length / cm																										
0	14.4	10.3	15.8	21.1	9.8	18.7	17.0	17.5	15.1	7.7	8.9	-	16.3	-	16.1	–	–	–	–	–	–	–	–			
5			14.9					20.9																		
10	22.8	15.8	18.6	31.7	11.1	17.7	16.5	18.9	17.9	11.9	13.8	19.8	13.4	18.1	17.7	22.5	18.0	–	–	–	27.7	–	22.2			
15			24.9					24.3																		
20	34.6	24.5	32.8	40.8	16.8	25.7	24.0		21.6	17.0	31.9	18.2	20.2	18.8	–	25.1	22.2	26.7	24.9	27.4	27.1	31.0	25.8	35.0		
30	48.9	27.7		58.5	22.7	34.2	30.6		27.4	25.2	32.8	20.5	29.8	19.8	20.8	24.8	27.5	27.1	28.6	30.0	27.3	28.7	24.0	38.6		
40	60.3	30.5		87.2		50.0			32.5	25.8		21.5	39.0	18.9	18.8	29.7	32.3	29.8	36.0	31.9	28.2	32.7	33.9	46.5		
50	76.8	40.3				62.1				35.2		24.0		17.6	19.2	34.9	33.6	41.0	38.9	30.3	–	34.7	39.3	41.0		
60												25.5		27.6			45.6	39.1	42.3	36.8	37.0	40.7	42.6	42.2		
70														31.3						40.7	40.0	38.6				
80														27.7								41.6				
90														27.4												
100														19.9												
110														36.0											mean	Stdev
min	14.4	10.3	14.9	21.1	9.8	17.7	16.5	17.5	15.1	7.7	8.9	18.2	13.4	17.6	16.1	22.5	18.0	26.7	24.9	27.4	27.1	28.7	22.2	35.0	18.8	6.9
max	76.8	40.3	32.8	87.2	22.7	62.1	30.6	24.3	32.5	35.2	32.8	25.5	39.0	36.0	20.8	34.9	45.6	41.0	42.3	40.7	40.0	41.6	42.6	46.5	40.6	15.6
mean	43.0	24.9	21.4	47.9	15.1	34.8	22.0	20.4	22.9	20.5	21.8	21.6	23.8	23.9	18.5	27.4	29.9	32.7	34.1	32.9	31.2	35.4	31.3	40.7	28.3	8.3
slope	1.25	0.56	0.88	1.59	0.44	0.92	0.48	0.37	0.44	0.54	0.90	0.13	0.62	0.13	0.06	0.29	0.51	0.39	0.45	0.24	0.23	0.21	0.43	0.17	0.51	0.37
r	1.00	0.99	0.93	0.97	0.97	0.96	0.94	0.80	0.99	0.99	0.94	0.92	0.93	0.71	0.72	0.94	0.97	0.90	0.99	0.92	0.91	0.92	0.95	0.62	0.91	0.10
stems length / cm																										
0	3.3	5.8	11.5	7.1	6.2	6.0	5.3	9.3	8.0	2.8	1.3	6.0	1.2	1.4	3.4	3.6	3.4	3.6	4.9	3.7	4.2	3.4	1.4	6.3		
10			6.6					6.0																		
12.5									3.4																	
20			4.7					2.6																		
25	3.4	2.0		6.8	1.5	1.8	5.8		5.7	1.6	0.8	9.0	0.8	1.3	3.2	2.5	2.7	3.5	3.9	2.2	2.1	1.9	1.7	3.2		
30			3.7					3.3																		
37.5									4.9																	
40			3.9					3.9																		
50	3.4	1.9		3.6	2.4	2.8	4.6	3.9	3.4	0.9	1.8	7.8	1.1	1.8	1.3	1.5	2.8	2.3	2.4	1.3	2.2	0.9	1.4	2.2		
60								3.4																		
62.5									4.2																	
75	3.0	3.0		3.6	1.9	2.3	4.6			0.6	2.0	3.8	1.3	1.8	3.7	3.3	1.7	2.1	3.8	1.4	3.5	1.4	0.4	1.0		
100	2.9	1.0				1.4				0.4		3.8		2.0	2.2	2.0	1.1	0.5	3.3	1.1	2.0	0.5	1.1	1.0		
125	3.8	2.2				1.8						3.4		1.9	1.8	1.6	1.1			0.1	2.3	1.0	0.7	2.6		
150												3.4		1.1	2.6	0.8				1.9	–	1.0	0.7	2.3		
175														1.0						4.4	1.8	0.5	0.6	1.9		
200														2.1						1.1		0.9			mean	Stdev
min	2.9	1.0	3.7	3.6	1.5	1.4	4.6	2.6	3.4	0.4	0.8	3.4	0.8	1.0	1.3	0.8	1.1	0.5	2.4	0.1	1.8	0.5	0.4	1.0	1.7	1.3
max	3.8	5.8	11.5	7.1	6.2	6.0	5.8	9.3	8.0	2.8	2.0	9.0	1.3	2.1	3.7	3.6	3.4	3.6	4.9	4.4	4.2	3.4	1.7	6.3	5.0	2.6
mean	3.3	2.7	6.1	5.3	3.0	2.7	5.1	4.6	4.9	1.3	1.5	5.3	1.1	1.6	2.6	2.2	2.1	2.4	3.6	1.9	2.6	1.3	1.0	2.6	2.9	1.5
root	171.2	75.1	18.9	97.4	17.1	15.9	28.6	24.3	48.9	299.8	266.4	17.4	19.3	62.2	23.6	12.2	15.3	21.8	17.0	26.1	34.0	18.1	10.2	27.1	57.0	78.4
soil	235.2	68.3	16.3	95.4	7.9	88.0	17.0	41.6	56.2	529.2	431.0	28.5	34.4	95.8	44.6	18.1	27.9	76.5	76.3	21.8	29.4	44.4	48.2	34.9	90.3	####

