This study follows the lead of our research of several years on the use of wild animals in global ecological monitoring [2, 5]. The goal of this study was to evaluate the radionuclide accumulation in birds and mammals in Ethiopia by means of multielement analysis. Ethiopia is attractive as a putatively “clean” global control for studying accumulation and migration of artificial radionuclides in food chains of natural ecosystems. The fact is that Ethiopia and the neighboring states are free of nuclear-power plants or other facilities of atomic industry and are located far from any nuclear weapons testing areas. Ethiopia has also been assumed to be uncontaminated with radionuclides derived from the Chernobyl accident in April, 1986.

About 1500 nuclear explosions were detonated in the period from 1945 to 1986, with more than 90% of them performed by the United States and the Soviet Union [1]. This increased the background radioactivity level at the earth’s surface, especially in the Northern Hemisphere. Peaks of nuclear testing escalation and radionuclide discharges into the atmosphere were observed in 1954–1958 and 1961–1962. The experimental explosions during these particular periods have led to the global contamination of the environment with such biogenic radionuclides as $^{137}$Cs and $^{90}$Sr.

The United Nations Scientific Committee on the Effects of Atomic Radiation and researchers from various countries estimated the total amount of $^{90}$Sr that had been generated in explosions and released into the atmosphere during nuclear weapons testing until 1976 inclusive to be $603 \times 10^{15}$ Bq [7, 9]. The amount of $^{137}$Cs accumulated during the same period in the water, air, and surface of our planet was estimated to be $925 \times 10^{15}$ Bq [4]. By 1980, all these radionuclides had deposited at the earth’s surface, so that less than 2% remained in the stratosphere [11].

In this study, the data of radiochemical analysis of animals that were obtained according to the program of the Soviet–Ethiopian Expedition in 1987–1989 and the bones of animals that were found dead on roads or along high-voltage power transmission lines in 1998 were compared. The skeletons were prepared and pooled in 1 kg batches separately for each species.

The material for this study were the collections of birds and mammals of the Complex Russian–Ethiopian Biological Expedition organized according to the Russian–Ethiopian Agreement on Cooperation in Economy, Science, and Technology. Part of the specimens (1987–1989) were collected in the Omo River Basin and the Gambella Region (dry savanna-type landscapes). The other specimens (1998) were collected in the central and southwestern areas of Ethiopia, i.e., within 100 km around Addis Ababa (dry anthropogenic and savanna-type landscapes) and 50 km to the south of Jima (rainforest).

The collection of 1987–1989 consisted of 14 specimens belonging to 10 mammalian species: the warthog Phacochoerus aethiopicus ($n = 1$), the oribi Ourebia ourebi ($n = 1$), the bushbuck Tragelaphus scriptus ($n = 1$), the common reedbuck Redunca redunca ($n = 1$), the “kip” Damaliscus lunatus ($n = 1$), the gerenuk Litocranius walleri ($n = 3$), the klipspringer Oreotragus oreotragus ($n = 3$), the waterbuck Kobus defassa ($n = 1$), and Salt’s dik-dik Madoqua saltiana ($n = 1$). The radionuclide content in the samples collected in 1987 was determined in February, 1987.

The bone collection of 1998 included three species (all specimens were found dead on roads or under high-voltage power transmission lines): the civet Civettictis civetta ($n = 1$), the African marabou Leptoptilus crumeniferus ($n = 2$), and the Indian white-rumped vulture (African race) Gyps bengalensis ($n = 2$). Bone specimens of domestic hens ($n = 5$) reared on local foods and bought from Addis-Ababa residents (chicken is a common item in food of the local population) were also used in analysis.

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*Department of Ecology, Rostov State University, Bol’shaya Sadovaya ul. 105, Rostov-on-Don, 344006 Russia
E-mail: bird@ms.math.rsu.ru

**Severtsov Institute of Ecology and Evolution, Russian Academy of Sciences, Leninskii pr. 33, Moscow, 117071 Russia

***Institute of Biology, Komi Research Center, Ural Division, Russian Academy of Sciences, Syktyvkar, 167000 Komi Republic, Russia

† Deceased.
The radiochemical method was used to analyze the biological specimens for artificial ($^{137}$Cs, $^{134}$Cs, $^{90}$Sr, $^{238}$, $^{239}$, $^{240}$Pu) and natural ($^{40}$K) radionuclides. Eight carcasses of small passerine birds from fringes of the primary tropical rainforest in the vicinity of Jima were also subjected to multielement analysis by inductively coupled plasma-mass spectrometry (ICP-MS) on a PlasmaQuad instrument (VG Elemental) in the Institute of the Geology of Ore Deposits, Petrography, Mineralogy, and Geochemistry, Russian Academy of Sciences (Moscow, Russia). Specifically, four olive sunbirds ($Nectarinia olivacea$), one yellow-bellied sunbird ($Nectarinia venusta$), two yellow-eyed canaries ($Serinus mozambicus$), and one tawny-flanked prinia ($Prinia subflava$) were studied.

