

are important for fitness, by analyzing the behavior of species near the vertices.

Using only basic assumptions, Schuetz *et al.* and Shoval *et al.* provide powerful tools for generating and testing hypotheses about which capabilities are selected for in nature. Future research could apply these methodologies in a variety of biological systems. However, several fascinating questions remain unanswered. Is it true that only

a handful of tasks affect the fitness of organisms, or is this an artifact of our limited experimental data and measurement abilities? Further advancing our understanding of evolution as a multi-objective problem will require deciphering how contrasting goals are combined to define fitness, determining why specific points on the Pareto front are chosen and not others.

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10.1126/science.1223193

GEOCHEMISTRY

Tracking the Fukushima Radionuclides

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On 11 March 2011, the Fukushima Daiichi Nuclear Power Plant (FDNPP) lost cooling capability during the magnitude-9.0 Tohoku earthquake and the subsequent tsunami (1). The incident led to severe damage of the plant and the release of large amounts of radionuclides to the environment. Local contamination still prevents over 100,000 residents from returning to their homes. Detailed maps are beginning to provide a picture of the contamination patterns (see the first figure), but as radionuclides migrate and diffuse through the environment (see the second figure), continual monitoring is required to guide remediation and ensure human safety.

Deposition of radionuclides on land mostly stemmed from the release to the atmosphere of relatively volatile fission products, most importantly ¹³⁷Cs and ¹³¹I (2). From 12 March to 6 April 2011, an estimated $\sim 150 \times 10^{15}$ Bq of ¹³¹I and $\sim 13 \times 10^{15}$ Bq of ¹³⁷Cs were released into the atmosphere (3); higher values of up to 50×10^{15} Bq for ¹³⁷Cs have also been suggested, with radioactivity detected throughout the Northern Hemisphere (4).

Airborne monitoring by the Ministry of Education, Culture, Sports, Science, and Technology (MEXT) and the U.S. Department of Energy (DOE) from April to November 2011 and concurrent ground-based observations have yielded detailed deposition distribution maps of radionuclides (see the first figure) (5). Due to strong

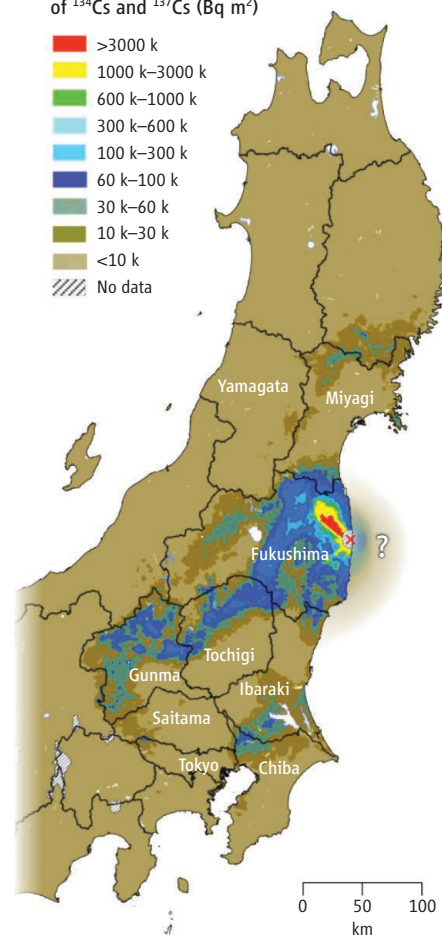
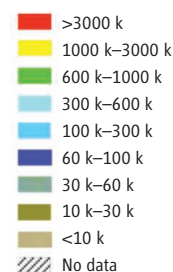
westerly winds prevailing in early spring in this area, about 70 to 80% of the radionuclides emitted from FDNPP were deposited over the western North Pacific Ocean (6). The remainder was deposited on land, especially northwest of the FDNPP (7, 8). The I:Cs emission ratio may have differed between emission events from the damaged reactors; combined with air-mass movements and precipitation, this led to different wet deposition patterns for each radionuclide (9).

¹³¹I has a half-life of ~ 8 days and thus diminishes quickly. However, because of the importance of assessing the radiological dose from ¹³¹I, which could have a large effect on public health of local residents, MEXT is planning a surrogate nuclide ¹²⁹I mapping effort. ¹³⁷Cs has a much longer half-life of ~ 30 years. It adheres strongly to clay minerals and therefore mostly stays in the top 5 cm of soil (10). In nearly half of the 20-km exclusion zone around the FDNPP, ¹³⁷Cs deposition exceeded 600,000 Bq m⁻²; in the most highly contaminated areas, deposition exceeded 3,000,000 Bq m⁻² (5). Rebound and resuspension of aerosols into the atmosphere and of soil particles in water systems can lead to changes in the extent and location of contamination (see the second figure). Such radionuclide transport and redeposition may lead to new radioactivity “hot-spots” on land or in terrestrial waters, and to transport of radionuclides to the sea.

