Appendix H

Internal Dose Estimates from Global Fallout

Radiation Dose to the Population of the Continental United States from the Ingestion of Food Contaminated with Radionuclides from High-yield Weapons Tests Conducted by the U.S., U.K., and U.S.S.R. between 1952 and 1963

Final Report

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Report to the National Cancer Institute
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Radiation Dose to the Population of the Continental United States from the Ingestion of Food Contaminated with Radionuclides from Nuclear Tests at the Nevada Test Site

Part I. Estimates of Dose

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TABLE OF CONTENTS

ABSTRACT

According to a Congressional request to the Department of Health and Human Services, a feasibility study is being conducted to study the health consequences to the American peoples of nuclear weapons tests. This report concerns calculations of the dose from the consumption of food contaminated by radionuclides deposited or distributed with global fallout, which originated from high-yield tests conducted in the Northern Hemisphere by the U.S., the U.K. and the U.S.S.R. Such tests were conducted in 1952–1958 and 1961–1962. Results of this part of the feasibility study indicate that such doses can be calculated, as have similar doses from the tests conducted at the Nevada Test Site. The methods of calculation for ^{90}Sr, ^{131}I, and ^{137}Cs are based upon the methods developed and used earlier by the Off-Site Radiation Exposure Review Project; these methods employed seasonally adjusted values of radioecological transfer of radionuclides to humans.

For ^{90}Sr and ^{137}Cs, doses were calculated on a yearly basis for 1953 through 1972 for each county in the contiguous U.S. for adults and for persons born on 1 January 1951; doses during the latter years were well beyond the time period of the actual tests, but these long-lived radionuclides were still being deposited from the reservoir in the stratosphere. Doses from ^{131}I were estimated only on a country-average basis, as county-by-county deposition levels were not available; doses from ^{131}I were estimated for the 1953–1963 years. Doses from ^{3}H and ^{14}C were calculated with the use of specific activity models, and calculations were carried out for the actual doses received in 1952–2000. Detailed results are provided in a CD that accompanies this report. Summary results in the form of coded maps are provided for ^{90}Sr and ^{137}Cs. The total estimated collective effective dose from the five radionuclides considered is estimated to be 66,000 person Sv; the collective dose to the thyroid is 210,000 person Sv. The estimated per caput effective dose is 400 μSv. These doses are somewhat smaller than the doses previously estimated to have occurred in the contiguous U.S. from the atmospheric tests conducted at the Nevada Test Site. The more important radionuclides in global fallout (on an effective dose basis) were ^{14}C and ^{137}Cs, whereas the dose from the Nevada tests is dominated by ^{131}I.

A comparison is made of the doses calculated with the current method with doses that can be derived from measurements of global fallout radionuclides in milk as reported by the U.S. Public Health Service's Pasteurized Milk Network for the time period of 1960–1963 first quarter. The results are in good agreement for ^{90}Sr and ^{131}I; calculated results for ^{137}Cs are higher than those based upon the milk measurements, but this is expected as a substantial fraction of dose from ^{137}Cs arises from the consumption of meat.

A list is provided of major references concerning the occurrence of global fallout and calculations of dose from these radionuclides.

The presently available calculations of dose from ^{131}I in global fallout are limited and are not available on a county-by-county basis. Recommendations are provided on how to improve this situation by the use of measured values of global fallout in milk, other foods, cattle thyroids, and air.

PREFACE

Congress has asked the Department of Health and Human Services (HHS) to study the health consequences to the American people of nuclear weapons tests. Within that framework a purchase order has been received to assist in the determination of radiation dose to the American people from large atmospheric nuclear weapons tests conducted by the U.S. and the U.K. in the Pacific and by the former U.S.S.R., primarily near the Arctic Circle. Such doses are commonly referred to as resulting from "global fallout."

The tasks to be performed under the terms of the purchase order are:

1. "The primary work to be performed is to prepare crude estimates of the doses of internal radiation received by the American people as a result of the aboveground tests carried out at sites outside the continental U.S. including the Marshall Islands, Kazakhstan, and Russia. These estimates would be:

   - "Based on a review of the readily available literature and information found in scientific journals and published reports; it is not expected that sophisticated computer models should be developed or used for this purpose. For the purposes of this assessment, an electronic database of fallout deposition will be provided by NCI;
   - "Averaged over states or latitudinal bands of the continental U.S., with indications on how the high-risk populations could be identified. However, if feasible, primary calculations should be carried out on a county by county basis, and averaged only for presentation purposes;
   - "Calculated separately for the most important radionuclides produced in nuclear weapons tests. These would include, but would not be limited to H-3, C-14, Sr-90, Cs-137, and I-131. Estimates of dose from Sr-90 and Cs-137 will use the deposition databases provided by NCI while estimates of dose from H-3 and C-14 will use methods published by other investigators and by UNSCEAR in its 1993 report as well as in previous reports. Estimates of dose from I-131 will also use the data provided by NCI, though the dose estimates to be reported will be limited to a nationwide collective dose estimate.
   - "Provided in terms of absorbed doses for some of the most radiosensitive organs and tissues (red bone marrow, gastro-intestinal tract, and thyroid).
   - "Calculated by year of testing in the 1950s and 1960s, and summed over the most significant tests worldwide (other than those tests conducted at the Nevada Test Site), with a comparison to the published UNSCEAR latitudinal averages for all tests.
   - "Calculated for persons born on 1 January 1951 and residing continuously in the counties of birth. This calculation will use age-corrected coefficients.

2. "For selected areas of the continental U.S. and for selected years of fallout, compare the internal dose estimates calculated in item 1 for Sr-90, Cs-137, and I-131 with those derived from the measurements of fallout radionuclides in foodstuffs.

3. "Provide a list of the most significant references regarding: (1) the networks of measurements of fallout radionuclides in air and foodstuffs, and (2) the assessment of the doses from internal radiation.
4. "The report to be provided shall discuss limitations on presently calculating county-specific dose estimates from global sources of I-131 and shall discuss feasibility for future work and methods that might be implemented in such work."

The funds made available to accomplish this work consisted of $24,900. Thus, it was necessary to find very efficient means to accomplish this complex task.

INTRODUCTION

In previous reports (Anspaugh 2000; Beck 1999) doses were estimated for the 48 contiguous states from fallout derived from the tests of nuclear weapons-related devices at the Nevada Test Site (NTS). Results in Beck (1999) were for external exposure and dose, and results in Anspaugh (2000) were for doses from the ingestion of contaminated foods. The latter report was based upon estimates of deposition density as calculated by Beck (1999) for 19 radionuclides. These radionuclides were selected for analysis on the basis of screening calculations that had been performed previously by Ng et al. (1990) for the Off-Site Radiation Exposure Review Project (ORERP); these screening calculations indicated that 21 radionuclides were estimated to be responsible for about 95% of the total dose from the ingestion pathway for the radionuclides released at the NTS. Doses were not calculated in Anspaugh (2000) for two (^{135}I and ^{239}Np) of the 21 radionuclides, as estimates of deposition density were not available[*] at the time when the calculations were made. Most of the 19 radionuclides had relatively short half lives, but were more important in a dosimetric sense than the long-lived radionuclides due to the rapid entry of local and regional fallout into food chains.

For global fallout the radionuclides of concern are different for several reasons. The first is that global fallout by definition consists of radioactive debris that is globally dispersed due to its injection into the high atmosphere by large explosions. Due to its injection at high altitudes, global fallout typically does not return to earth for one or more years. During this time the short-lived fission products decay to small levels, and, except for unusual occurrences, the short-lived radionuclides of interest for NTS fallout are not of concern. Two radionuclides, ^{90}Sr and ^{137}Cs, have long half lives (about 30 y each) and do not decay appreciably before they return to earth. Historically, these radionuclides have been studied extensively due to their presence in global fallout and due to concern about adverse health effects from the ingestion of these two radionuclides.

Another factor of importance is that global fallout originates from high-yield weapons that typically derive much of their yield from fusion reactions. These explosions produce or "spill" large amounts of ^{3}H, and the intense neutron flux also produces large amounts of ^{14}C through the reaction ^{14}N(n,p)^{14}C. Because ^{3}H and ^{14}C enter their respective hydrogen and carbon cycles and do not deposit in the same manner as do radionuclides associated with particulate matter, the usual methods of calculating deposition and dose are not appropriate; rather the

[*] Estimates of deposition density for ^{239}Np are now available from Beck (personal communication). If more detailed studies are to follow the current feasibility studies, the dose from ^{239}Np should be included.

specific activity approach has been used (UNSCEAR 1993). In order to calculate the dose from ^{3}H and ^{14}C, it is necessary to derive source terms (the activity created per unit fusion-explosion energy) and to estimate the fusion yields as a function of time. In general there is little movement of radionuclides across the hemispheric boundary, so it is also important to know the fusion yield in the northern hemisphere for this assessment. Most of the fusion yields occurred in the northern hemisphere, but with substantial amounts near the equator. The conservative assumption is made here that the resulting radionuclides remained in the northern hemisphere.

The fusion yields estimated to have occurred in the northern hemisphere as a function of time are indicated in Table 1. These values were derived from total yield values reported in UNSCEAR (1993), DOE (1994), and Mikhailov et al. (1996); and with subtraction of the fission yields derived by Beck (2000).

Due to widespread concern about global fallout and its effects on man, scientists from many countries have studied fallout beginning in the 1950s. Such concern was a primary reason that led to the formation of the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), which has studied global fallout over many years and has issued a number of assessments of dose with primary interest on calculating global averages of dose. In its most recent assessment of global-fallout dose the UNSCEAR (1993) provided the estimates indicated in Table 2 of the doses from the ingestion of food contaminated by global fallout.

Table 1. Estimated fusion yields exploded in the northern hemisphere as a function of time. Values are estimated from total yields in UNSCEAR (1993), DOE (1994), and Mikhailov et al. (1996); minus the fission yields estimated by Beck (2000). Explosions close to the equator are conservatively considered to have injected their debris into the northern hemisphere only.

Year	Fusion yield, megatons
1952	5.0
1953	0.36
1954	17
1955	0.88
1956	13
1957	3.9
1958	31
1959	0
1960	0
1961	69
1962	99
Total	240

Table 2. Effective dose commitments estimated by UNSCEAR (1993) for the northern temperate zone (40°–50° latitude) from radionuclides produced by the testing in the atmosphere of large nuclear weapons. Estimates below are for "global" fallout and arise primarily from the injection of radionuclides into the upper atmosphere of the northern hemisphere.

Radionuclide	Dose commitment, μSv
^{3}H	48
^{14}C	78[a]
^{55}Fe	14
^{89}Sr	2.3
^{90}Sr	170
^{131}I	79
^{137}Cs	280
^{140}Ba	0.42
^{238}Pu	0.0009
$^{239+240}Pu$	0.50
^{241}Pu	0.004
^{241}Am	1.5
Sum	670

[a] The UNSCEAR (1993) value of 2600 μSv over all time was multiplied by a factor of 0.03, the portion estimated to be delivered in 50–70 y.

On the basis of the data in Table 2, and in accordance with the requirements for the purchase order, the radionuclides selected for examination during this feasibility study include ^{3}H, ^{14}C, ^{90}Sr, ^{131}I, and ^{137}Cs. These radionuclides account for all but a small fraction of the estimated dose to man from global fallout. The prominence of ^{131}I on the list may be surprising, as its half life is only eight days. The appearance of ^{131}I in global fallout has tended to be sporadic, but contaminated milk in the U.S. had been observed on a number of occasions (e.g., Dahl et al. 1963; Terrill et al. 1963). Possible mechanisms for these sporadic occurrences have been suggested by Machta (1963) and include

- The subsidence of large air masses contaminated with debris from U.S.S.R. tests at its Novaya Zemlya site near the Arctic Circle, and
- The penetration of large thunder storms into the upper troposphere and stratosphere that resulted in the scavenging of fresh debris from the U.S. tests in the Pacific.

The assessment of dose from ^{14}C is particularly difficult, due to its long half life of 5730 y. The UNSCEAR (1993) has assessed the intergenerational dose due to this radionuclide, and under such considerations it is the most significant radionuclide in global fallout. The relative importance of ^{14}C is much less, if the dose during the first 50–70 y is considered. Further, the carbon cycle is complex (as evidenced by the current controversy over global warming due to the release of carbon dioxide), and dose assessments must rely on complicated models. Thus, the projections of dose into the future for this radionuclide are only approximate, but estimates of dose through the present time are firmly based upon measurements of ^{14}C in food, water, and humans.

Estimates of dose from ^{3}H are considered to be more reliable, as this radionuclide has a much shorter half life of 12 y, and the hydrogen cycle is not as complicated as that of carbon. As for ^{14}C, estimates of dose through the present time are firmly based upon measurements of ^{3}H in food, water, and humans.

The purpose of this report is to fulfill the requirements of the purchase order referenced in the Preface. The estimates of dose (Task 1) from global fallout for the radionuclides indicated above are summarized in Part I of this report, as are the methods used to perform the calculations. An accompanying CD-ROM contains the detailed results of the calculations on a county-by-county basis for ^{90}Sr and ^{137}Cs; more details of the results for ^{3}H, ^{14}C, and ^{131}I are also provided on the CD, but results for these radionuclides are available only as averages over the continental U.S. Part II of this report contains all other information requested (Tasks 2, 3, and 4).

METHODS

The methods of dose calculation used in this report for ^{90}Sr, ^{131}I, and ^{137}Cs are similar to those used previously for the calculations of dose from tests at the NTS (Anspaugh 2000). The specific activity approach is used to calculate doses from ^{3}H and ^{14}C; the methods used for ^{3}H and ^{14}C are similar to those used by the UNSCEAR (1993).

Nuclear events of interest

This report includes doses from all high-yield nuclear events that took place within the northern hemisphere during the years from 1952 through 1963; such tests were stopped in 1963 by the U.S., the U.K., and the U.S.S.R. Tests at the NTS are not included in this report, as such tests were not high-yield, and doses from the ingestion of contaminated foods from NTS tests have been included in a previous assessment (Anspaugh 2000).

Because tests of high-yield weapons inject much of their debris into the stratosphere from which it devolves slowly over time, it is not generally possible to identify global fallout with a particular test. Rather, doses have been calculated on a monthly basis for ^{90}Sr, ^{131}I, and ^{137}Cs and on a yearly basis for ^{3}H and ^{14}C.

Internal dose from ^{90}Sr and ^{137}Cs

Doses from ^{90}Sr and ^{137}Cs were estimated by a process similar to that used for radionuclides from NTS fallout (Anspaugh 2000). The basic calculation is shown in equation (1):

$$D = P \times I \times F_g , \tag{1}$$

where D = Absorbed dose, Gy, or equivalent/effective dose, Sv;
P = Deposition density of the radionuclide of interest at time of fallout arrival, Bq m^{-2};

I = Integrated intake by ingestion of the radionuclide per unit deposition, Bq per Bq m^{-2}; and

F_g = Ingestion-dose coefficient for the radionuclide, Gy Bq^{-1} or Sv Bq^{-1}.

Deposition density. Values of deposition density, P, for ^{90}Sr were furnished by Beck (2000) on behalf of the National Cancer Institute (NCI) on a county-by-county basis averaged over each month for the years of 1953 through 1972.[†] Values for the deposition density for ^{137}Cs were derived from those of ^{90}Sr by multiplying the ^{90}Sr results by a factor of 1.5, as recommended by Beck (2000) [a similar relationship has been used by UNSCEAR (1993)].

Integrated intake. Monthly average values of integrated intake, I, were derived from Whicker and Kirchner (1987) by interpolation of the date-specific values in that publication. The age-related values used in this study are shown in Figs. 1 and 2 for ^{90}Sr and ^{137}Cs, respectively.