a. dry weight basis

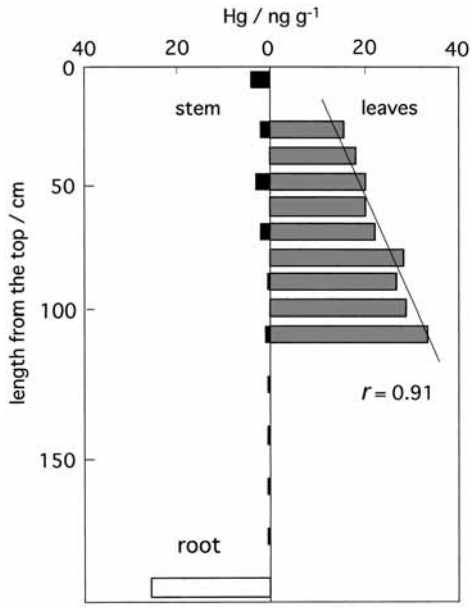

Fig. 1. The typical distribution of mercury in *Solidago altissima* L.

tration of roots changed from 50 to 2000 ng g^{-1}. On the other hand, no significant variation was observed for the leaves and stems, and their mercury concentration was still within the natural levels. Cho and Park[12] investigated mercury-induced oxidative stress in tomato seedlings. In their study, 10 μM mercury chloride was added daily to pots for 20 days. After the treatment, the mercury concentration in roots became as high as 820 mg kg^{-1}, but the relative accumulation ratio for shoots was only 2% compared to roots. These results suggest that the mercury in soil and/or water in soil can easily be absorbed in roots, but does not move into the stems and leaves from the roots.

3.4 *Role of the plant in the biogeochemical cycling of mercury*

In natural environments, the mercury concentration in the roots was lower than that of soil, but a high correlation was observed between the root and soil concentrations, which suggested that the mercury concentration in roots reflects the mercury concentration in soil. In stems, the mercury concentration was ten times lower than that in roots. It seems that the transport of mercury from the roots to the stems either does not occur or is a very slow process. On the other hand, the older leaves contained a higher concentration of mercury, which was one order higher than that in stems, and this had no correlation with that in roots, stems and soil. Even in the background site, the leaves accumulated mercury, but the mercury in the leaves did not originate from the soil via the roots and stems, but is likely to have originated from ambient air. Bennett *et al*.[13] measured heavy metals in wild rice from northern Wisconsin, and they concluded that the pathway for volatile elements, such as mercury, arsenic and lead, to the plants could be atmospheric. In the current study, uptake

