Accumulation of Radioactive Cesium Released from Fukushima Daiichi Nuclear Power Plant in Terrestrial Cyanobacteria Nostoc commune

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(Received March 18, 2013—Accepted September 5, 2013—Published online November 19, 2013)

The Fukushima Daiichi Nuclear Power Plant accident released large amounts of radioactive substances into the environment and contaminated the soil of Tohoku and Kanto districts in Japan. Removal of radioactive material from the environment is an urgent problem, and soil purification using plants is being considered. In this study, we investigated the ability of 12 seed plant species and a cyanobacterium to accumulate radioactive material. The plants did not accumulate radioactive material at high levels, but high accumulation was observed in the terrestrial cyanobacterium Nostoc commune. In Nihonmatsu City, Fukushima Prefecture, N. commune accumulated 415,000 Bq/kg dry weight $^{134}$Cs and 607,000 Bq kg$^{-1}$ dry weight $^{137}$Cs. The concentration of cesium in N. commune tended to be high in areas where soil radioactivity was high. A cultivation experiment confirmed that N. commune absorbed radioactive cesium from polluted soil. These data demonstrated that radiological absorption using N. commune might be suitable for decontaminating polluted soil.

Key words: Nostoc commune, terrestrial cyanobacteria, radioactive cesium, Fukushima Daiichi Nuclear Power Plant

Materials and Methods

Collection of seed plants and cyanobacterium N. commune

Twelve species of seed plants and cyanobacterium N. commune were collected in 2012 from a site belonging to Iwaki Meisei University in Fukushima Prefecture, Japan. The site is approximately 45 km from the Fukushima Daiichi Nuclear Power Plant. N. commune was also collected from 34 habitats in Akita, Miyagi, Fukushima, Ibaraki, Tochigi, Chiba, Tokyo, Kyoto, Osaka, Yamaguchi, and Fukushima prefectures, Japan, in 2011 and 2012 (Fig. 1).

Detection of radioactive cesium and iodine

Field materials collected were transported to the laboratory in a polyethylene bag at 15–20°C to avoid damage during transportation. Plant and cyanobacterial samples were washed with water and dried at room temperature. Dried samples were desiccated at 60°C for 48 h, pulverized using a mill, and placed in U-8 plastic vials ($\Phi$56 mm×68 mm high). Vials were stored in a desiccator until measurement. Radioactive cesium ($^{134}$Cs, $^{137}$Cs) and iodine ($^{131}$I) were measured using a GEM40P4-76 Ge semiconductor detector (Seiko EG & G, Tokyo, Japan). Soil samples were dried at 60°C for 48 h, sifted through a $\Phi$2.8 mm mesh, and placed in V-11 plastic vials ($\Phi$128 mm×76 mm high). Levels of $^{134}$Cs, $^{137}$Cs, and $^{131}$I were measured using a CAN-OSP-NAI NaI scintillation counter (Hitachi-Aloka Medical, Tokyo, Japan) or a Ge semiconductor detector.

Cultivation experiments

We used N. commune cultivated on Miyakojima Island, Okinawa, Japan, for this experiment. Dried N. commune (30 g) was soaked in distilled water for 1 h and then put on the surface of polluted sand or loam soil (1 kg) in a plastic box (40 cm length×32 cm width×7 cm height). The samples were cultivated outdoors for 30 days in November 2011. The concentration factor was calculated using the formula (radioactive cesium concentration in N. commune)/(radioactive cesium concentration in soil), where the cesium concentration was measured in Bq kg$^{-1}$ dry weight (DW).
Results and Discussion

We investigated soil contamination by radioactive material at a site of Iwaki Meisei University. In April 2012, the radioactivity was distributed within the top 10 cm of topsoil (Table 1). The concentration of $^{137}$Cs was 2,530 Bq kg$^{-1}$ DW at depths of 0–5 cm, 424 Bq kg$^{-1}$ DW at 5–10 cm, 31 Bq kg$^{-1}$ DW at 10–15 cm, and 5 Bq kg$^{-1}$ DW at 15–20 cm. $^{131}$I was not detected, perhaps because of its short half-life (8.02 days).

In all the 12 seed plant species studied, we detected relatively low concentrations of radioactive cesium (Table 2). Accumulation levels in larger plants such as Solidago canadensis var. scabra tended to be lower than in smaller plants. In S. canadensis var. scabra, the concentrations of $^{137}$Cs were 78 Bq kg$^{-1}$ DW in shoots and 100 Bq kg$^{-1}$ DW in roots. In contrast, the small plant Vicia sativa ssp. nigra accumulated 557 Bq kg$^{-1}$ DW $^{137}$Cs in shoots and 1,520 Bq kg$^{-1}$ DW in roots. We believe that V. sativa ssp. nigra absorbed more radioactive cesium because of its small root system. Overall, more radioactive material accumulation was concentrated in the roots than in the shoots. In the shoots, $^{134}$Cs levels were 29–410 Bq kg$^{-1}$ DW and $^{137}$Cs levels were 43–557 Bq kg$^{-1}$ DW. In the roots, $^{134}$Cs levels were not detected (ND) to 1,120 Bq kg$^{-1}$ DW and $^{137}$Cs levels were ND–1,520 Bq kg$^{-1}$ DW. These data suggested that seed plants generally do not easily transport radioactive cesium into shoots. In contrast, high concentrations of $^{134}$Cs (32,300 Bq kg$^{-1}$ DW) and $^{137}$Cs (46,200 Bq kg$^{-1}$ DW) were observed in terrestrial cyanobacterium N. commune.