### Table 1. Chemical composition of bird carcasses, μg/g dry weight: (a) olive sunbirds $Nectarinia olivacea$ ($n = 4$), (b) yellow-bellied sunbird $Nectarinia venusta$ ($n = 1$), (c) yellow-eyed canary $Serinus mozambicus$ ($n = 2$), and (d) tawny-flanked prinia $Prinia subflava$ ($n = 1$)

<table>
<thead>
<tr>
<th>Element</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
<th>Element</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
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<td>Na</td>
<td>3910–7160*</td>
<td>5540</td>
<td>4480–6510</td>
<td>5730</td>
<td>Cd</td>
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<tr>
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<td>1130–2000</td>
<td>1090</td>
<td>1870–2140</td>
<td>892</td>
<td>Sn</td>
<td>0–1.3</td>
<td>14</td>
<td>0–1.1</td>
<td>61</td>
</tr>
<tr>
<td>Al</td>
<td>180–1520</td>
<td>328</td>
<td>335–1470</td>
<td>–</td>
<td>Sb</td>
<td>0–0.15</td>
<td>0</td>
<td>0–0.26</td>
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<tr>
<td>P</td>
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<td>27600</td>
<td>28400–29700</td>
<td>25600</td>
<td>Te</td>
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<td>0</td>
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<tr>
<td>S</td>
<td>4360–3620</td>
<td>3080</td>
<td>2950–34300</td>
<td>3350</td>
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<td>0.23–2.0</td>
<td>0</td>
<td>0–0.17</td>
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<tr>
<td>K</td>
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<td>6240</td>
<td>6900–8270</td>
<td>6220</td>
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<tr>
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<td>17600</td>
<td>22500–17400</td>
<td>13800</td>
<td>Ba</td>
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<td>15</td>
<td>16–133</td>
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<tr>
<td>Sc</td>
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<td>1.2</td>
<td>0–2.4</td>
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<td>La</td>
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<td>0.05</td>
<td>0.39–2.1</td>
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<tr>
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<td>133</td>
<td>69–281</td>
<td>136</td>
<td>Ce</td>
<td>0.11–2.2</td>
<td>0.24</td>
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<td>0–88</td>
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<td>Nd</td>
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<td>0.1–0.19</td>
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<td>Gd</td>
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<td>0</td>
<td>0</td>
<td>Tb</td>
<td>0–0.05</td>
<td>0.01</td>
<td>0.01–0.07</td>
<td>0</td>
</tr>
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<td>Cu</td>
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<td>3.9</td>
<td>0–4.2</td>
<td>0</td>
<td>Dy</td>
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<td>94</td>
<td>77–574</td>
<td>92</td>
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<td>0</td>
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<td>0.04–0.23</td>
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<tr>
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<td>0.07</td>
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<td>3.6–6.3</td>
<td>1.5</td>
<td>Ta</td>
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<td>0.03</td>
<td>0.06–0.21</td>
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<tr>
<td>Sr</td>
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<td>12–17</td>
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<td>0.01</td>
<td>0–0.08</td>
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<td>Nb</td>
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<td>0.06–1.4</td>
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<td>0–0.86</td>
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<td>0–0.35</td>
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<tr>
<td>Mo</td>
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<td>0</td>
<td>0.39–0.7</td>
<td>0.23</td>
<td>Pb</td>
<td>0–3.9</td>
<td>0</td>
<td>0–1.1</td>
<td>0</td>
</tr>
<tr>
<td>Ru</td>
<td>0–0.01</td>
<td>0</td>
<td>0.01</td>
<td>0</td>
<td>Bi</td>
<td>0–0.03</td>
<td>0.01</td>
<td>0.01–0.0</td>
<td>0.08</td>
</tr>
<tr>
<td>Pd</td>
<td>0–0.08</td>
<td>0.04</td>
<td>0.03–0.08</td>
<td>0</td>
<td>Th</td>
<td>0–0.14</td>
<td>0</td>
<td>0.03–0.19</td>
<td>0</td>
</tr>
</tbody>
</table>
| Ag      | 0–0.88 | 0 | 0–0.12 | 0 | * Shown are the range limits.