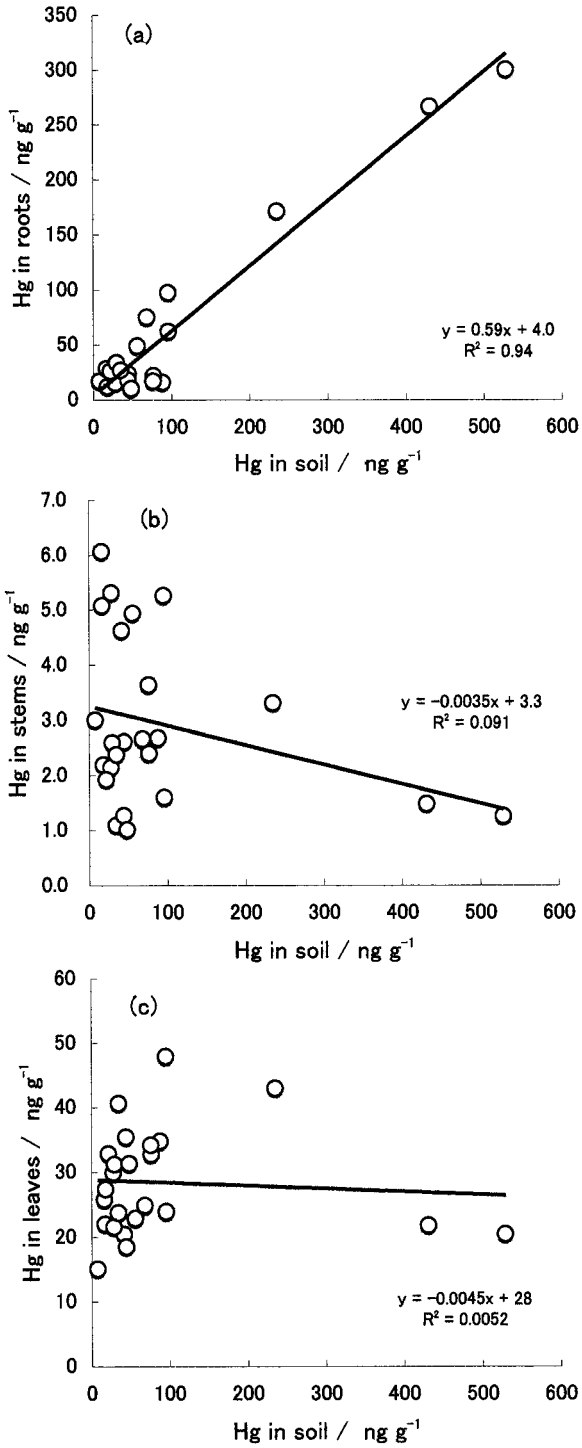

Fig. 2. The correlations of mercury between soil and (a) roots, (b) stems, and (c) leaves.

Table 2
Effect of mercury added to soil on the mercury distribution in the plant body.

plant parts	Hg contents / ng g^{-1} [a]	
	background (n = 19)	Hg addition[b] (n = 2)
leaves[c]	17.9±7.7	18.3±6.1
stems[c]	2.8±2.4	5.6±1.5
roots	53±98	2000±307
soil	160±178	497

a. wet weight basis.
b. 200 ml of 1 mg l^{-1} $HgCl_2$ solution (as Hg) was added into the soil every two days (total 4 times).
c. mean concentration of each sample plant.

of mercury from atmosphere by plant leaves was also suggested.

A positive correlation between mercury and organic matter content in soil had been reported, and it had also been observed that the mercury was trapped and retained more effective by the organic matter.[14] The plants take up and accumulate the mercury in their leaves from the air and deliver the accumulated mercury into the soil when the leaves fall. The falling leaves and decomposed matter may also play a role as the mercury adsorber in the soil. The roots can adsorb the mercury from the soil; however, the mercury does not move from the roots and is not released into the air via plant body. The mercury originating from air may be taken into an animal body if the leaves are eaten. The transfer of mercury from plant to animals is an interesting subject for future study.

On the other hand, the leaves of *S. altissima* may be preferable as a bioindicator for monitoring the level of mercury in the atmosphere because the concentration of mercury in the leaves is not affected by the mercury concentration in soil. The usefulness of *S. altissima* as a bioindicator should be discussed in a further investigation.

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