Values of integrated intake are complex functions of age- and season-dependent intake rates of different foods and the season-dependent radioecological movement of radionuclides through food chains. Whicker and Kirchner (1987) developed the PATHWAY model to estimate integrated intake for the ORERP studies. The food-consumption rates used in the

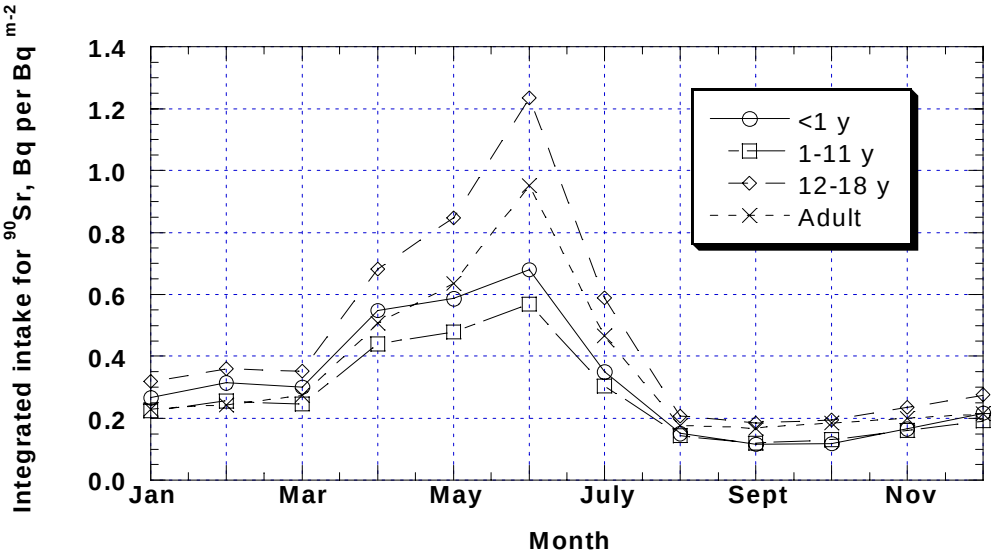

Fig. 1. Monthly average values of integrated intake of ^{90}S for four age groups. Data were derived from Whicker and Kirchner (1987).

[†] These years do not match the years of testing indicated on the previous page. Fallout from the 1952 tests occurred mainly in 1953 and afterward; fallout from the tests in the early 1960's was still measurable in 1972.

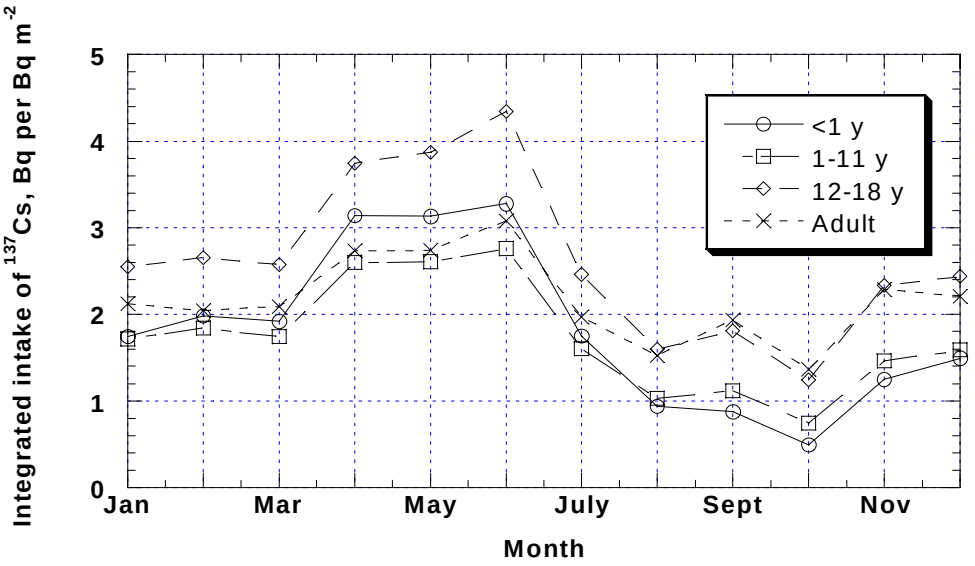

Fig. 2. Monthly average values of integrated intake of ^{137}Cs for four age groups. Data were derived from Whicker and Kirchner (1987).

PATHWAY model are shown in Table 3. The fractions of different food types that are assumed to be locally produced are indicated in Fig. 3, and the consumed fraction of non-leafy vegetables and fruits assumed to be freshly produced is shown in Fig. 4.

The radioecological component of PATHWAY is complex and includes many factors:

- Initial retention of radionuclides by vegetation;
- Loss of radionuclides from vegetation as a function of time;

Table 3. Food-consumption rates used in the PATHWAY code (Whicker and Kirchner 1987). Estimates are based primarily on data summarized by Rupp (1980) for rural families.

Food type	Food-consumption rates by age group, fresh kg day^{-1}			
	<1 y	1–11 y	12–18 y	≥19 y
Milk	0.800	0.623	0.635	0.360
Milk products	0.144	0.074	0.143	0.062
Beef	0.044	0.113	0.210	0.277
Poultry	0.003	0.017	0.028	0.030
Eggs	0.017	0.026	0.036	0.053
Leafy vegetables	0.002	0.021	0.036	0.062
Stored fruits and vegetables	0.207	0.266	0.356	0.360
Grains	0.025	0.025	0.151	0.137

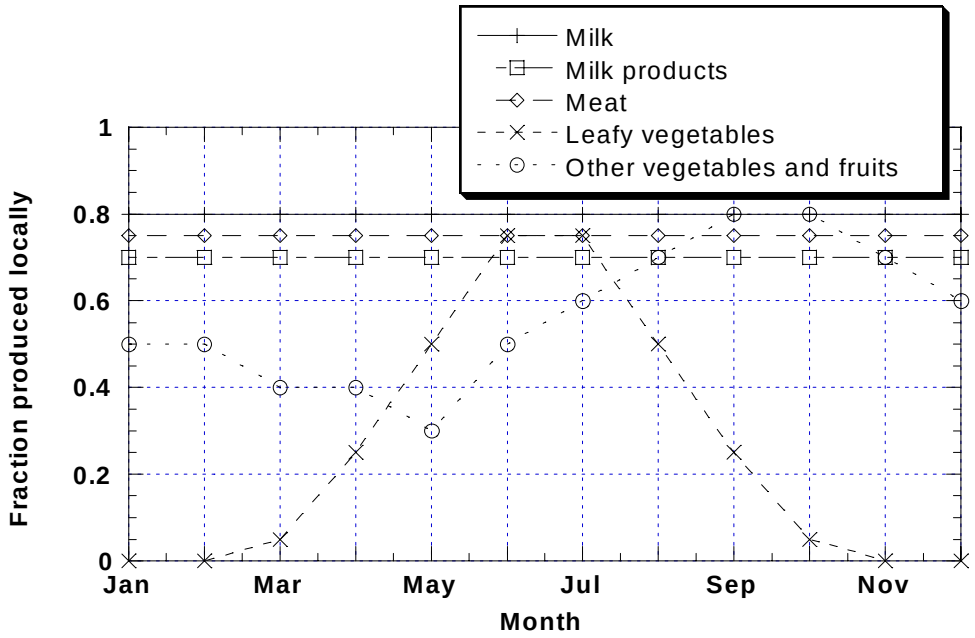

Fig. 3. Fraction of food that is assumed to be locally produced for several different food categories. Values for eggs are the same as those for milk. From Whicker and Kirchner (1987).

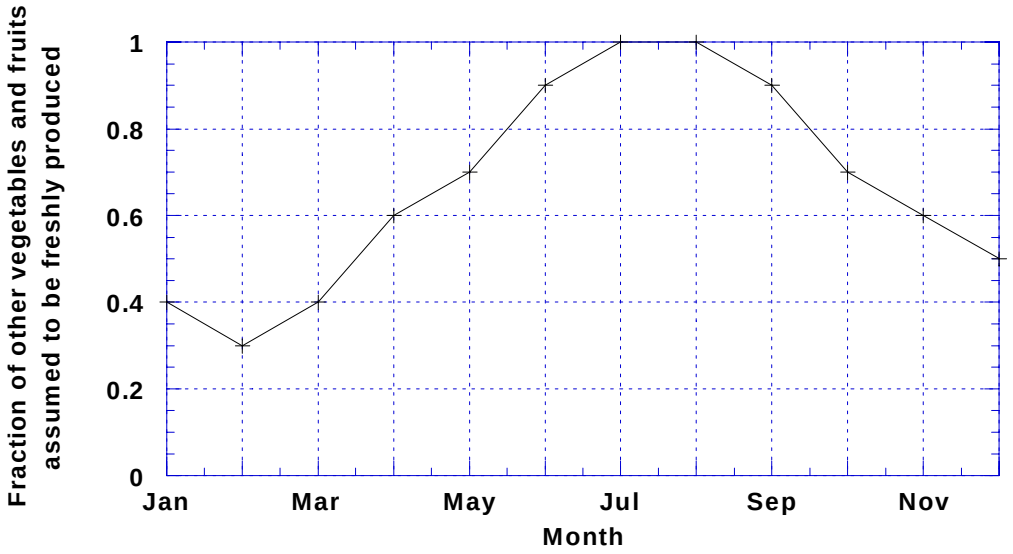

Fig. 4. Consumed fraction of non-leafy vegetables and fruits assumed to be freshly produced. From Whicker and Kirchner (1987).

- Dilution of radionuclide concentration in fresh vegetation by plant growth;

- Movement of radionuclides through several soil compartments;
- Uptake of a radionuclide through the soil-root system; and
- Recontamination of plant surfaces by resuspension and redeposition and by rain splash.

One of the critical factors that is known to vary substantially is the initial retention of fallout by fresh vegetation, particularly when deposition occurs with precipitation (Anspaugh 1987; NCI 1997). The value used for this parameter in PATHWAY is 0.39 m^2 kg^{-1}. Its value is known to vary with particle size (and distance from the site of detonation) for dry deposition and with rainfall rate for wet deposition. In addition, values vary substantially for reasons that are not yet explicable. Thus, uncertainty in this parameter contributes substantially to the uncertainty in the estimates of internal dose.

Although the values of integrated intake were originally derived for dry deposition in the semi-arid western areas of the U.S. nearby the NTS, this same value has been used for the entire study performed here. Based upon the experimental data reported by Hoffman et al. (1989), the value of 0.39 m^2 kg^{-1} is actually a reasonable value for retention of radionuclides in rainfall, except during conditions of very light rain when higher values have been observed.

Dose coefficients. The ICRP (1989, 1993, 1995, 1996) has provided compilations of dose coefficients, F_g, for ingestion of radionuclides by members of the general public. These published values, however, are incomplete in the sense that dose coefficients are not listed for all organs for all age groups. Recently, the ICRP (1998) has made available a CD-ROM system that allows the calculation of equivalent and effective doses for all organs for the six age groups[‡] considered by the ICRP. The dose-coefficient values provided by the ICRP represent the dose from a given intake that will occur over the next 50 years for adults or until age 70 y for the younger age groups; such values are commonly referred to as coefficients of committed dose.

ICRP (1998) is the source of dose coefficients used for this dose assessment. As for previously performed assessments (Ng et al. 1990), the ICRP dose coefficients have been considered to be average values (or arithmetic means). For the assessment for doses from tests at the NTS (Anspaugh 2000), the ICRP coefficients were converted to geometric means, so that uncertainties could be propagated in a consistent manner. As the deposition-density values provided by Beck (2000) for global fallout do not have attached uncertainty values, the dose coefficients used for this assessment have been used directly from ICRP (1998). The dose coefficients used in this study are indicated in Table 4.

For ^{90}Sr, dose coefficients for the unlisted organs are essentially the same as the dose coefficient for the thyroid; as ^{90}Sr (and its progeny) is a "pure" beta-emitting radionuclide that localizes in the bone, the higher doses are to the bone marrow and to the bone surface. The dose coefficient for ^{90}Sr is also somewhat higher for the colon, due to the transit of the beta emitter. On the other hand, ^{137}Cs is distributed throughout the body and delivers most of its dose from the emission of a gamma ray by its short-lived progeny ^{137m}Ba. Thus, while dose coefficients for

[‡] The six age groups considered by the ICRP are 1) "three months" [0 to 12 months], 2) "one y" [from 1 y to 2 y], 3) "five y" [>2 y to 7 y], 4) "10 y" [>7 y to 12 y], 5) "15 y" [>12 y to 17 y], and 6) "adult" [>17 y].

^{137}Cs for the colon are nearly twice as high as the effective dose coefficient, the dose coefficients for the unlisted organs are approximately the same as the effective dose coefficient.

Table 4. Age-dependent dose coefficients for members of the public used in this study for ^{90}Sr and ^{131}I. Values are from ICRP (1998)

ICRP age category	Dose coefficient for the indicated radionuclide and organ, Sv Bq^{-1}						
	^{90}Sr Bone Sur[a]	^{90}Sr Colon[b]	^{90}Sr Red marr[c]	^{90}Sr Thyroid	^{90}Sr Effective	^{137}Cs Colon	^{137}Cs Effective
3 mo	2.3×10^{-6}	1.2×10^{-7}	1.5×10^{-6}	1.2×10^{-8}	2.3×10^{-7}	3.8×10^{-8}	2.1×10^{-8}
1 y	7.3×10^{-7}	8.9×10^{-8}	4.2×10^{-7}	5.5×10^{-9}	7.3×10^{-8}	2.3×10^{-8}	1.2×10^{-8}
5 y	6.3×10^{-7}	4.5×10^{-8}	2.7×10^{-7}	2.9×10^{-9}	4.7×10^{-8}	1.5×10^{-8}	9.6×10^{-9}
10 y	1.0×10^{-6}	2.6×10^{-8}	3.7×10^{-7}	1.8×10^{-9}	6.0×10^{-8}	1.3×10^{-8}	1.0×10^{-8}
15 y	1.8×10^{-6}	1.5×10^{-8}	4.9×10^{-7}	1.1×10^{-9}	8.0×10^{-8}	1.5×10^{-8}	1.3×10^{-8}
Adult	4.1×10^{-7}	1.3×10^{-8}	1.8×10^{-7}	6.6×10^{-10}	2.8×10^{-8}	1.5×10^{-8}	1.3×10^{-8}

[a] Bone surface
[b] Weighted mass average of dose coefficients for the lower and upper large intestine
[c] Red bone marrow

Age groups. Doses were calculated on a county-by-county basis for adults and for an individual who was born on 1 January 1951.

Dose from ^{131}I

For ^{131}I calculations were also based on eqn (1). Beck (2000) did not provide county-by-county estimates of deposition density for ^{131}I, as more analysis would be required beyond that possible for this feasibility study. Rather, rough estimates of deposition density were provided on a population-weighted basis for the entire country. As for ^{90}Sr and ^{137}Cs, monthly averages of age-dependent integrated intake values were derived from Whicker and Kirchner (1987). The values used in this study are shown in Fig. 5. Dose coefficients were taken from the ICRP (1998); the values used are listed in Table 5. Calculations were made for adults and for individuals born on 1 January in each of the years from 1951 through 1963. In addition, because the dose from ingestion of ^{131}I varies strongly with age, per caput values of dose were calculating by considering the age distribution of the population in 1960 and by calculating a population-weighted average value of dose. For the latter calculation, age-dependent values of integrated intake and dose coefficients were used.

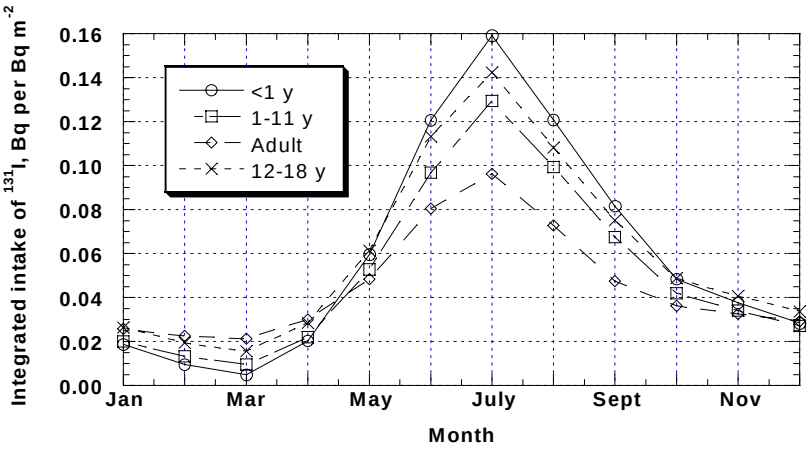

Fig. 5. Monthly average values of integrated intake for four age groups for ^{131}I. Data were derived from Whicker and Kirchner (1987).