The radiochemical method was used to analyze the biological specimens for artificial ($^{137}$Cs, $^{134}$Cs, $^{90}$Sr, $^{238}$, $^{239}$, $^{240}$Pu) and natural ($^{40}$K) radionuclides. Eight carcasses of small passerine birds from fringes of the primary tropical rainforest in the vicinity of Jima were also subjected to multielement analysis by inductively coupled plasma-mass spectrometry (ICP-MS) on a PlasmaQuad instrument (VG Elemental) in the Institute of the Geology of Ore Deposits, Petrography, Mineralogy, and Geochemistry, Russian Academy of Sciences (Moscow, Russia). Specifically, four olive sunbirds ($Nectarinia olivacea$), one yellow-bellied sunbird ($Nectarinia venusta$), two yellow-eyed canaries ($Serinus mozambicus$), and one tawny-flanked prinia ($Prinia subflava$) were studied.

### Analysis of Element Content in the Animals

ICP-MS, a new technique for chemical elemental analysis of the body composition, was first used in animal ecology studies only recently [3, 8, 10]. This technique provides data for estimating the accumulation of...
natural radionuclides and rare chemical elements, which are detectable at concentrations greater than \( n \times 10^{-12} \). The data of this analysis are shown in Table 1. The bodies of Ethiopian birds contained no Rh, Re, Ir, Hg, Tl, or U. These are the elements that we have found in small passerine birds inhabiting other areas, e.g., in all birds studied in the Rostov oblast and most specimens from the Krasnodar krai (Russia). However, birds from Adygeya (Russia) also had no Ir [3]. We estimated the natural radionuclide (thorium and uranium) content in small passerine birds from eight different areas (Fig. 1). Analysis of variance showed that both thorium and uranium contents significantly varied among the areas (d.f. = 8 + 32, \( F = 10.304, P < 0.001 \) for thorium and d.f. = 8 + 32, \( F = 17.345, P < 0.001 \) for uranium). The lowest content of natural radionuclides was observed in the bird carcasses from Ethiopia.

**Accumulation of Artificial Radionuclides**

Table 2 shows the artificial radionuclide contents in bones of the mammals collected in January 1987.

Interestingly, a natural radioisotope \(^{40}\text{K}\) was present at a higher level than the artificial long-lived \(^{137}\text{Cs}\) in all but one of the samples. The second interesting fact was the ubiquitous presence of \(^{134}\text{Cs}\) at well-detectable concentrations. The only conceivable source of this radionuclide with the half-life of 2.06 years is the Chernobyl fallout. During the Chernobyl accident, the environmental contamination with \(^{134}\text{Cs}\) accounted for 0.15 mCi. This is half the amount of \(^{137}\text{Cs}\), the main long-lived Chernobyl-derivable contaminant [6]. As the measurements of \(^{134}\text{Cs}\) were made nine months after the Chernobyl accident, these data provide irrefutable evidence that the accident plume also passed over Ethiopia. The radiological studies in Ethiopia were undertaken in order to understand whether this country can serve as a clean control in studies of radionuclide migrations along food chains in natural ecosystems. The results of these measurements demonstrated that Ethiopia is not free of radioactive contamination and that the level of its radioactive contamination does not significantly differ from that of Turkmenistan [5] and Mongolia (Tables 2, 3).

We compared the data on the radionuclide content in birds and mammals in Ethiopia with those obtained in other arid regions [2] and the data of Krivolutskii and Sokolov on arid ecosystems of Australia (Table 4). Analysis of variance showed that \(^{137}\text{Cs}\) in birds and mammals significantly varied among areas (d.f. = 3 + 25, \( F = 9.006, P = 0.003 \)). For \(^{80}\text{Sr}\), the effect of the factor “area” was not significant (d.f. = 4 + 29, \( F = 1.479, P = 0.2341 \)). The radionuclide content was 23 times greater in animals from the Rostov oblast (Russia) than in those from Australia and 10 times greater than in ani-

### Table 2. Radionuclide content in the bones of wild mammals of Ethiopia nine months after the Chernobyl accident (data of 1987, Bq/kg dry weight)