Many other, less volatile radionuclides may also have been emitted to the environment. Plutonium (Pu) deposition has been detected at a site 1.7 km from FDNPP and at several sites between 20 and 30 km from FDNPP (11). Reported ²⁴¹Pu/²³⁹Pu ratios (12)

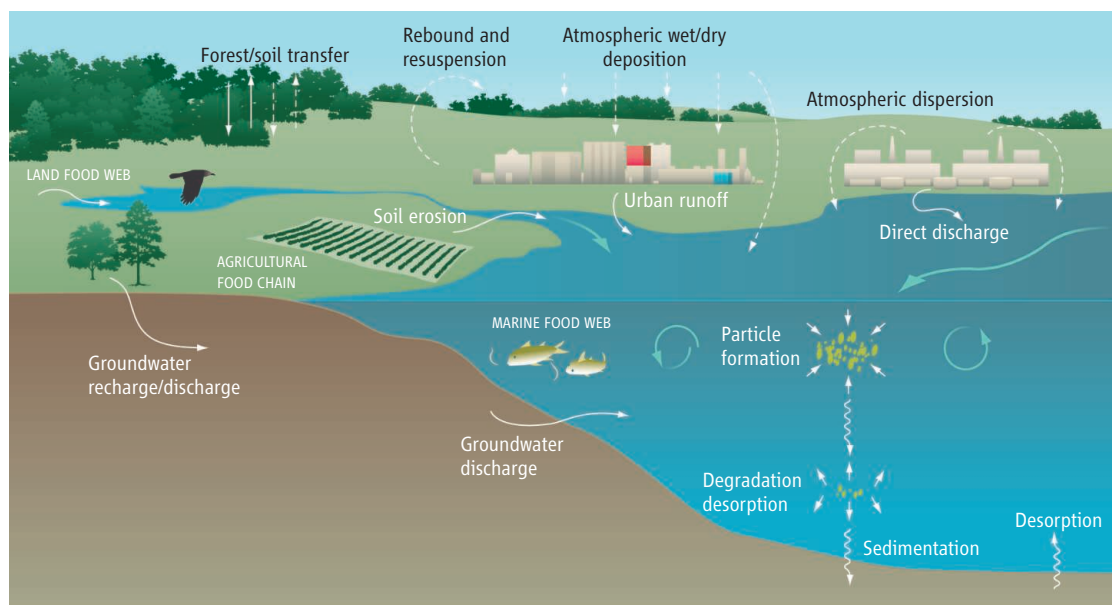
Ongoing radionuclide monitoring and tracking efforts are required following the nuclear accident at the Fukushima Daiichi Nuclear Power Plant.

Total disposition of ¹³⁴Cs and ¹³⁷Cs (Bq m⁻²)



Radionuclide deposition. ¹³⁴Cs and ¹³⁷Cs distribution map [redrawn from (5)]. The distribution of radiocesium in the oceanic system is not readily available, but is estimated to be below 10,000 to 100,000 Bq m⁻² in coastal sediments and waters off Fukushima (5).

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Radionuclide migration. Material cycle processes of radionuclide deposition and migration. Future remediation efforts will require long-term monitoring even at low levels of contamination.

were much higher than those from the global fallout during the era of atmospheric nuclear weapon tests. Long-term dose assessments from Pu and other alpha emitters are important in public health management because of their relatively larger health effect and longer half-lives; such assessments should include ^{241}Pu and its decay product ^{241}Am . The Pu isotopic composition also provides information about the reactor damage. The neutron activity of the damaged core can also be elucidated from a significant rise in the atmospheric level of the neutron-activated radionuclide ^{35}S (13).

Oceanic radionuclide contamination from FDNPP has several sources (see the second figure). When MEXT began to monitor marine radioactivity on 23 March 2011, up to 77 Bq of ^{131}I per liter and 24 Bq of ^{137}Cs per liter were observed in seawater 30 km offshore of the plant. Variable ^{131}I to ^{134}Cs and ^{137}Cs ratios indicated that this material originated from atmospheric deposition (14, 15). Presumed atmospheric deposition also reached remote oceanic stations up to 1900 km away in the North Pacific in late April 2011 (16).

In coastal waters, direct discharge prevailed. Seawater radioactivity peaked at the end of March through the first week of April (14); about 4×10^{15} Bq of ^{137}Cs was released by direct discharge through the end of May (15, 17). From late April, the radioactivity dropped sharply; by June, seawater radioactivity readings were below the detection limit at most sampling points, except in the immediate vicinity of the power plant. This

was, however, partly because of the seawater radioactivity measurement method adopted in the government-organized monitoring; methods with a lower detection limit are readily available but were not used.

Simulation studies (15–17), direct observation (6), and a comprehensive survey by an American vessel in June 2011 (18) show that the contaminated water eventually headed eastward along the Kuroshio Current while spreading and being diluted. The most distinct effect of the FDNPP incident at sea was a high level of contamination within a short period, followed by rapid flushing.

Nevertheless, Cs readings from fish samples taken from Fukushima coastal waters, where commercial fishing is practically banned, still exceed the guideline (19). The radioactivity in fish appears not to follow the rapid decrease in seawater radioactivity. A comprehensive survey of radioactivity in the marine food web is called for.

Although the radiocesium distribution around the FDNPP is relatively well understood (see the first figure), the processes by which it is transferred—e.g., from forest canopy to ground soil and aquifers, terrestrial biota, river and lake systems, and eventually to marine systems—are yet to be depicted quantitatively. For other radionuclides, even the distribution is not well-known. It is thus crucial that monitoring efforts continue, subject to quality control, and that they are complemented by detailed analyses of transfer processes with the aid of high-resolution model simulations. These studies are essential for assessing the external and internal radio-

logical doses, including food consumption, to which local populations have been exposed.

Decontamination in access-restricted areas to which local residents are planned to return is given highest priority in government policy. Decontamination certainly should be pursued until the radiological dose to the public is reduced to a reasonable level, although this level is subject to substantial public debate. The proposed decontamination strategy centers on removal and isolation of topsoil and cleansing of house walls and roofs with water. To evaluate the effectiveness and sustainability of the strategy and avoid recontamination of surrounding regions, these decontamination efforts must be accompanied by tracking migration of radioactivity. Decision-making must be based on scientific knowledge, public disclosure, and comprehensive communication (20).

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10.1126/science.1219493