Table 5. Age-dependent dose coefficients for ^{131}I used in this study for members of the public. Values are from ICRP (1998)

ICRP age category	Dose coefficient for ^{131}I for the indicated organ, Sv Bq^{-1}				
	Bone surface	Colon	Red marrow	Thyroid	Effective
3 mo	6.1×10^{-10}	2.6×10^{-9}	5.2×10^{-10}	3.7×10^{-6}	1.8×10^{-7}
1 y	4.4×10^{-10}	1.5×10^{-9}	3.7×10^{-10}	3.6×10^{-6}	1.8×10^{-7}
5 y	2.8×10^{-10}	6.5×10^{-10}	2.2×10^{-10}	2.1×10^{-6}	1.0×10^{-7}
10 y	1.9×10^{-10}	2.8×10^{-10}	1.6×10^{-10}	1.0×10^{-6}	5.2×10^{-8}
15 y	1.4×10^{-10}	1.5×10^{-10}	1.2×10^{-10}	6.8×10^{-7}	3.4×10^{-8}
Adult	1.3×10^{-10}	1.2×10^{-10}	1.0×10^{-10}	4.3×10^{-7}	2.2×10^{-8}

Dose from ^{3}H and ^{14}C

Doses for these two globally dispersed radionuclides were calculated on the basis of the specific activity approach. As the fusion yield in the northern hemisphere is an important input to the calculation for both radionuclides, the data shown in Table 1 were used as input values. Another important input is the amount of ^{3}H and ^{14}C created per Mt of fusion. UNSCEAR (1993) gives a value of 740 PBq Mt^{-1} for ^{3}H; a reasonable estimate for ^{14}C is 0.85 PBq Mt^{-1}.

Doses from ^{3}H were calculated with use of the NCRP (1979) model; a rough estimate can also be made on the basis of the estimated natural production rate of 37 PBq per y per hemisphere and the measured concentrations of ^{3}H in surface waters. The annual absorbed dose in tissue from naturally occurring ^{3}H was derived in UNSCEAR (1982) to be 10 nSv. Based upon these values a rough estimate of the average dose commitment from ^{3}H is

$$240\,\mathrm{Mt} \times 740\,\frac{\mathrm{PBq}}{\mathrm{Mt}} \times 10\,\frac{\mathrm{nSv}}{\mathrm{y}} \times \frac{1}{37}\,\frac{\mathrm{y}}{\mathrm{PBq}} = 48{,}000\,\mathrm{nSv}\ . \qquad (2)$$

However, this result does not provide any information on how this dose might be delivered over time. Use of the NCRP (1979) model provides a more sophisticated approach that

simulates the world's hydrological cycle through the use of seven compartments, which consist of atmospheric water, surface soil water, deep groundwater, surface streams and fresh water lakes, saline lakes and inland seas, ocean surface, and the deep ocean. The use of the hydrological cycle is appropriate, as most of the ^{3}H released is in the form of tritiated water or is soon converted to that form (from HT) in soil. Calculations are then made by considering the specific activity of ^{3}H in the various water compartments and the rate of change among the compartments.

Example results from the NCRP (1976) model of the dose over time from the release of 1 PBq of ^{3}H to the northern hemisphere are shown in Fig. 6. The annual dose falls off rapidly with time due to the mixing of the released ^{3}H into the larger compartments. The summary result of the data shown in Fig. 6 is that the release of 1 PBq of ^{3}H to the atmosphere in the northern hemisphere would result in a dose of 0.38 nSv to each person living in the hemisphere. The latter result is consistent with the value computed from eqn (2) of 0.27 nSv with consideration of the substantial uncertainty in both results.

The dose from the release of ^{14}C can be assessed in a rather similar way, although the carbon cycle is much more complicated. From UNSCEAR (1982, 1993) the natural production rate of ^{14}C is roughly 1 PBq y^{-1}, and the resulting equilibrium specific activity produces an annual effective dose of about 12 μSv. A calculation similar to that of eqn (2) could be made, but it would be potentially misleading due to the very long half life of ^{14}C and the very long time (more than one individual's life time) to achieve equilibrium. Thus, in order to calculate doses over the first 50 y from the release of ^{14}C, a compartment model for the global circulation of carbon was used. The model chosen is that of Titley et al. (1995), which is the latest model that has been widely accepted and which builds upon previously accepted models. The Titley et al. model is complicated and contains 23 compartments with separate compartments of two to four layers in each ocean. Carbon is considered to be in the form of CO_2, which is the form that enters the food chain. The model takes into account temperature changes, photosynthesis in the surface layers of the oceans, and transfer of carbon down the water column.

Example results of model calculations are shown in Fig. 7, which is a plot showing the annual doses from the release of 1 PBq of ^{14}C to the northern hemisphere. The summary result of the data shown in Fig. 7 is that the release of 1 PBq of ^{14}C to the atmosphere of the northern hemisphere would result in a dose of 0.7 μSv to each person living in the hemisphere over the following 50 y.

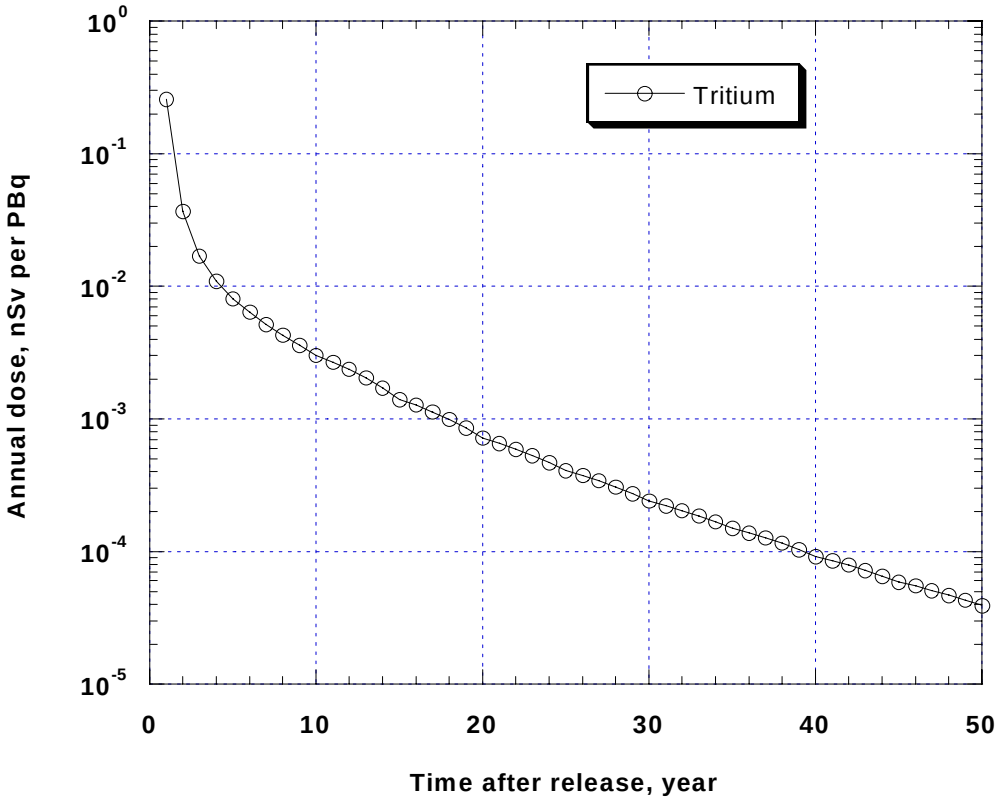

Fig. 6. Annual dose as a function of time following the release of 1 PBq of ^{3}H to the atmosphere of the northern hemisphere. Results are based upon the NCRP (1979) model of tritium in the hydrological cycle.

These model results for ^{3}H and ^{14}C are approximate, and no attempt has been made to derive age-dependent values. This is broadly appropriate for these two radionuclides and any other beta-emitting radionuclide that can be assessed using a specific activity approach. Also, as both radionuclides are distributed throughout the body, all organ and effective dose coefficients are presumed to be numerically equal.

Collective dose

Collective doses were also calculated. For ^{90}Sr and ^{137}Cs for which results were available on a county-by-county basis, the adult dose for each county was multiplied by its 1954 population with data supplied by Beck (2000) to give a county specific collective dose for each year (1953–1972). The use of adult doses for this calculation tends to underestimate the true collective dose; however, for ^{90}Sr and ^{137}Cs this effect is not as significant as it is for ^{131}I. Collective doses for each county were also summed to give a collective dose for each year. Finally, doses for all years were also summed to give the total collective dose to the 48 contiguous states.

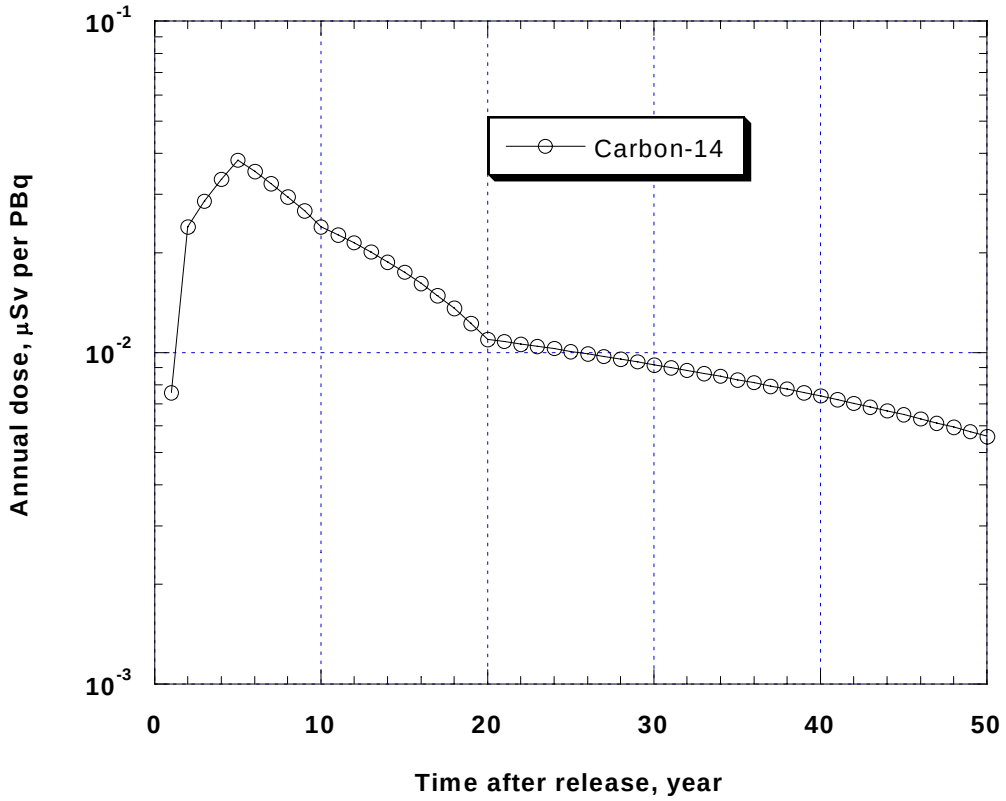

Fig. 7. Annual effective dose following the release of 1 PBq of ^{14}C to the atmosphere of the northern hemisphere. Results are based upon the model of Titley et al. (1995).

For ^{131}I deposition values were not available on a county-by-county basis, but on a population-weighted basis for the entire country. Collective doses were calculated by using the same procedure as mentioned in a previous section for per caput doses. That is, calculations were made with consideration of the age distribution of the population and appropriate values of age-dependent integrated intake and dose coefficient.

For ^{3}H and ^{14}C rough estimates of individual doses were calculated on a country-average basis; such values do not have an age dependence. Collective doses were calculated by simply multiplying the individual doses for the country by the country population in 1954.

RESULTS AND DISCUSSION

The results of the calculations made for this project are provided on a CD that accompanies this report. Information on the CD is organized as follows:

- There is one folder labeled “SrCs” that contains 21 workbooks; 20 are labeled GB1953 through GB1972 and one is labeled GB53-72, which is a summary of the doses for the 20-y period. Each of the 20 workbooks for individual years contains two spreadsheets; the first is labeled “Sheet1” and contains county-by-county data for estimates of

committed dose from ^{90}Sr and ^{137}Cs. Values are provided both for "adults" and for a person born on 1 January 1951. For ^{90}Sr estimates are provided for bone surface, colon, red marrow, thyroid, and effective dose; for ^{137}Cs estimates are provided for colon and effective doses. The second spreadsheet is labeled "Collective" and contains calculated values for collective dose on a county-by-county basis. In addition to data for the parameters indicated above, the sum of collective effective dose from both ^{90}Sr and ^{137}Cs is calculated. The summary workbook "GB53-72" contains similar data in two spreadsheets, but summarized over the entire period of the calculation.

- There is one spreadsheet labeled "GBLI131" that contains all calculations for dose from global fallout due to ^{131}I. Calculations are provided for bone surface, colon, red marrow, thyroid, and effective dose for adults and for persons born on 1 January in the years 1951 through 1963. Collective doses and per caput doses are provided on the same spreadsheet; such calculations were made using the fraction of the population falling into various age groups and appropriate values of age-dependent integrated intake and dose coefficient.
- A final spreadsheet is labeled "TritCarb" and contains estimates of dose for ^{3}H and ^{14}C. Doses are estimated on the basis of the inputs of fission yield from Table 1 and the time dependent annual dose factors from Figs. 6 and 7. Each year's input is tracked separately and summed for each individual year. The calculations extend through the year 2000.

The intent of the following material is to summarize the data contained on the CD in the files mentioned above.

Doses for individuals

^{90}Sr and ^{137}Cs. Estimates of committed dose are available on the CD-ROM for each county in the contiguous U.S.; values are provided for adults and for a person born on 1 January 1951. For ^{90}Sr estimates are given for dose to the bone surface, colon, red marrow, and thyroid and for effective dose. For ^{137}Cs estimates are given for dose to the colon and for effective dose. Reasons for the selections of these organs are discussed in the Methods Section. Such large amounts of data are more easily summarized graphically. Figs. 8–23 provide representative results for three years[§] and the sum of committed doses for the entire 1953–1972 period. Figs. 8–11 are results for the 1955 year. Figs. 8 and 9 present doses to the red bone marrow from ^{90}Sr for an adult and for a person born on 1 January 1951. Figs. 10 and 11 present effective doses from ^{137}Cs for an adult and for a person born on 1 January 1951. This pattern is repeated for the years of 1959 and 1963; the doses were the highest for the latter year. Finally, Figs. 20–23 present doses for the two age groups to the red bone marrow from ^{90}Sr and effective dose from ^{137}Cs that are summed over the entire period of calculation (1953–1972).

The appearance of the maps in Figs. 8–23 is influenced by the choice of the dose ranges used for the display. There are five dose ranges used for each map, and these dose ranges were selected in the following way with Figs. 8 and 9 used as illustrations. First, all of the data for the committed dose to the selected organ (or effective dose) for the selected radionuclide for the

[§] The 1955, 1959, and 1963 years that are plotted represent local maxima in dose; the committed dose in 1963 (resulting largely from explosions in 1962) was the highest.

3071 counties for both the adult and the person born on 1 January 1951 were combined into a single file and sorted. For Figs. 8 and 9 this combined file represented the committed doses to the red bone marrow from ^{90}Sr for the adult and for the person born on 1 January 1951 for all 3071 counties. Then, 10% of the 6142 combined sorted doses were assigned the color blue (lower doses) for each map, 25% green, 30% yellow, 25% orange, and 10% red (higher doses). Examination of Figs 8 and 9 indicates several features.

First, it is clear that the higher committed doses from ^{90}Sr occurred to persons living in the eastern third of the country, although there are also "hot spots" in the Midwest, and in parts of California, Idaho, Oregon, and Washington. These areas of higher committed dose are related primarily to the amounts of rainfall that occurred in these locations. Second, comparison of the two figures indicates that a person born on 1 January 1951 received higher committed doses than a person who was an adult, although these doses are not greatly different. For Figs. 10 and 11 the same technique was used, except that committed effective doses due to ^{137}Cs are plotted. The same geographical pattern is evident, but in this case the dose to the person born on 1 January 1951 is lower than to the adult. Whether doses are higher or lower for a particular age group depends upon 1) the time of year when the fallout occurred, which in turn affects 2) the relative values of the age-dependent integrated intakes [see Figs. 1 and 2], and 3) the values of the age-dependent dose coefficients [Table 4].

The per caput doses over the entire period of analysis are summarized in Table 6 for adults and for a person born on 1 January 1951. In general, the doses calculated for a person born in 1951 from ^{90}Sr are two-three times higher than for the adult, but the doses from ^{137}Cs are essentially the same for the two age groups. The sum of effective doses from ^{90}Sr and ^{137}Cs is 170 μSv for the adult and 210 μSv for the person born in 1951.