<table>
<thead>
<tr>
<th>Species</th>
<th>Date of collection</th>
<th>(^{137}\text{Cs})</th>
<th>(^{134}\text{Cs})</th>
<th>(^{40}\text{K})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warthog</td>
<td>23.01.87</td>
<td>45.5</td>
<td>14.8</td>
<td>26.5</td>
</tr>
<tr>
<td>Oribi</td>
<td>23.01.87</td>
<td>25.2</td>
<td>16.5</td>
<td>328.6</td>
</tr>
<tr>
<td>Bushbuck</td>
<td>21.01.87</td>
<td>40.6</td>
<td>15.5</td>
<td>60.6</td>
</tr>
<tr>
<td>Common reedbuck</td>
<td>22.01.87</td>
<td>1.9</td>
<td>1.9</td>
<td>48.5</td>
</tr>
<tr>
<td>Topi</td>
<td>22.01.87</td>
<td>5.9</td>
<td>1.7</td>
<td>10.6</td>
</tr>
</tbody>
</table>
mals from Ethiopia. Therefore, compared to Australia, eastern Africa is the area that experienced an increased global fallout of radionuclides. Note that all the natural ecosystems studied were contaminated with radioactive plutonium, in addition to radioactive cesium and strontium.

In conclusion, artificial radionuclides were found in animals of Ethiopia at concentrations corresponding to the level of radioactive contamination of the Palearctic biota. The presence of trace amounts of plutonium and $^{134}$Cs within one year after the Chernobyl accident suggested that Ethiopia also experienced the global radioactive fallout. Thorium was found in trace amounts, whereas uranium was absent. Therefore, we conclude that wild animals of Ethiopia are useful objects for global ecological monitoring, but they cannot serve as a radioecologically clean control.

ACKNOWLEDGMENTS

We are grateful to A.A. Darkov, A. Varshavskii, and P. Morozov for their assistance during the field work and to O.F. Chernova and D.A. Krivolutskii for their materials.

This work was supported by the Russian State Science and Technology Program “Biodiversity” and the Russian Foundation for Basic Research.

**Table 3.** Radionuclide content in bones of wild mammals and biota of Ethiopia in 1989 and 1998, Bq/kg dry weight

<table>
<thead>
<tr>
<th>Species</th>
<th>Date of collection</th>
<th>Radionuclide</th>
<th>137Cs</th>
<th>90Sr</th>
<th>238, 239, 240Pu</th>
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<tr>
<td>Soil (rainforest)</td>
<td>1998</td>
<td>8.76</td>
<td>10.9</td>
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<tr>
<td>Abyssinian cherry (ash)</td>
<td>1998</td>
<td>1.2</td>
<td>7.97</td>
<td>6.0</td>
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<tr>
<td>Birds</td>
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<td></td>
</tr>
<tr>
<td>Hen</td>
<td>1998</td>
<td>0.41</td>
<td>60.8</td>
<td>–</td>
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</tr>
<tr>
<td>African marabou</td>
<td>1998</td>
<td>1.9</td>
<td>6.6</td>
<td>2.0</td>
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<tr>
<td>Indian white-rumped vulture</td>
<td>1998</td>
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<td>198.71</td>
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<td>9.739</td>
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<tr>
<td>Gerenuk</td>
<td>1989</td>
<td>1.053</td>
<td>16.01</td>
<td>0.9</td>
<td></td>
</tr>
</tbody>
</table>

**Table 4.** Radionuclide contents in birds and animals inhabiting various arid regions in the 1990s (Bq/kg dry weight; mean ± standard deviation)

<table>
<thead>
<tr>
<th>Region</th>
<th>Radionuclide</th>
<th>137Cs</th>
<th>90Sr</th>
<th>238, 239, 240Pu</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rostov oblast</td>
<td>2</td>
<td>81.55</td>
<td>154.5</td>
<td>1.35 ± 1.77</td>
</tr>
<tr>
<td>Dagestan</td>
<td>3</td>
<td>8.40</td>
<td>173.5</td>
<td>–</td>
</tr>
<tr>
<td>Mongolia</td>
<td>13</td>
<td>8.31</td>
<td>147.6</td>
<td>0.57 ± 0.47</td>
</tr>
<tr>
<td>Ethiopia</td>
<td>11</td>
<td>3.51</td>
<td>67.95</td>
<td>0.94 ± 0.51</td>
</tr>
<tr>
<td>Australia*</td>
<td>–</td>
<td>–</td>
<td>43.88</td>
<td>&lt;2 ± 0</td>
</tr>
</tbody>
</table>

* Unpublished data of Krivolutskii and Sokolov.
REFERENCES