$^{134}$Cs and $^{137}$Cs were collected from 34 habitats between August 2011 and October 2012. The radioactivity concentrations of $^{134}$Cs and $^{137}$Cs are summarized in supplementary Table 1. The $^{134}$Cs concentrations ranged from not detectable (ND) to 415,000 Bq kg$^{-1}$ DW, while the $^{137}$Cs concentrations ranged from ND to 607,000 Bq kg$^{-1}$ DW. Radioactive iodine $^{131}$I was not detected in any samples. High radioactive cesium levels were observed in the samples from Fukushima Prefecture, where the Fukushima Daiichi Nuclear Power Plant is located. In particular, 415,000 Bq kg$^{-1}$ DW $^{134}$Cs and 607,000 Bq kg$^{-1}$ DW $^{137}$Cs were detected in N. commune from Nihonmatsu, where soil contamination was high (5,460 Bq kg$^{-1}$ DW $^{134}$Cs, 6,330 Bq kg$^{-1}$ DW $^{137}$Cs). However, much lower radioactivity levels (28,300 Bq kg$^{-1}$ DW $^{134}$Cs, 39,800 Bq kg$^{-1}$ DW $^{137}$Cs) were detected in the cyanobacterial sample from Koriyama, although soil radioactivity was very high.

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Table 1. Radioactivity concentration of $^{134}$Cs and $^{137}$Cs in the soil of Iwaki Meisei University, Iwaki City, Fukushima. Soil was collected in April 2012

| Depth       | $^{134}$Cs (Bq kg$^{-1}$ DW) | $^{137}$Cs (Bq kg$^{-1}$ DW) |
|-------------|-----------------------------|-----------------------------|
| 0–5 cm      | 1,630±298$^a$               | 2,530±461                   |
| 5–10 cm     | 250±73                      | 424±86                      |
| 10–15 cm    | 16±14                       | 31±11                       |
| 15–20 cm    | 4±1                         | 5±1                         |
| 20–25 cm    | ND$^b$                      | 6±2                         |
| 25–30 cm    | ND                          | ND                          |

$^a$3σ counting error.  
$^b$not detected.
Table 2. Radioactivity concentration of $^{134}$Cs and $^{137}$Cs in wild plants and cyanobacterium grown in Iwaki Meisei University, Iwaki City, Fukushima

| Species                          | Collection dates | Shoot $^{134}$Cs (Bq kg$^{-1}$ DW) | Shoot $^{137}$Cs (Bq kg$^{-1}$ DW) | Root $^{134}$Cs (Bq kg$^{-1}$ DW) | Root $^{137}$Cs (Bq kg$^{-1}$ DW) |
|----------------------------------|------------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|
| **Dicotyledoneae**               |                  |                                   |                                   |                                   |                                   |
| Artemisia indica var. maximowiczii | 16 April 2012    | 91±12$^a$                         | 184±15                            | 63±9                              | 76±9                              |
| Bidens pilosa var. pilosa        | 13 October 2012  | 55±10                             | 93±11                             | 541±51                            | 1,040±61                          |
| Cerastium glomeratum            | 2 May 2012       | 39±11                             | 59±11                             | ND$^b$                             | 125±28                            |
| Hypochoeris radicata            | 2 June 2012      | 227±16                            | 354±19                            | 192±18                            | 308±21                            |
| Petasites japonicus             | 16 April 2012    | 124±21                            | 174±25                            | 128±12                            | 171±13                            |
| Rumex acetosa                   | 24 April 2012    | 93±11                             | 141±13                            | 206±10                            | 314±12                            |
| Solidago canadensis var. scabra  | 8 June 2012      | 54±6                              | 78±7                              | ND                                | 100±9                             |
| Veronica persica                 | 2 May 2012       | 78±10                             | 136±12                            | ND                                | 244±64                            |
| Vicia sativa subsp. nigra       | 2 May 2012       | 410±21                            | 557±24                            | 1,120±48                          | 1,520±53                          |
| **Monocotyledoneae**             |                  |                                   |                                   |                                   |                                   |
| Poa annua                       | 8 May 2012       | 172±17                            | 219±20                            | 506±39                            | 691±43                            |
| Dactylis glomerata               | 15 June 2012     | 29±7                              | 43±7                              | 106±21                            | 182±22                            |
| Imperata cylindrica              | 26 June 2012     | 73±11                             | 129±12                            | 101±17                            | 214±21                            |
| **Cyanobacteria**                |                  |                                   |                                   |                                   |                                   |
| Nostoc commune                  | 24 April 2012    | 32,300±101                        | 46,200±125                        |                                   |                                   |

$^a$ 3σ counting error.