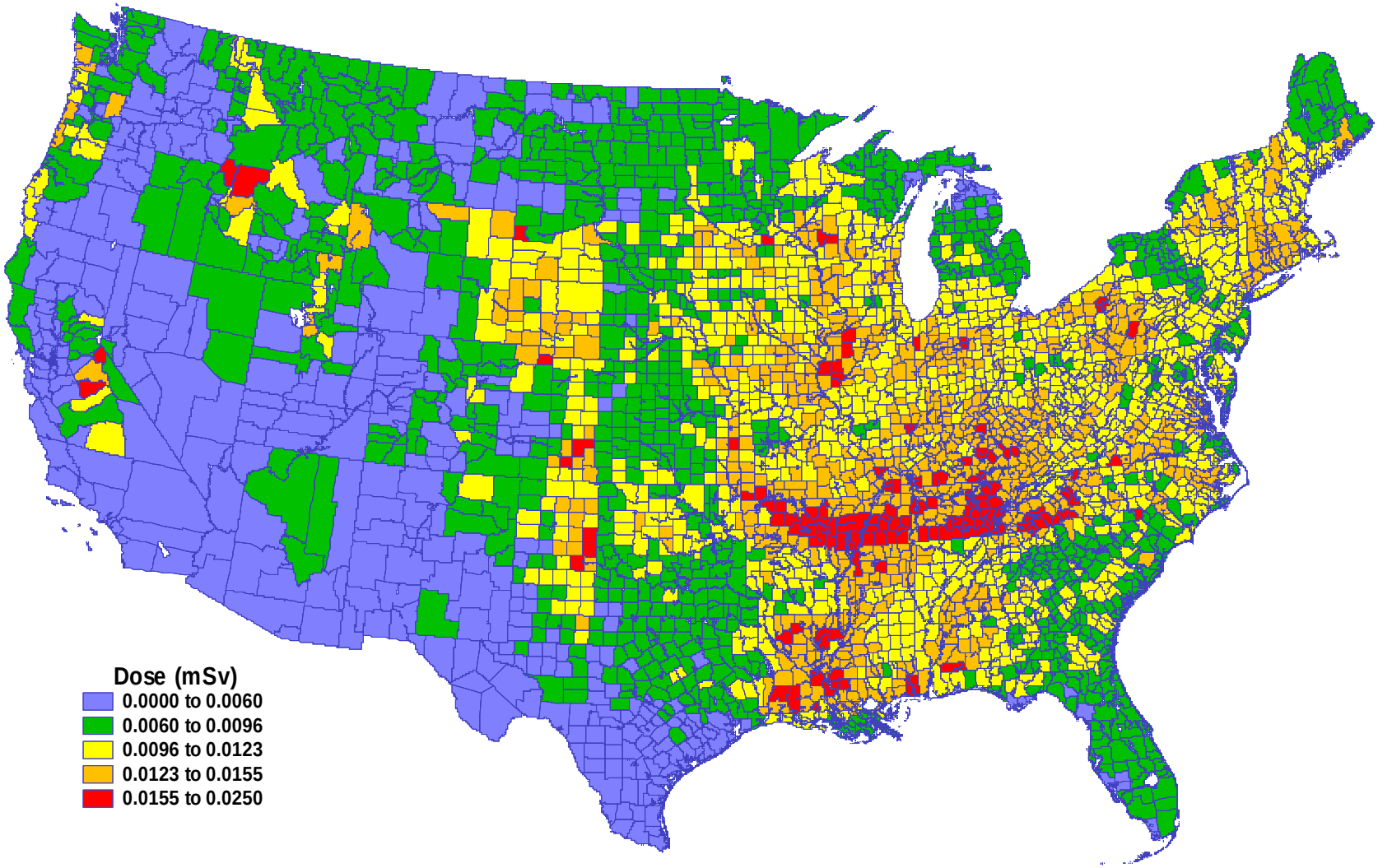

Fig. 8. Map of the committed dose (mSv) for an adult to the red bone marrow from ^{90}Sr deposited during 1955

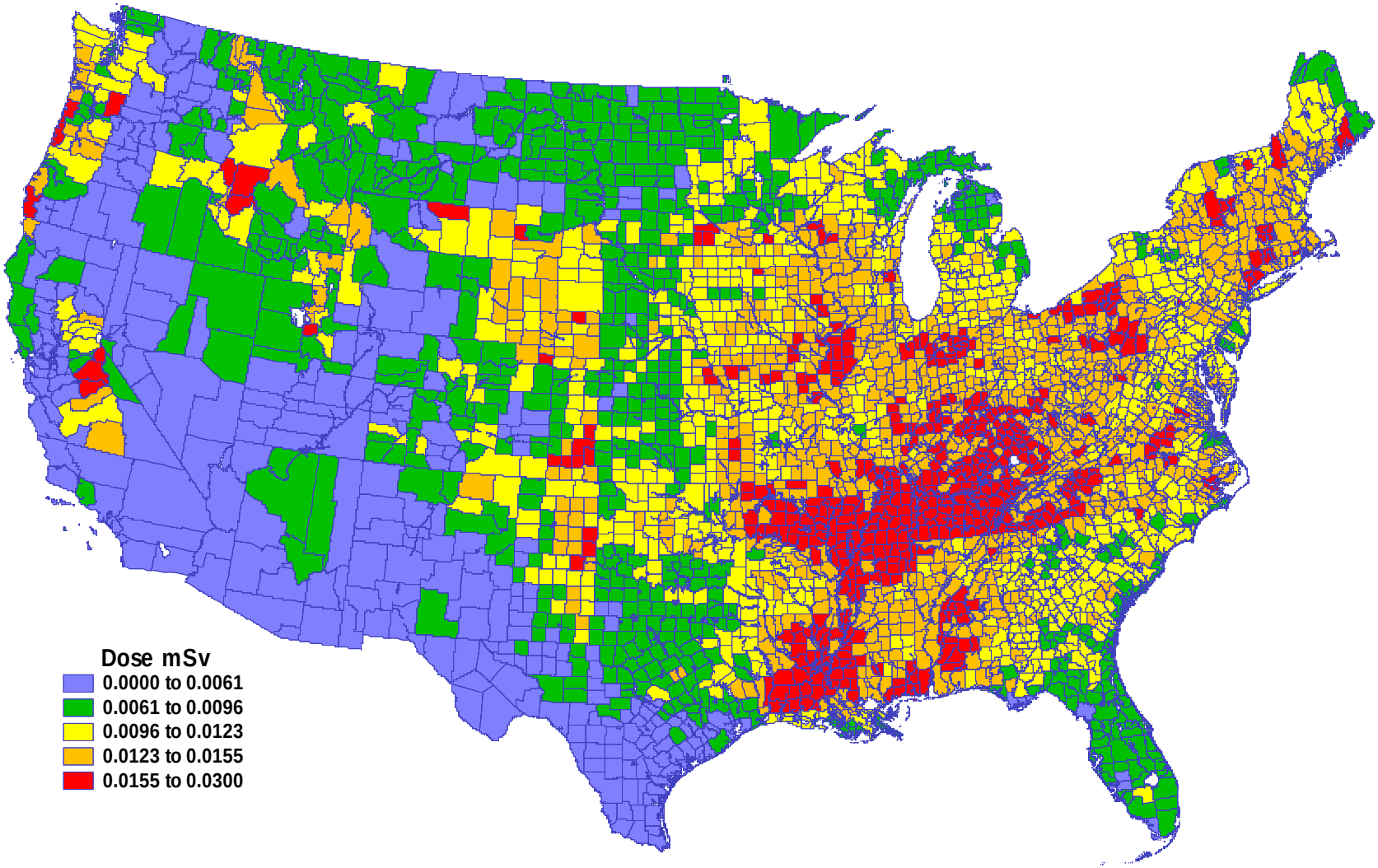

Fig. 9. Map of the committed dose (mSv) for a person born in 1951 to the red bone marrow from ^{90}Sr deposited during 1955.

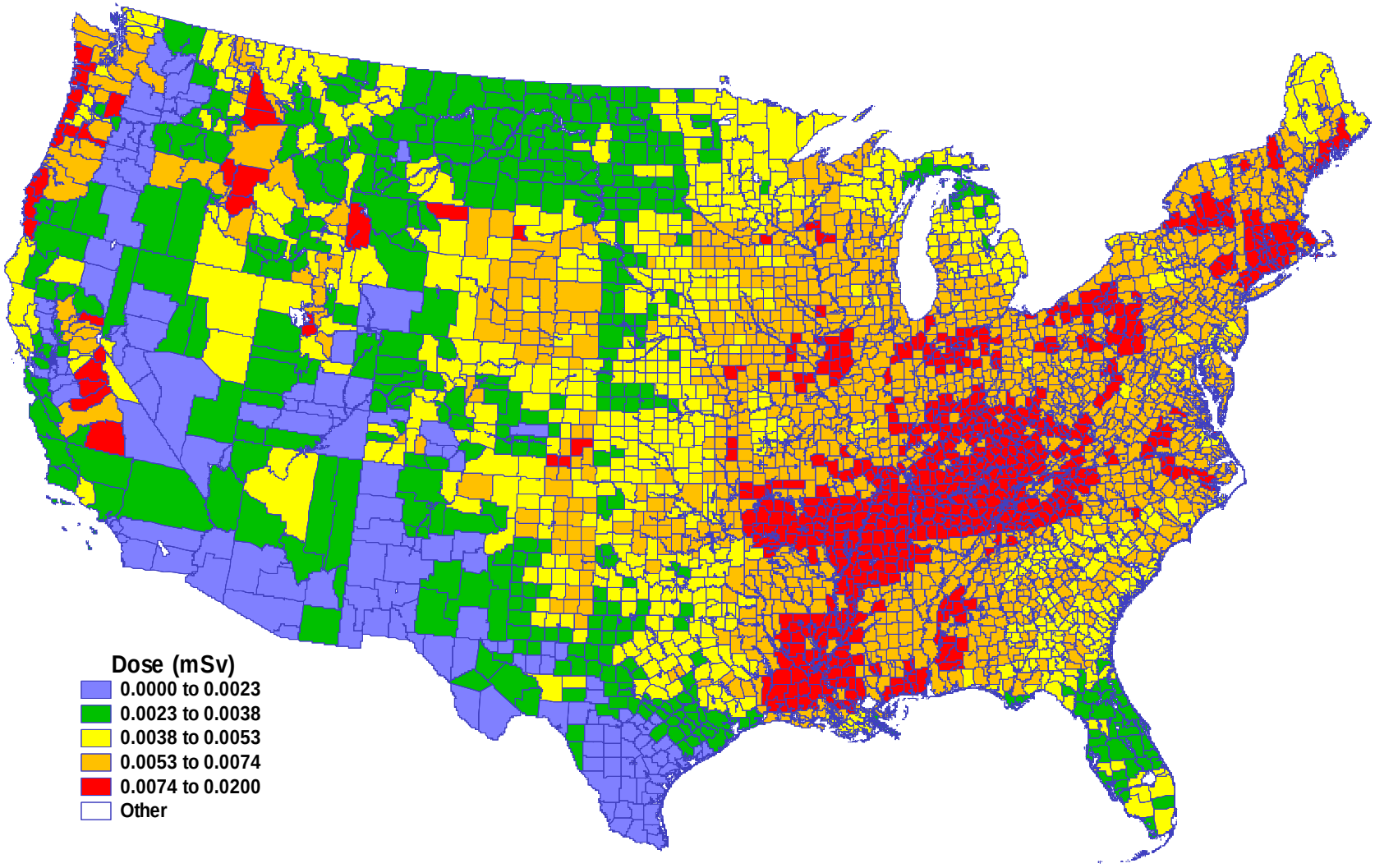

Fig. 10. Map of the committed effective dose (mSv) for an adult from ^{137}Cs deposited during 1955.

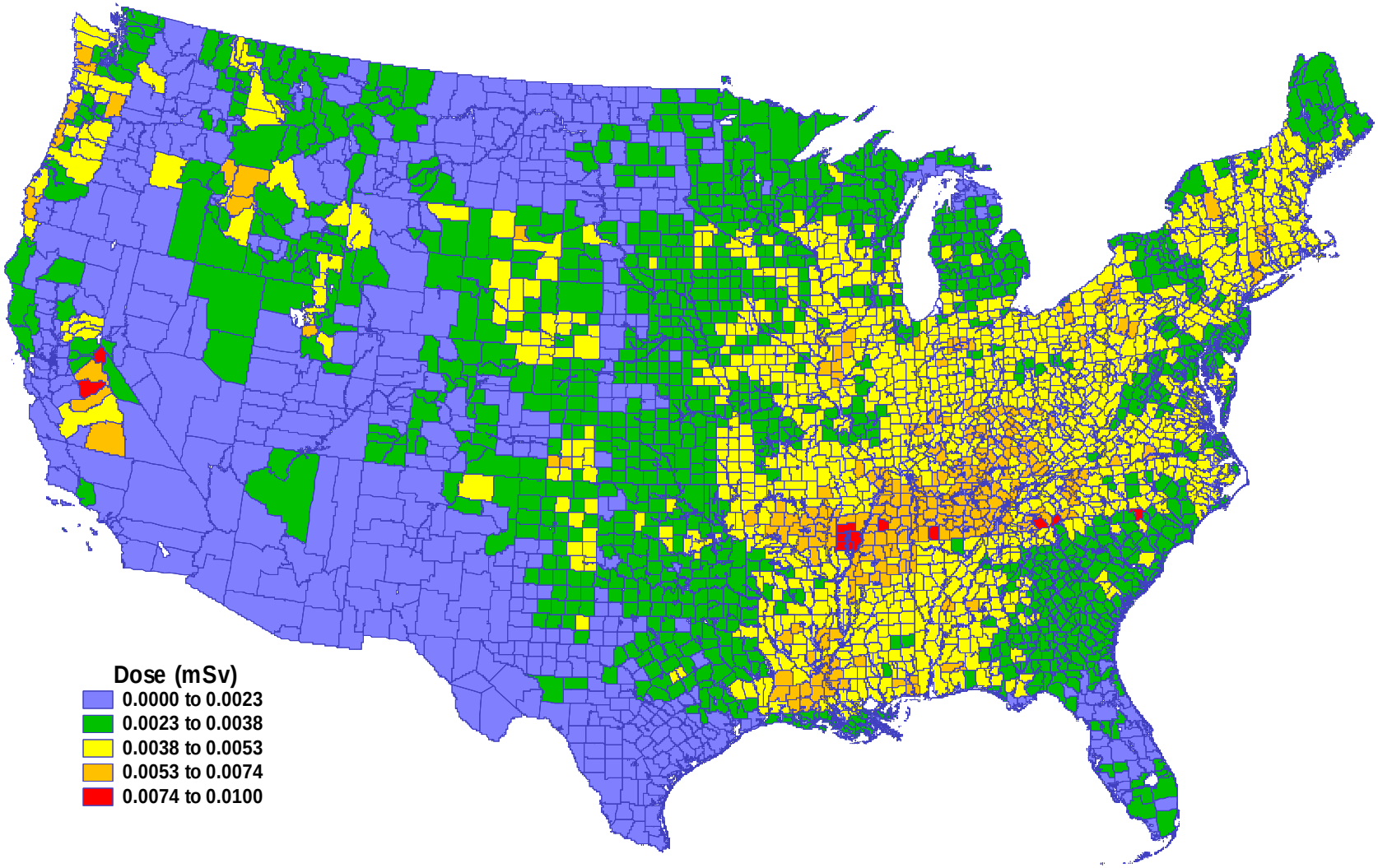

Fig. 11. Map of the committed effective dose (mSv) for a person born in 1951 from ^{137}Cs deposited during 1955.

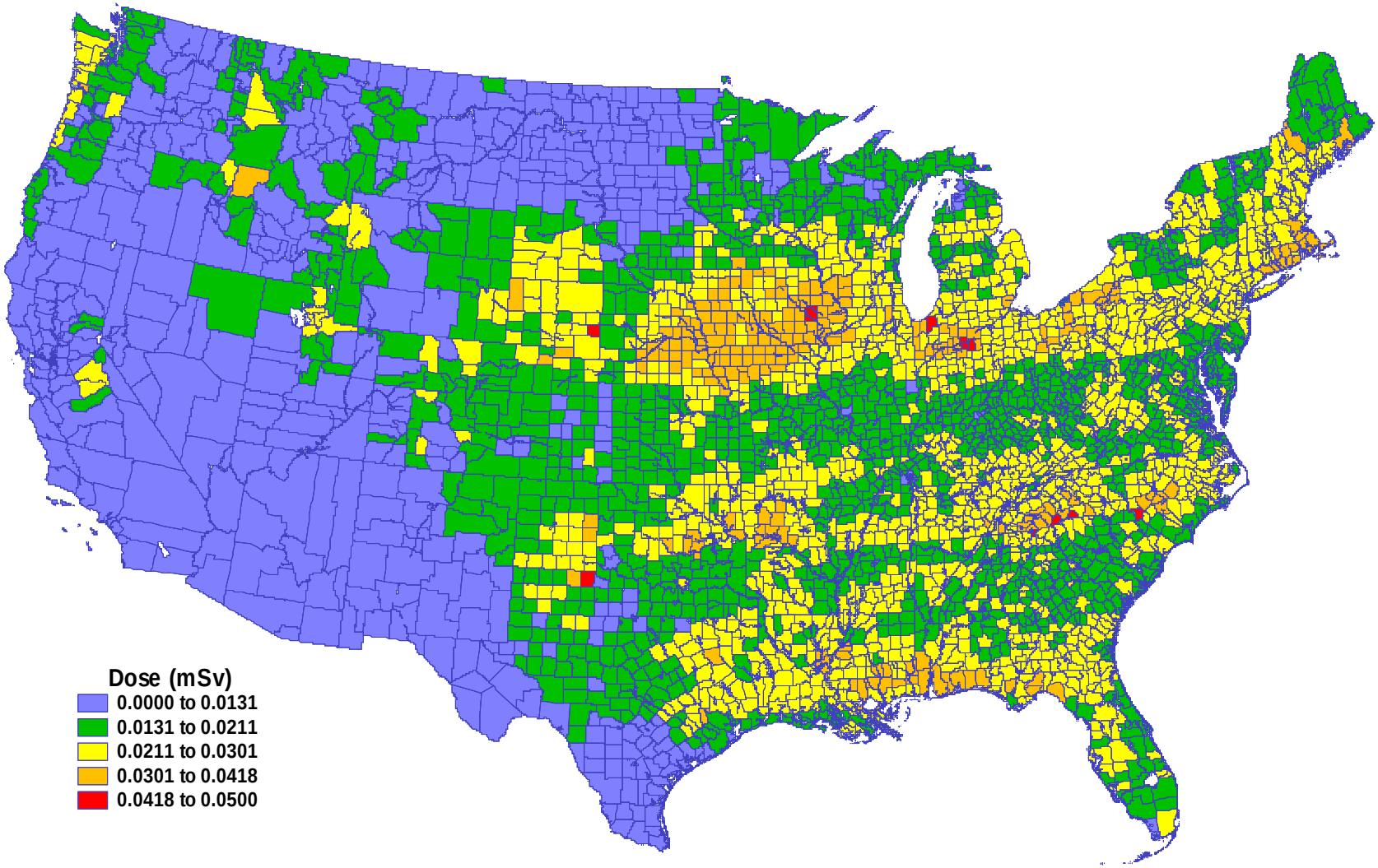

Fig. 12. Map of the committed dose (mSv) for an adult to the red bone marrow from ^{90}Sr deposited during 1959.

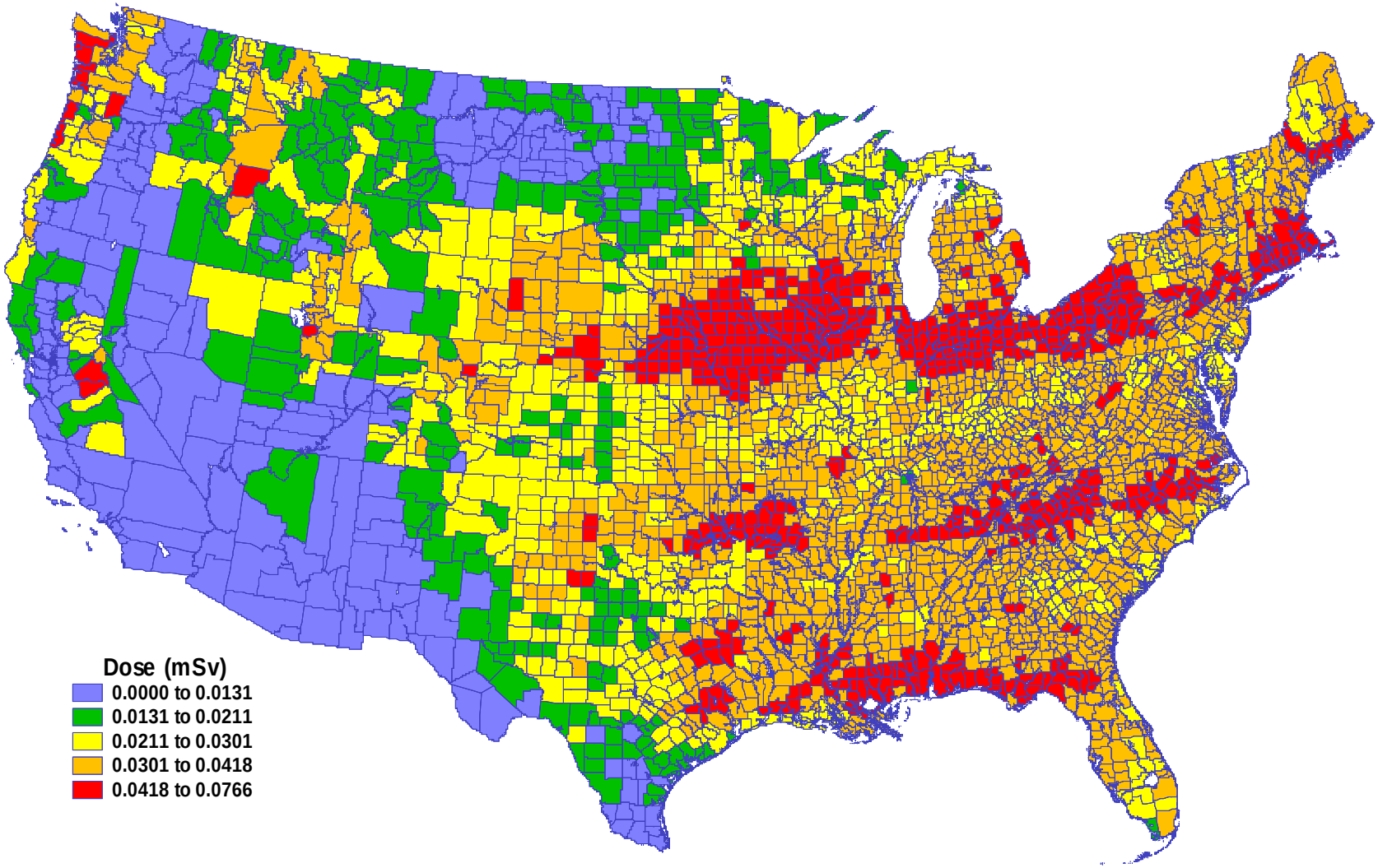

Fig. 13. Map of the committed dose (mSv) for a person born in 1951 to the red bone marrow from ^{90}Sr deposited during 1959.

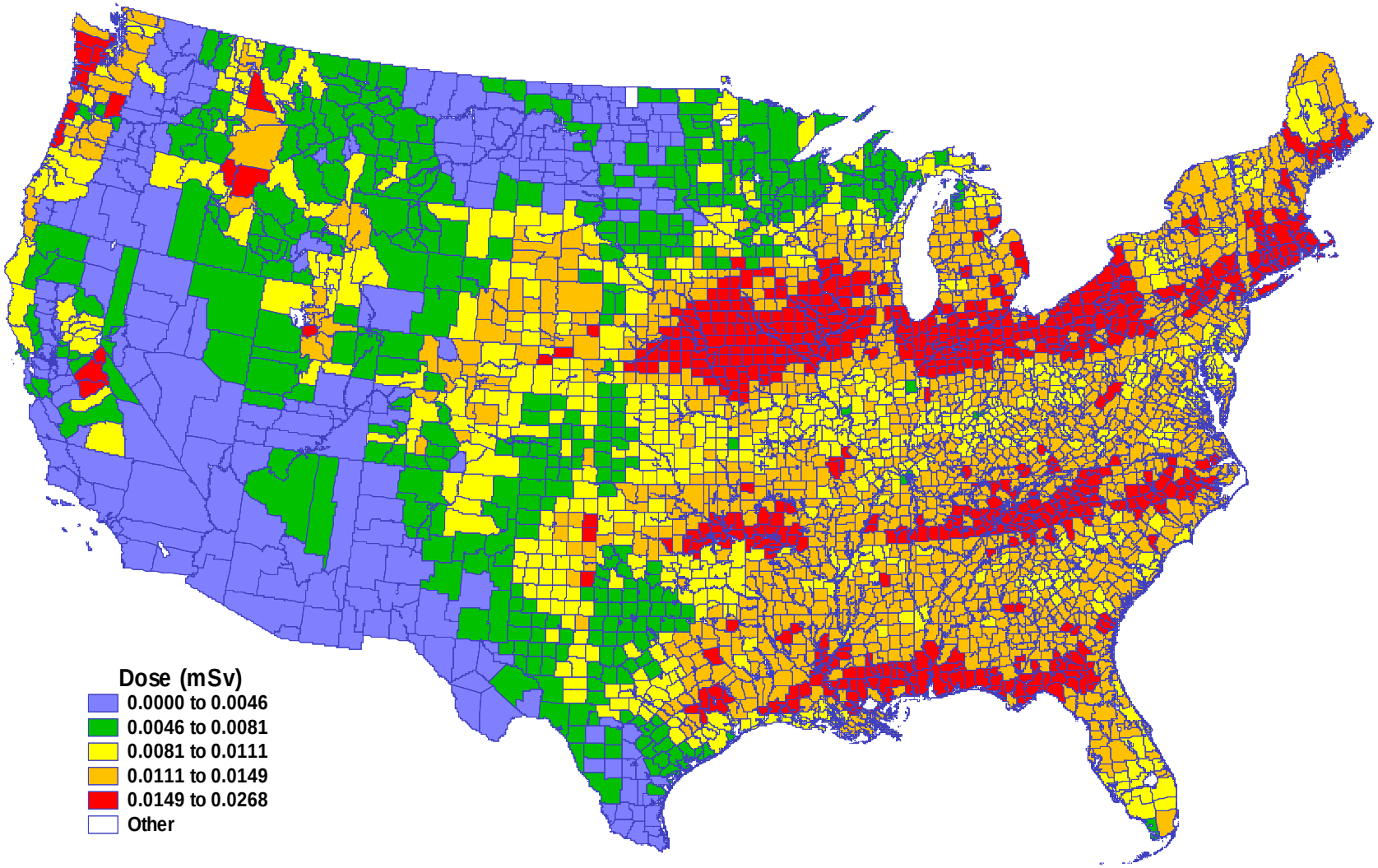

Fig. 14. Map of the committed effective dose (mSv) for an adult from ^{137}Cs deposited during 1959.

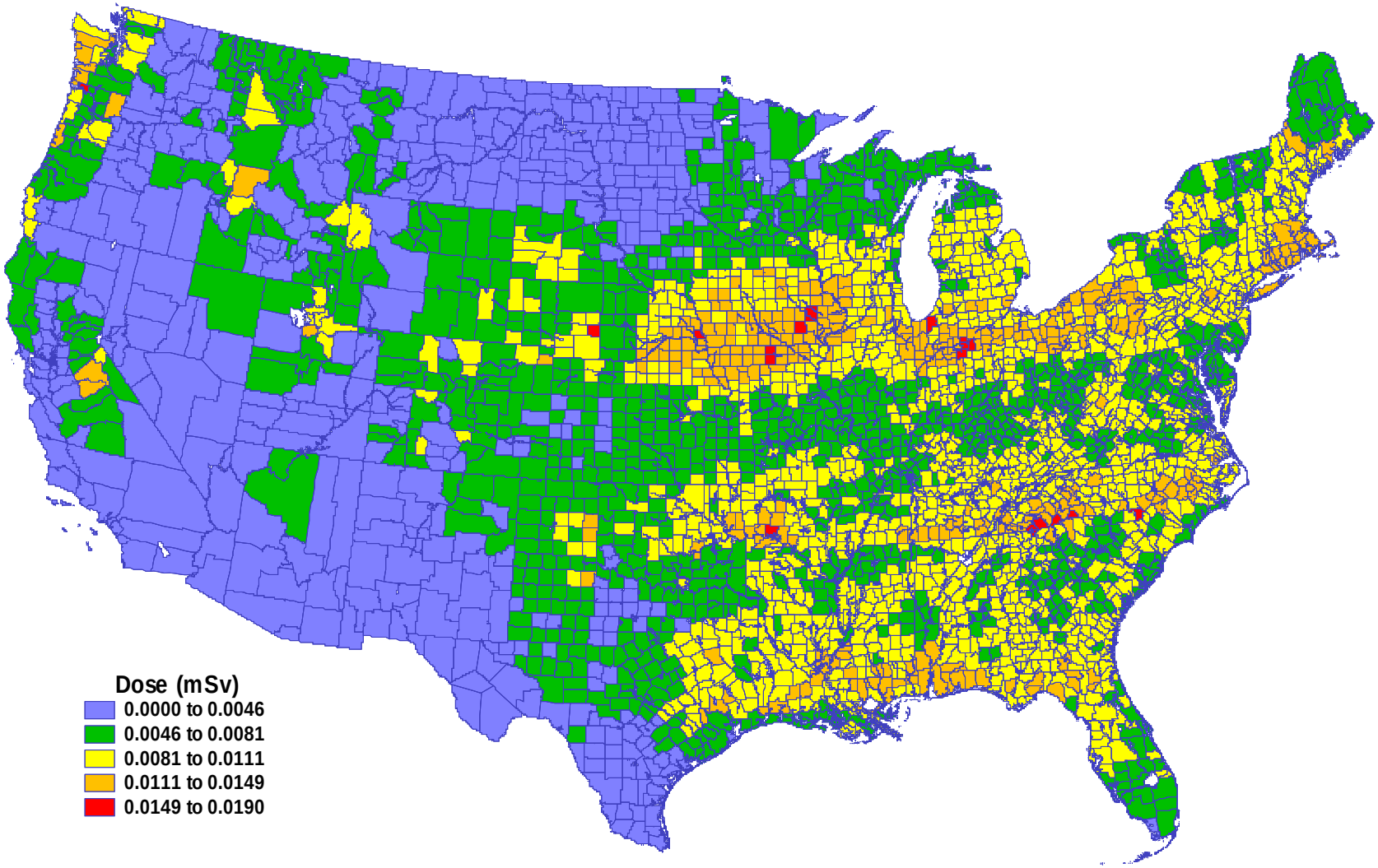

Fig. 15. Map of the committed effective dose (mSv) for a person born in 1951 from ^{137}Cs deposited during 1959.

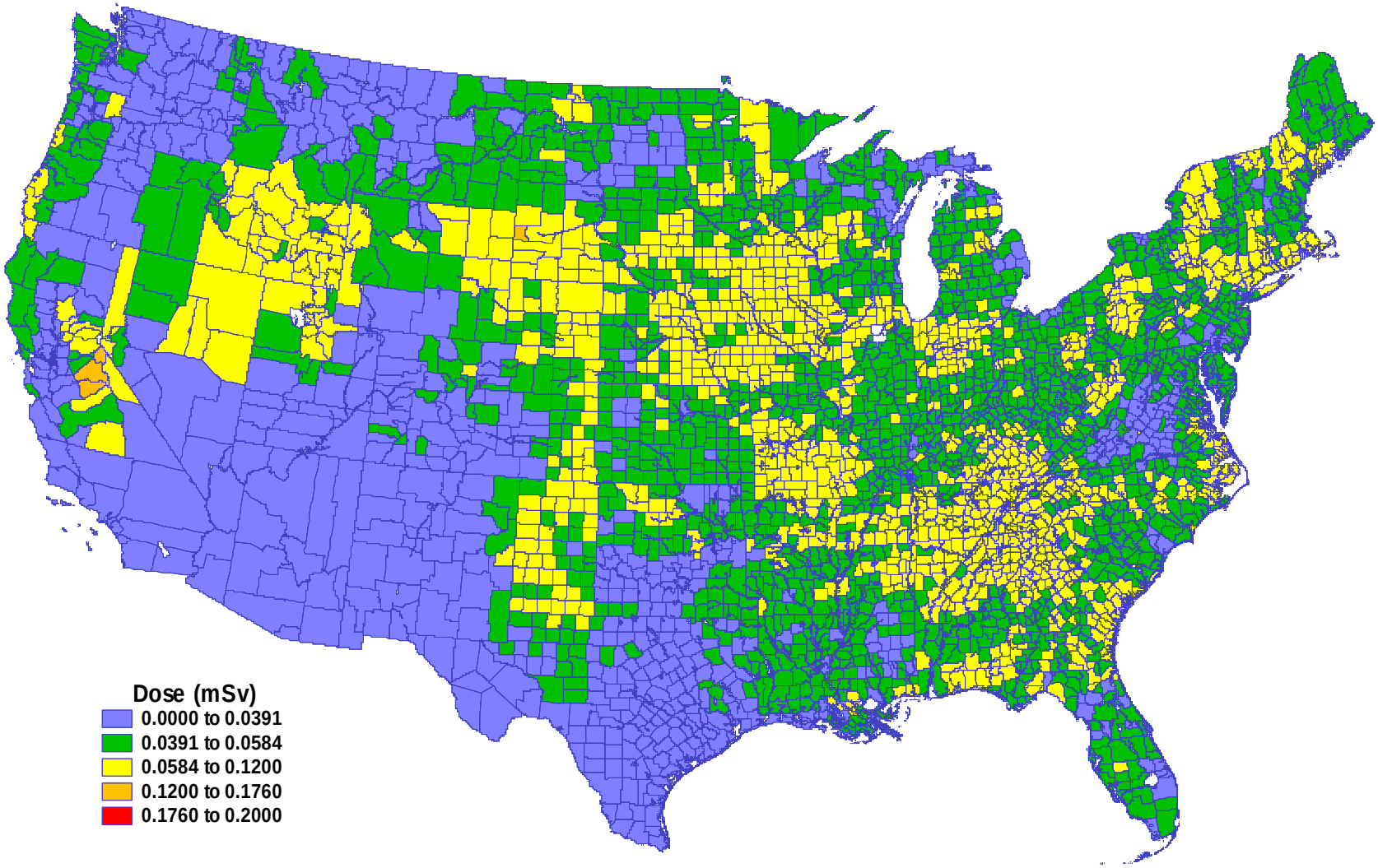

Fig. 16. Map of the committed dose (mSv) for an adult to the red bone marrow from ^{90}Sr deposited during 1963.