$^b$ not detected.

Table 3. Radioactivity concentration of $^{134}$Cs and $^{137}$Cs in Nostoc commune grown in polluted soil. N. commune was cultivated outdoors for 30 days

| Soil type | Soil  | Nostoc commune | Concentration factor |
|-----------|-------|----------------|----------------------|
|           | $^{134}$Cs (Bq kg$^{-1}$ DW) | $^{137}$Cs (Bq kg$^{-1}$ DW) | $^{134}$Cs (Bq kg$^{-1}$ DW) | $^{137}$Cs (Bq kg$^{-1}$ DW) |
| Sand      | 4,980±300$^a$ | 6,070±365 | 3,100±47           | 4,420±55           | 0.62 | 0.73 |
| Loam      | 785±48        | 962±58     | 183±12             | 246±14             | 0.23 | 0.26 |

$^a$ 3σ counting error.

there (26,500 Bq kg$^{-1}$ DW $^{134}$Cs, 33,200 Bq kg$^{-1}$ DW $^{137}$Cs). N. commune grows throughout the year. We believe that the cyanobacteria sampled from Nihonmatsu existed at the time of the nuclear accident.

Relatively high concentrations of cesium were also detected in the samples from Miyagi, Ibaraki, and Chiba prefectures surrounding Fukushima. In Abiko City (Chiba Prefecture), approximately 200 km from the power plant, 5,380 Bq kg$^{-1}$ DW $^{134}$Cs and 7,590 Bq kg$^{-1}$ DW $^{137}$Cs were detected in N. commune. Abiko City was reported to have high levels of radioactive activity in rain after the accident. In contrast, radioactive cesium was not detected in samples from Osaka, Yamaguchi, and Fukushima prefectures; cesium released after the accident probably did not reach these areas.

The concentration of radioactive cesium in N. commune tended to be high where soil contamination was high. Growing on the soil surface, N. commune appeared to have been strongly exposed to radioactivity. As shown in supplementary Fig. 1, the radioactive cesium concentrations in the soil and in N. commune were directly proportional and relatively well correlated.

N. commune might absorb radioactive cesium from polluted soil or contaminated rainwater. To clarify how radioactive cesium was absorbed by N. commune, we cultivated the cyanobacterium in polluted sand and loam soils. Radioactive cesium was not detected from N. commune cultivated on Miyakojima Island, which was used for the experiment. During the experimental period, there were three rain showers, but radioactive cesium was not detected in rainwater. The temperature ranged 6–25°C. After 30 days, growth of N. commune was not observed, but it had absorbed radioactive cesium (Table 3). In polluted sand (4,980 Bq kg$^{-1}$ DW $^{134}$Cs, 6,070 Bq kg$^{-1}$ DW $^{137}$Cs), N. commune accumulated 3,100 Bq kg$^{-1}$ DW $^{134}$Cs and 4,420 Bq kg$^{-1}$ DW $^{137}$Cs. The concentration factors were 0.62 for $^{134}$Cs and 0.73 for $^{137}$Cs. Similarly, in polluted loam soil (785 Bq kg$^{-1}$ DW $^{134}$Cs, 962 Bq kg$^{-1}$ DW $^{137}$Cs), the cyanobacterium contained 183 Bq kg$^{-1}$ DW $^{134}$Cs and 246 Bq kg$^{-1}$ DW $^{137}$Cs, giving concentration factors of 0.23 for $^{134}$Cs and 0.26 for $^{137}$Cs. The concentration factors in the sand were higher than those in the loam soil. The reasons for this difference between soil types should be examined in the future.

The concentration factors for wild N. commune, shown in supplementary Table 1, were 0.85–76.01 for $^{134}$Cs and 0.98–95.89 for $^{137}$Cs, but were much lower for cultivated N. commune (0.23 and 0.62 for $^{134}$Cs, 0.26 and 0.73 for $^{137}$Cs). These results suggested that wild N. commune directly absorbed radioactively contaminated rainwater. However, N. commune absorbed more radioactive cesium from the soil than the seed plants. The $^{134}$Cs concentration factors were
0.07–0.39 in sunflower and 0.02–0.07 in soybean (5).

Removal of radioactive material from the environment is an urgent problem in affected areas, and soil decontamination using living organisms is being considered. In microbes, cesium-accumulating bacteria have been isolated (15, 16), but collecting these bacteria from polluted soil is difficult. In this study, we demonstrated that the terrestrial cyanobacterium *N. commune* can absorb high levels of radioactive cesium. Because *N. commune* forms jelly-like clumps, it can be easily collected from the soil surface. Furthermore, its weight decreases by about 90% when *N. commune* is dried. Radiological absorption by *N. commune* may be a viable strategy for decontaminating polluted soil. We will perform decontamination experiments using *N. commune* in the future.

Acknowledgements

The present study was supported by a Scientific Research Grant from the Mayekawa Houonkai Foundation and JSPS KAKENHI Grant Number 24780321 to H. Sasaki.

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