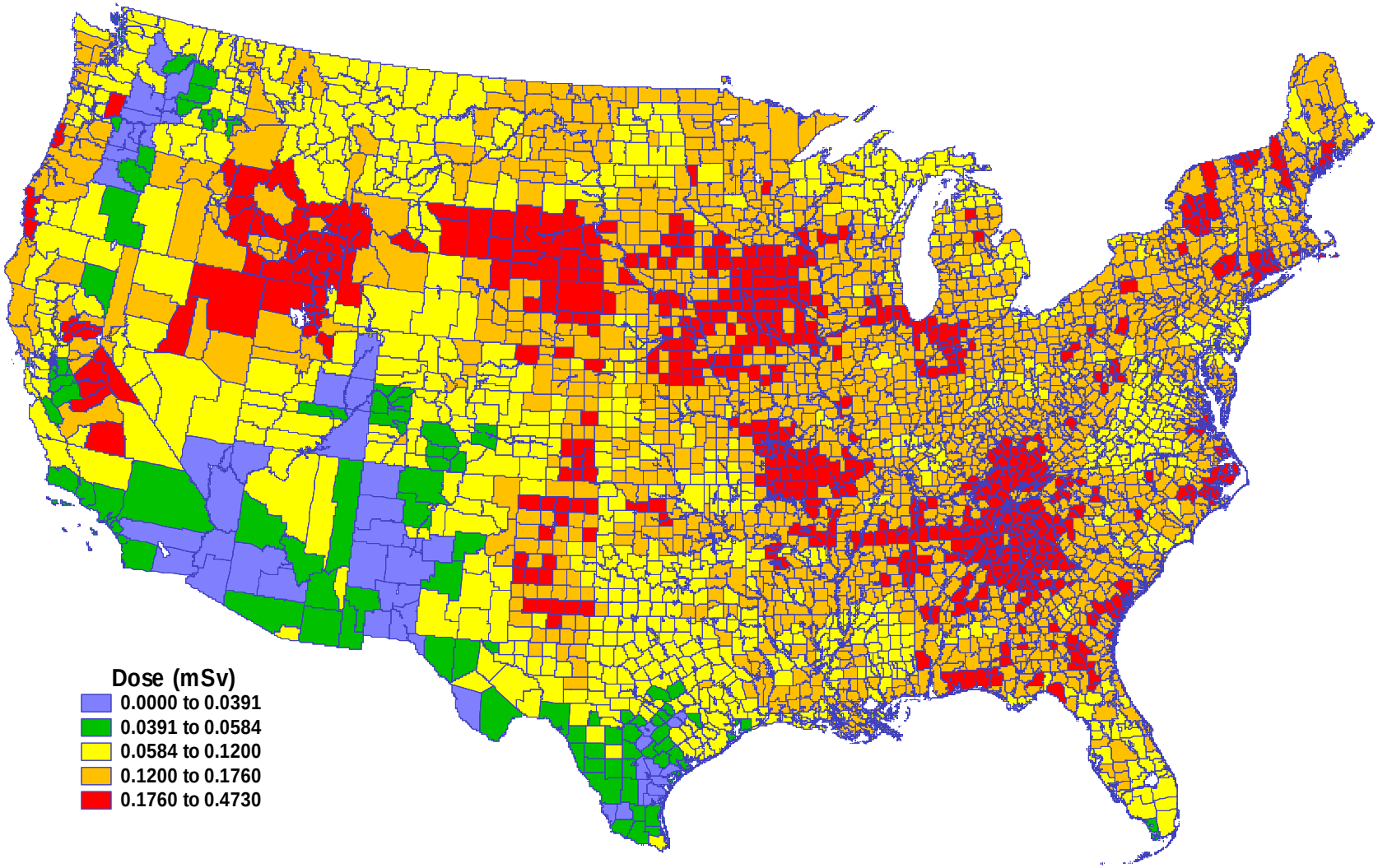

Fig. 17. Map of the committed dose (mSv) for a person born in 1951 to the red bone marrow from ^{90}Sr deposited during 1963.

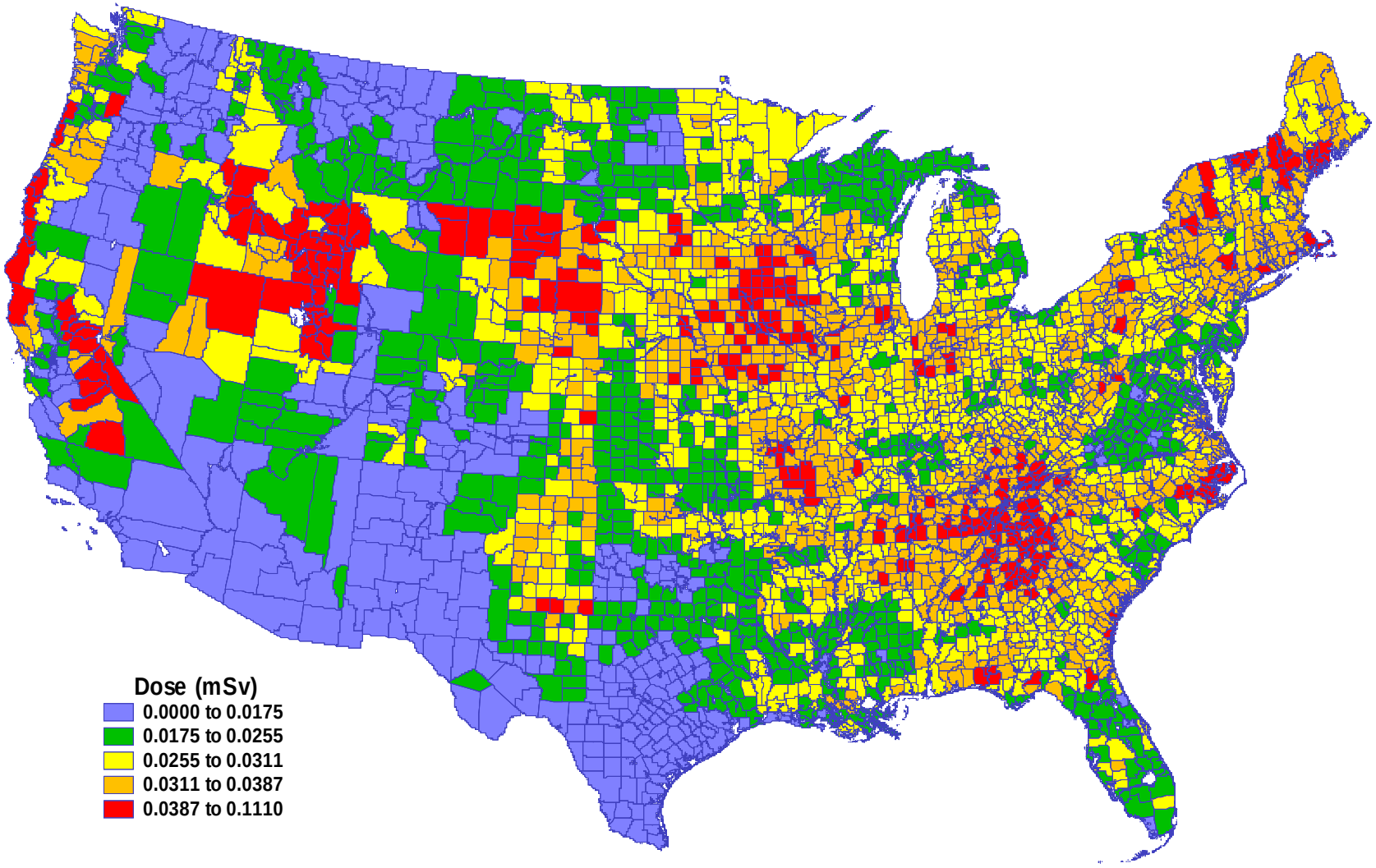

Fig. 18. Map of the committed effective dose (mSv) for an adult from ^{137}Cs deposited during 1963.

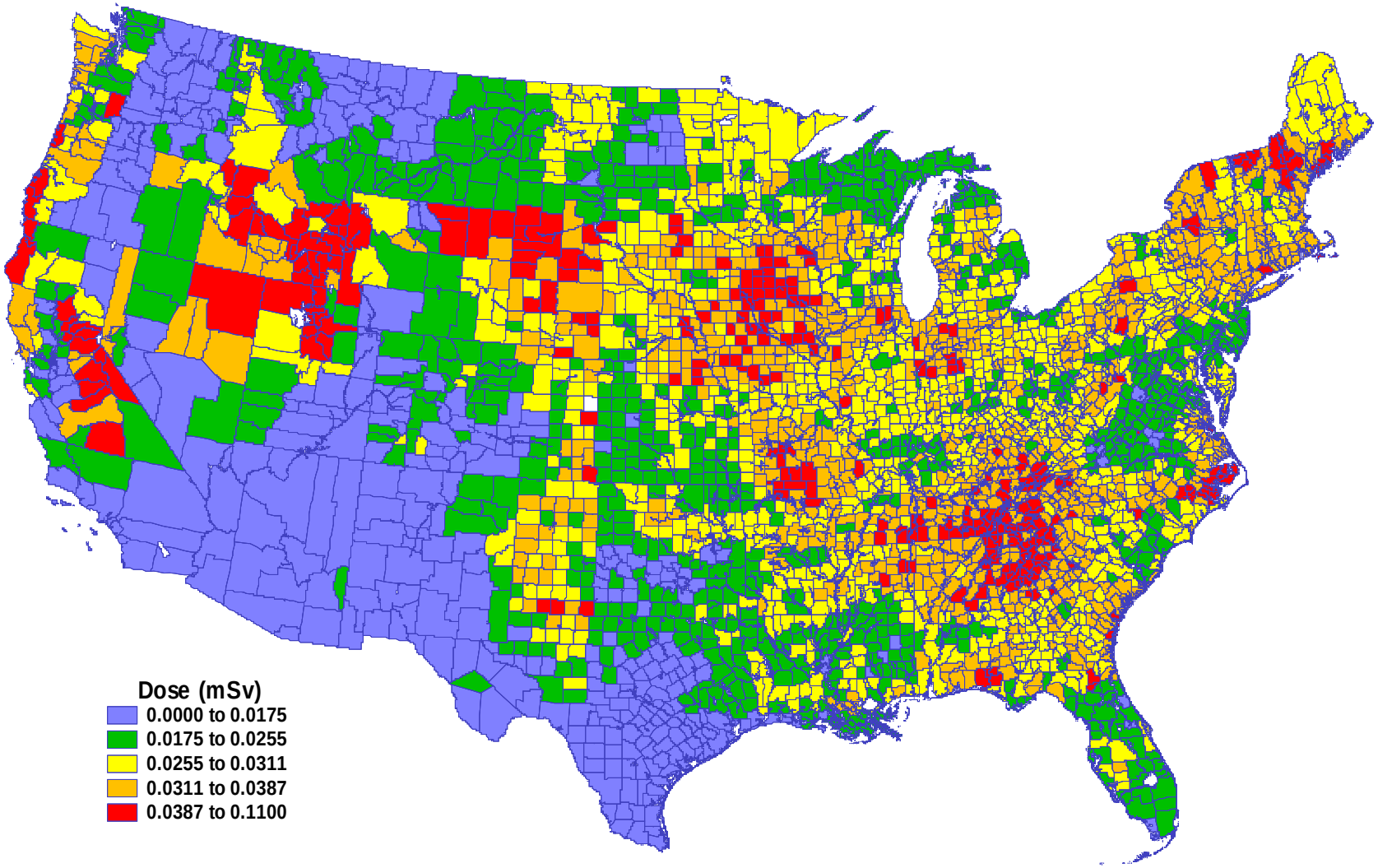

Fig. 19. Map of the committed effective dose (mSv) for a person born in 1951 from ^{137}Cs deposited during 1963.

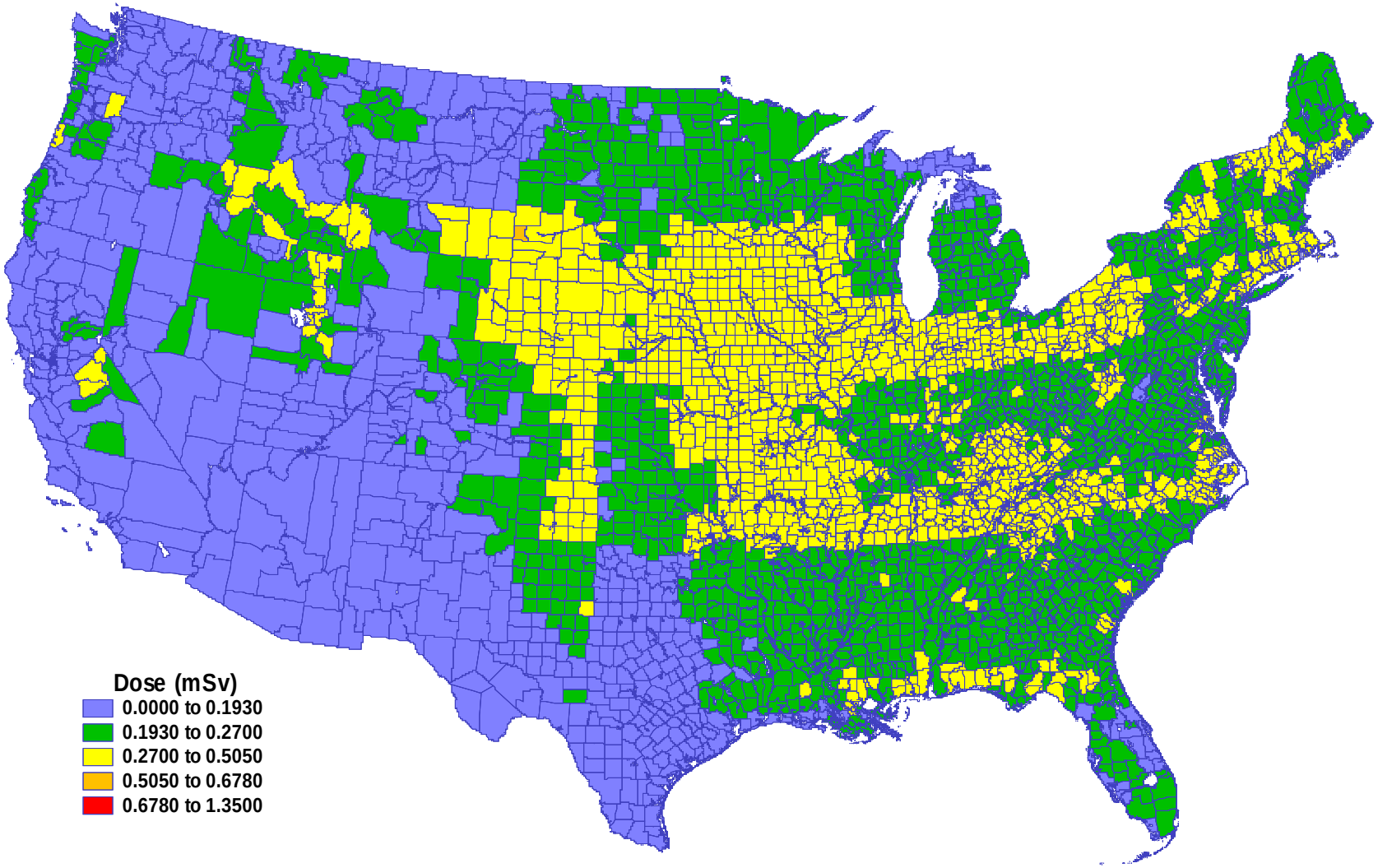

Fig. 20. Map of the committed dose (mSv) for an adult to the red bone marrow from ^{90}Sr deposited during 1953-1972.

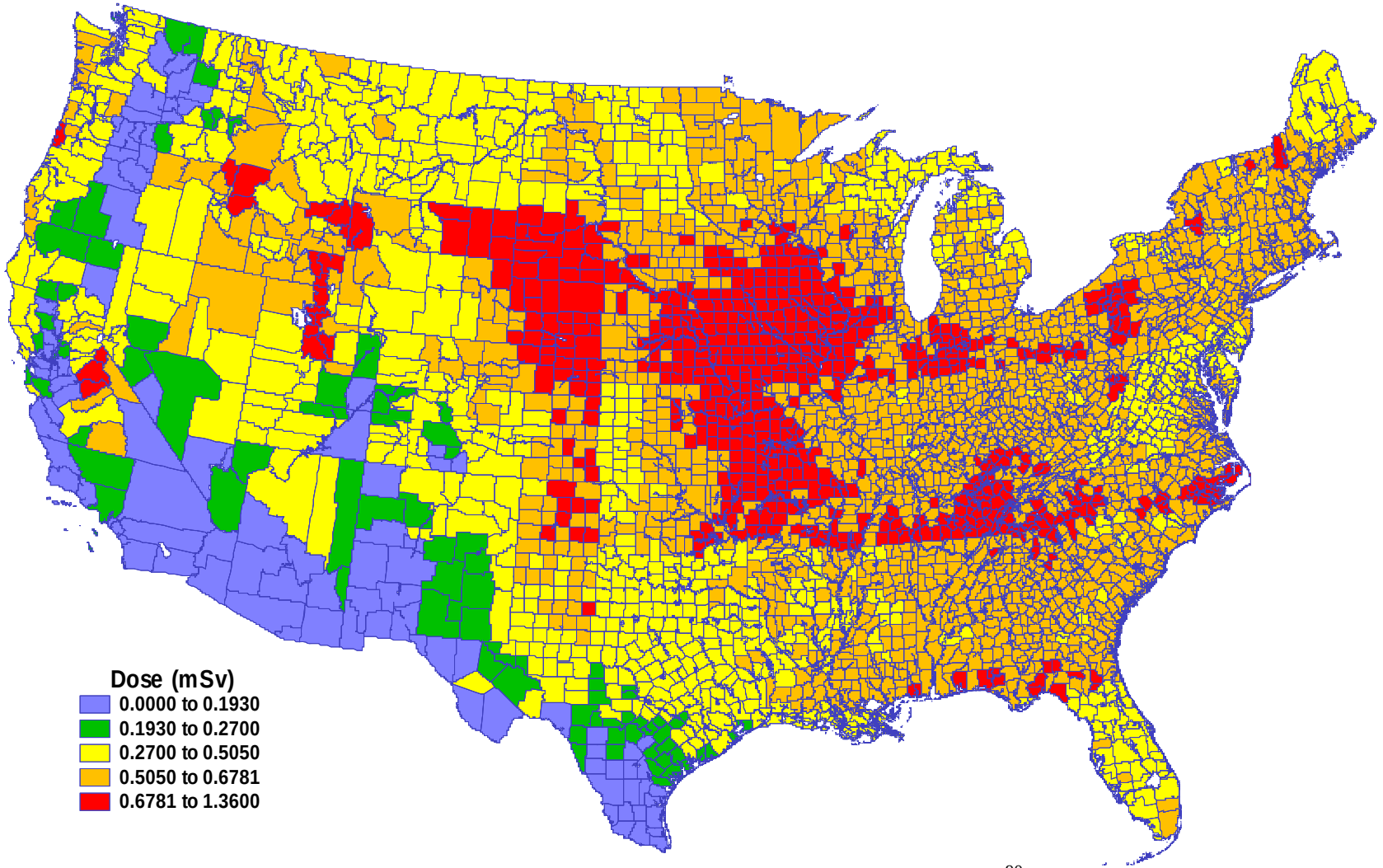

Fig. 21. Map of the committed dose (mSv) for a person born in 1951 to the red bone marrow from ^{90}Sr deposited during 1953-1972.

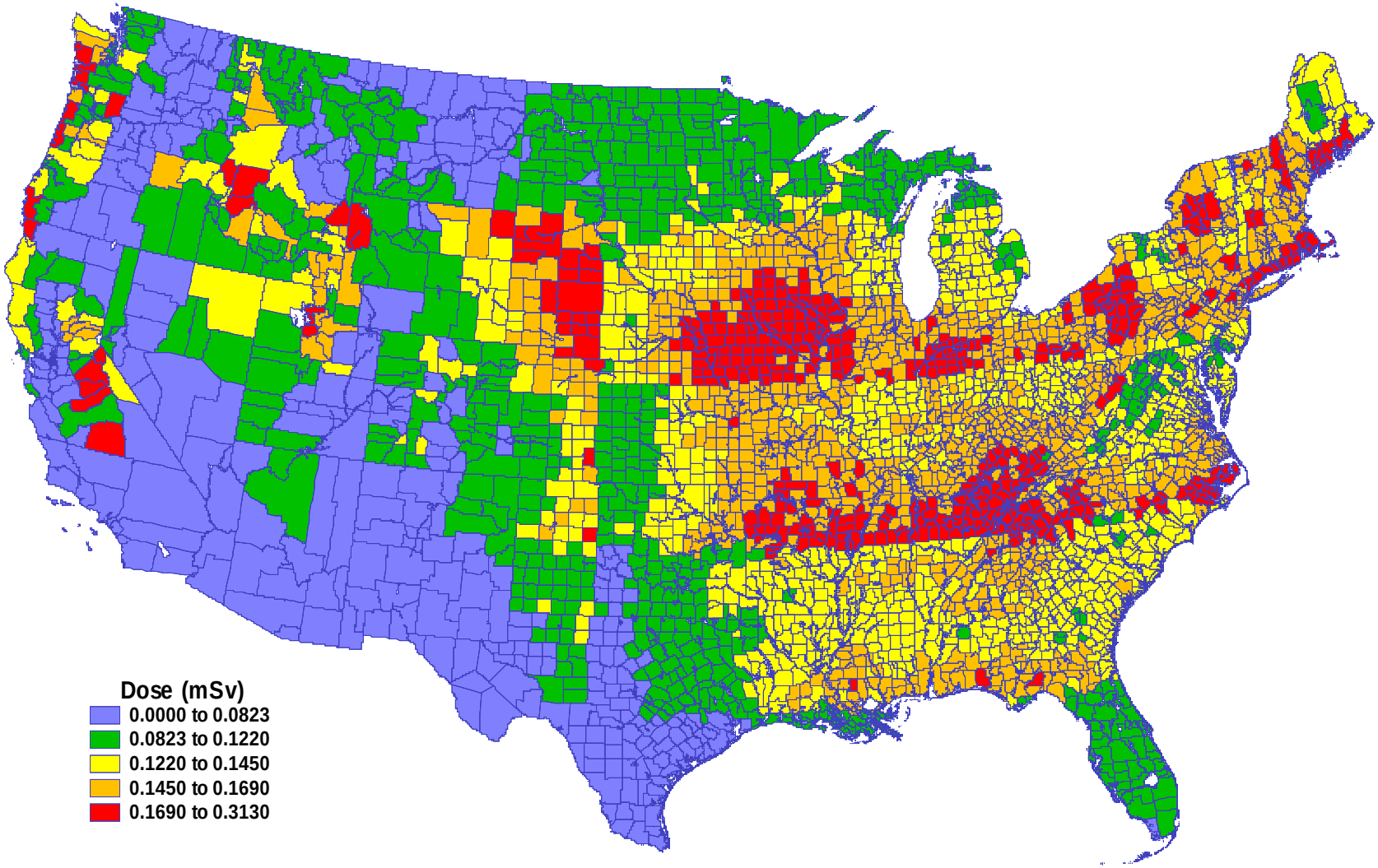

Fig. 22. Map of the committed effective dose (mSv) for an adult from ^{137}Cs deposited during 1953-1972.

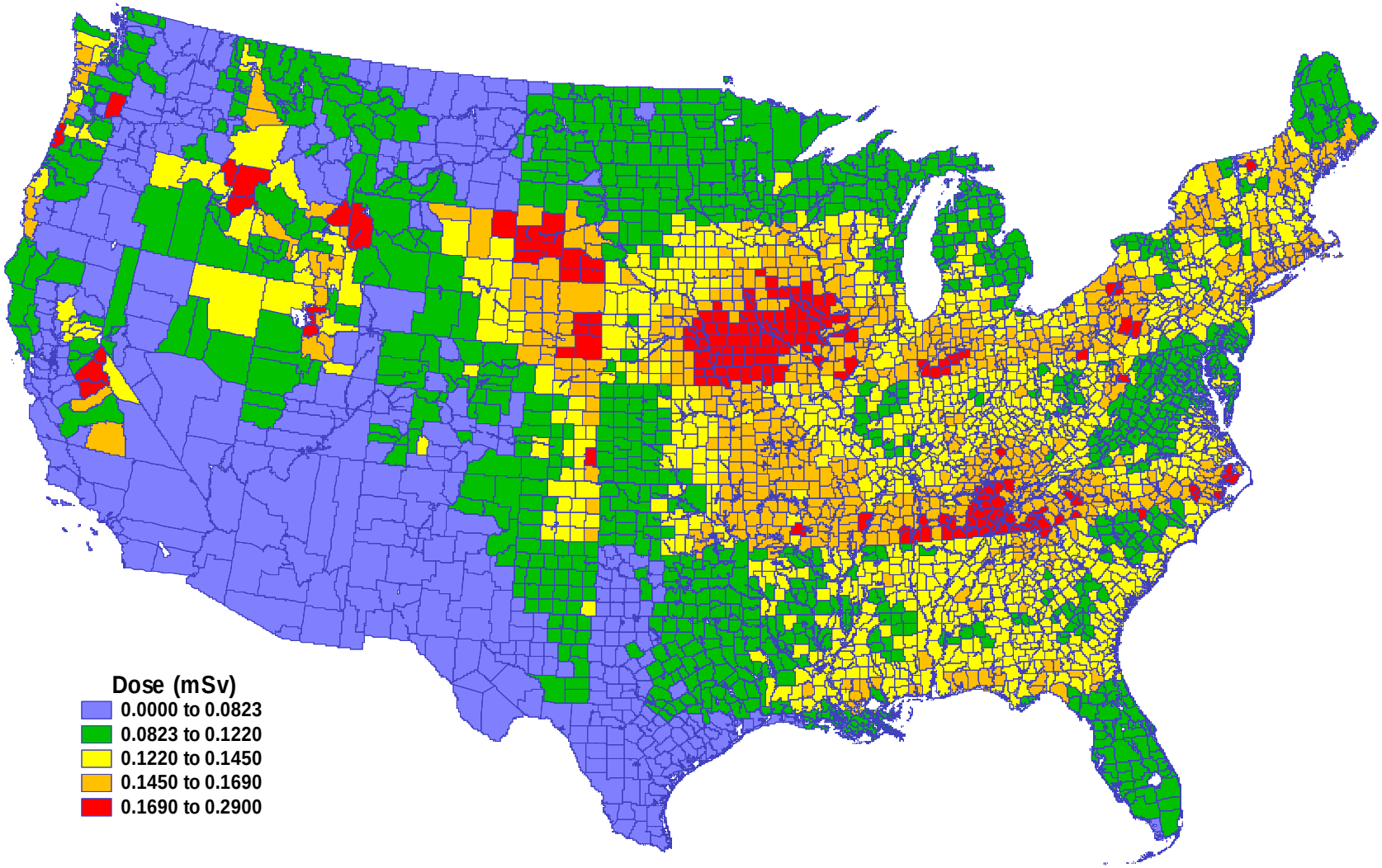

Fig. 23. Map of the committed effective dose (mSv) for a person born in 1951 from ^{137}Cs deposited during 1953-1972.

Table 6. Total per caput doses calculated for the 1953–1972 period from the deposition of ^{90}Sr and ^{137}Cs in global fallout. Upper values are for adults; lower values are for a person born on 1 January 1951. Values are averaged over the entire U.S.

Radionuclide	Individual organ or effective committed dose, μSv				
	Bone surface	Colon	Red marrow	Thyroid	Effective
	Adult				
^{90}Sr	540	17	240	0.86	37
^{137}Cs		160			130
	Person born on 1 January 1951				
^{90}Sr	1600	34	530	2.3	87
^{137}Cs		160			120

Another way of examining the committed doses for individuals is to look at the sum of effective doses from ^{90}Sr and ^{137}Cs on a county-by-county basis. Such values can be summed for each county over the entire period of 1953–1972. When this is done, the resulting highest dose of 380 μSv is found in Alpine County, California, and the lowest dose of 6.8 μSv occurred in Imperial County, California, a range of a factor of nearly 60. It is rather surprising that both the lowest and the highest doses occurred in the same state; however, the two counties differ markedly. Alpine County is in the Sierra Nevada Mountains and experiences a high amount of precipitation. Imperial County borders on Mexico and is shadowed by the mountains east of San Diego. Thus, it receives very little precipitation. A list of the 80 counties with the higher estimates of summed committed effective doses is given in Table 7.

One of the interesting features of Table 7 is that there are many counties with essentially the same estimated dose—this is to be expected given that global fallout is rather evenly dispersed and that the amount of annual precipitation is the most important factor in determining the amount of global fallout deposited in any one county. Another interesting feature is that the state with the highest number of counties in Table 7 is Iowa (22) followed by Tennessee (14) and North Carolina (11).

Counties with the lower estimates of dose are listed in Table 8. Again, it is noted that there is a large number of counties with essentially equal doses, which are lower than those in Table 7 due primarily to the low amounts of annual precipitation in these counties. The state with the highest number of occurrences in Table 8 is Texas (29) followed by California (12) and Washington (9). Three states–California, Oregon, and Utah–contain counties that occur on both lists. This is due to the highly diverse climatic conditions found in these three states.

Fig. 24 is a plot of the country-average sum of committed effective dose from ^{90}Sr and ^{137}Cs as a function of time for two age cohorts: adults in 1951 and those born on 1 January 1951. The influence of changing intake rates and dose coefficients with age is seen. The relative position of the two curves changes as the person born in 1951 ages and is assigned different intake rates and dose coefficients.

^{131}I. As mentioned above, it was not possible for Beck (2000) to provide estimates of ^{131}I deposition on a county-by-county basis for this feasibility study. Rather, estimates of deposition through time were provided as country-average values. Because the dose from ingestion of ^{131}I is strongly age dependent, dose estimates were calculated for adults and for persons born on 1 January of each of the years 1951 through 1963. The calculations of dose from ^{131}I were not extended through 1972, as was done for ^{90}Sr and ^{137}Cs; this is because testing ended in 1963, and ^{131}I is too short-lived to contribute to doses in the later years. All doses from the ingestion of ^{131}I were estimated on the basis of age- and season-dependent intake factors and age-dependent dose coefficients.

Table 7. Counties with higher estimates of total individual effective dose from ^{90}Sr and ^{137}Cs.

State	County	Dose, μSv	State	County	Dose, μSv
CA	Alpine	380	TN	Bradley	260
SD	Lawrence	350	IA	Black Hawk	260
CA	Tuolumne	350	IA	Linn	250
NC	Transylvania	320	SD	Custer	250
ID	Valley	310	NE	McPherson	250
CA	Mariposa	310	IA	Dallas	250
NC	Richmond	290	UT	Weber	250
NC	Polk	280	NC	Yancey	250
ID	Adams	280	IA	Marshall	250
NC	Macon	280	IA	Delaware	250
NC	Clay	280	IA	Lucas	250
SD	Pennington	270	IA	Story	250
ID	Fremont	270	IA	Audubon	250
NE	Logan	270	IN	Montgomery	250
NE	Thomas	270	MO	Harrison	250
ID	Boise	270	IN	Fountain	250
TN	Sequatchie	270	IN	Warren	250
IA	Taylor	270	IA	Dubuque	250
IA	Iowa	270	IA	Louisa	250
NC	Cherokee	270	IA	Tama	250
NC	Graham	260	WY	Teton	250
TN	Marion	260	IA	Mahaska	250
TN	Grundy	260	TN	Hamilton	250
VT	Lamoille	260	MO	Atchison	250
MO	Worth	260	TN	Mcminn	250
MO	Nodaway	260	MO	Gentry	250
NE	Hooker	260	NE	Pawnee	250
NE	Nemaha	260	NC	Greene	250
NE	Richardson	260	NC	Lenoir	250
IA	Montgomery	260	IA	Franklin	250
UT	Salt Lake	260	IA	Shelby	250
IA	Page	260	MO	Holt	250
NC	Swain	260	MO	Putnam	250
TN	Bledsoe	260	IA	Benton	250
OR	Lincoln	260	TN	Scott	250
TN	Meigs	260	IA	Monroe	250
TN	Rhea	260	WY	Crook	250
TN	Van Buren	260	TN	Chester	250
IA	Jones	260	TN	McNairy	250
IA	Adair	260	TN	Hardin	240

Table 8. Counties with lower estimates of total individual effective dose from ^{90}Sr and ^{137}Cs.

State	County	Dose, μSv	State	County	Dose, μSv
CA	Imperial	6.8	WA	Franklin	52
AZ	Yuma	14	TX	Hudspeth	52
OR	Sherman	31	NM	Hidalgo	52
AZ	Maricopa	31	WA	Adams	52
OR	Gilliam	31	TX	Hidalgo	52
OR	Wasco	33	UT	Grand	52
TX	Presidio	35	NM	San Juan	53
NV	Clark	36	TX	Culberson	53
WA	Yakima	37	NM	Sierra	53
TX	El Paso	38	TX	Zavala	54
OR	Jefferson	38	CA	Orange	54
OR	Deschutes	38	TX	Live Oak	54
CA	Riverside	40	TX	Kleberg	54
NM	Dona Ana	40	NV	Esmeralda	55
CA	Merced	40	WA	Island	55
TX	Zapata	41	CO	Costilla	55
WA	Benton	42	CA	Santa Barbara	56
NM	Valencia	43	TX	Brooks	56
WA	Grant	44	TX	Kenedy	56
NM	Luna	44	AZ	Graham	56
AZ	Pinal	44	WA	Douglas	57
CA	Lassen	44	TX	Val Verde	57
TX	Brewster	45	TX	Jim Wells	57
TX	Jim Hogg	47	TX	Cameron	57
OR	Crook	47	TX	Nueces	57
WA	Klickitat	48	CO	Rio Grande	57
AZ	Pima	48	TX	Atascosa	58
CA	San Joaquin	48	TX	Willacy	58
TX	Webb	48	TX	Uvalde	59
TX	Starr	48	NM	Catron	59
TX	Duval	49	TX	Loving	59
OR	Wheeler	50	CA	San Diego	60
OR	Lake	50	UT	Wayne	60
CA	San Benito	50	CO	Conejos	60
NM	Socorro	50	TX	Frio	60
CA	Stanislaus	50	CA	Modoc	61
TX	Dimmit	51	UT	San Juan	61
WA	Chelan	51	CA	Inyo	61
TX	Mcmullen	51	AZ	Santa Cruz	62
TX	La Salle	51	TX	San Patricio	63

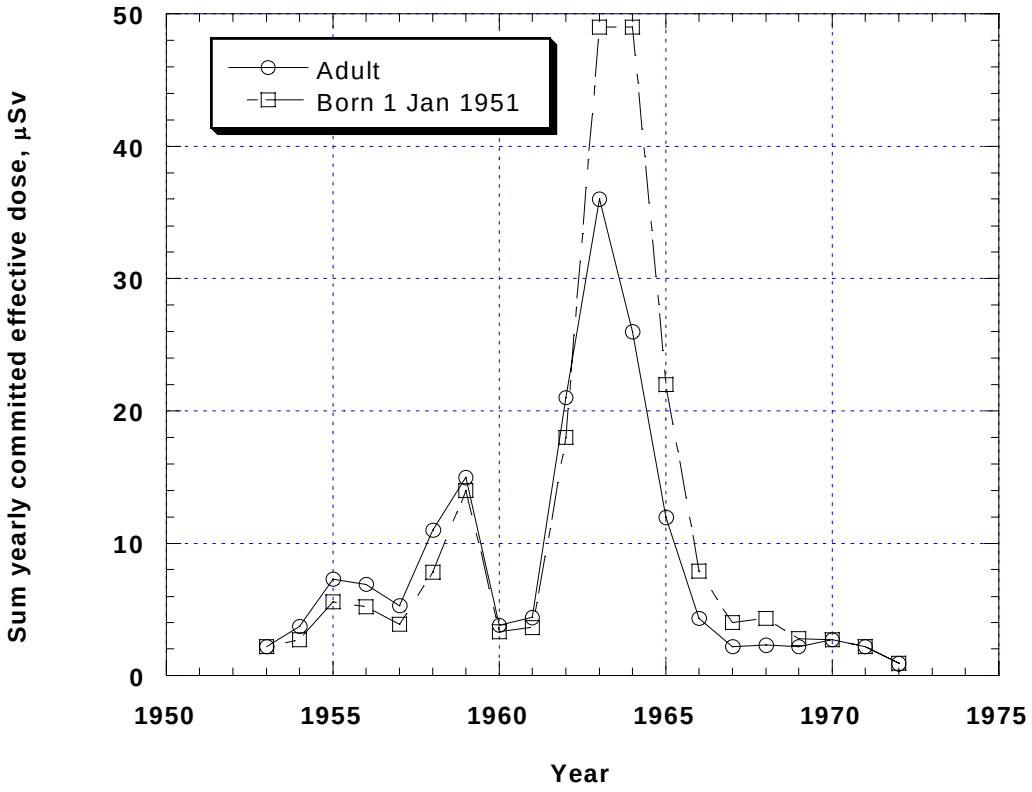

Fig. 24. Plot of the sum of committed effective doses from ^{90}Sr and ^{137}Cs as a function of time for two cohorts: those who were adults in 1951 and those born on 1 January 1951. Most of the variation in the doses between the two cohorts is due to changes in intake rates and in strontium metabolism as the young person ages.

The complete set of calculations of dose from the ingestion of ^{131}I is available on the CD-ROM in the workbook entitled "GBLI131." The year-by-year estimates of per caput bone surface, colon, red marrow, thyroid, and effective dose are summarized in Table 9. As expected, due to the accumulation of iodine in the thyroid, the dose to this organ is the highest at 960 μSv and the effective dose is less by a factor of 20.

The estimates of yearly per caput thyroid dose, along with thyroid doses to the adult and a person born on 1 January 1951, are plotted in Fig. 25. As the person born on 1 January 1951 ages, s/he was assigned the appropriate age-dependent intakes and dose coefficients with time. As indicated, the dose to the young person is substantially higher than the per caput dose and the dose to the adult is substantially lower than the per caput dose. The combined effects on cumulative dose of birth year and of the amount of fallout experienced during a particular year are illustrated in Fig. 26 for persons born on 1 January in the years 1951 through 1963. The highest dose was received by a person born on 1 January 1956. Such a person would have received a substantial dose at a young age from the relative peak of fallout in 1957 and would have still been young enough to have both a high intake and a high dose coefficient for the highest yearly amount of ^{131}I in fallout in

1962. The person born on 1 January 1951 received less dose, because by the time of the fallout peak in 1962 s/he was older and would have experienced less intake and had a lower dose coefficient.

Table 9. Year-by-year estimates of per caput dose from the ingestion of ^{131}I in fallout from high-yield weapons tests in the atmosphere. The estimates below are country averages, as reliable estimates of deposition on a county-by-county basis are not yet available.

Year	Per caput organ or effective dose, μSv				
	Bone surface	Colon	Red marrow	Thyroid	Effective
1953	0.0023	0.0045	0.0019	12	0.62
1954	0.011	0.020	0.0088	56	2.8
1955	0.00026	0.00046	0.00021	1.3	0.066
1956	0.031	0.059	0.025	170	8.2
1957	0.021	0.040	0.017	110	5.6
1958	0.044	0.083	0.036	230	12
1959	0.000021	0.000035	0.000017	0.10	0.0051
1960	0	0	0	0	0
1961	0.011	0.020	0.0088	58	2.9
1962	0.062	0.11	0.050	320	16
1963	0.00024	0.00040	0.00019	1.2	0.059
Sum	0.18	0.34	0.15	960	48

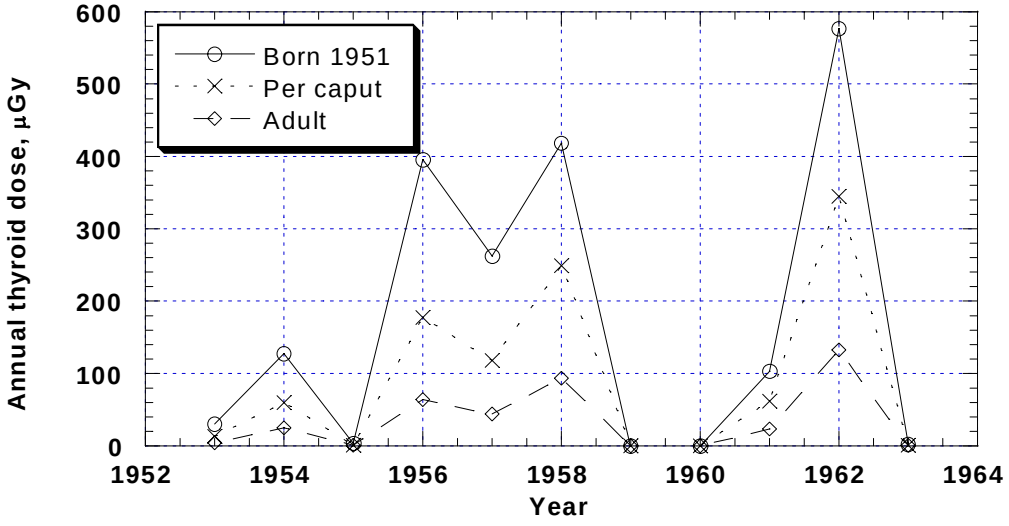

Fig. 25. Annual thyroid dose due to the ingestion of ^{131}I from global fallout as a function of year. Data are for three cohorts: those who were adults (≥18 y in 1953), the per caput value (population-weighted by age), and those born on 1 January 1951.

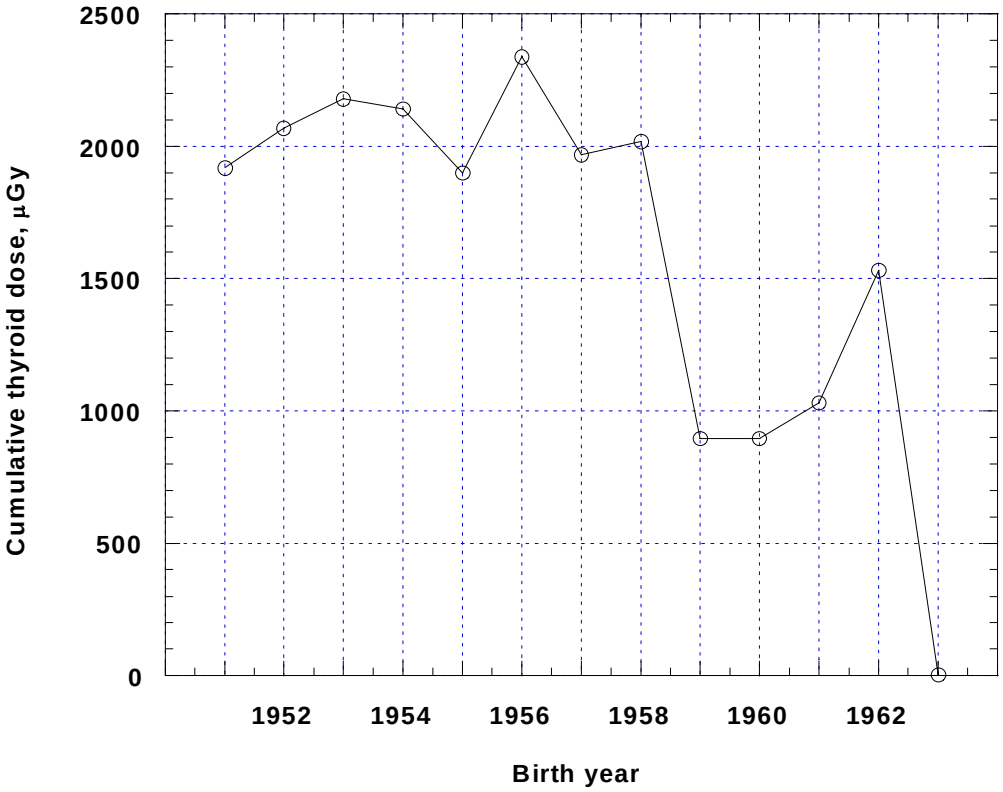

Fig. 26. Cumulative (1953 through 1963) thyroid dose as a function of birth year.

Tritium and ^{14}C. The calculated results for the individual effective doses from ^{3}H (tritium) and ^{14}C are given in Table 10. In contrast to the results for ^{90}Sr and ^{137}Cs the values in Table 10 are doses calculated to be actually received in the indicated year, whereas for ^{90}Sr and ^{137}Cs the computed values are for committed doses. The disparate treatments arise from the markedly different behavior of the two groups of radionuclides. Most of the intake of ^{90}Sr and ^{137}Cs will occur in the same year that the radionuclides are deposited in fallout and/or during the next year. However, ^{3}H and ^{14}C are in vapor or gaseous form and do not deposit with particulate matter. Rather, they take substantial time to be distributed throughout the world and their compartments of distribution are very large. Carbon-14 is also very long lived and will contribute to yearly dose for tens of thousands of years. In that regard it does not make sense within the framework of the present project goals to calculate a dose "commitment" that would be intergenerational. Therefore, the yearly doses for ^{3}H and ^{14}C have been calculated and summed only through the year 2000.

As indicated in Table 10, the calculated sums of effective doses through the year 2000 are 66 μSv for ^{3}H and 120 μSv for ^{14}C. The time dependencies of the doses from ^{3}H and ^{14}C are also plotted in Fig. 27, which is on a semi-logarithmic scale. Here, the effects of global distribution, size of compartments, and exchange rates are clearly evident; ^{3}H also has a much, much shorter half life. It is evident that the yearly dose from ^{3}H tracks more closely the amounts injected into the atmosphere, and the yearly dose from ^{3}H subsequently

decreases fairly rapidly due to its half life. In contrast, ^{14}C takes a long time to be distributed throughout its compartments, the yearly doses track the injection rates only slowly, and the yearly doses decrease with time much more slowly.

Table 10. Dose to an individual in the Northern Hemisphere from the creation or release of ^{3}H and ^{14}C from the testing of large fusion weapons in the atmosphere.

Year	Effective dose, μSv		Year	Effective dose, μSv	
	^{3}H	^{14}C		^{3}H	^{14}C
1952	0.95	0.032	1977	0.18	2.6
1953	0.20	0.10	1978	0.16	2.4
1954	3.4	0.24	1979	0.14	2.3
1955	0.69	0.51	1980	0.12	2.1
1956	2.8	0.68	1981	0.11	2.0
1957	1.3	0.95	1982	0.097	2.0
1958	6.3	1.3	1983	0.087	1.9
1959	1.1	1.7	1984	0.078	1.9
1960	0.58	1.9	1985	0.069	1.9
1961	14	2.4	1986	0.061	1.8
1962	21	4.0	1987	0.056	1.8
1963	3.8	5.4	1988	0.051	1.7
1964	2.0	5.6	1989	0.046	1.7
1965	1.4	6.2	1990	0.040	1.7
1966	1.1	6.3	1991	0.036	1.6
1967	0.86	5.8	1992	0.033	1.6
1968	0.71	5.3	1993	0.031	1.5
1969	0.59	4.8	1994	0.028	1.5
1970	0.50	4.4	1995	0.025	1.5
1971	0.43	4.1	1996	0.023	1.4
1972	0.38	3.8	1997	0.021	1.4
1973	0.33	3.5	1998	0.019	1.4
1974	0.28	3.2	1999	0.017	1.4
1975	0.24	3.0	2000	0.015	1.3
1976	0.20	2.8	Sum	66	120

Collective dose

The collective doses that can be calculated from the data contained in the CD-ROM accompanying this document are summarized in Table 11. The total collective effective dose is estimated to be 66,000 person Sv, and the total collective thyroid dose is estimated to be 210,000 "thyroid Sv." In calculating the sum of the dose to the thyroid, it was assumed that the dose to the thyroid from ^{3}H, ^{14}C, and ^{137}Cs was equal to the effective dose. This is a reasonable assumption, as these three radionuclides are distributed uniformly throughout the body.

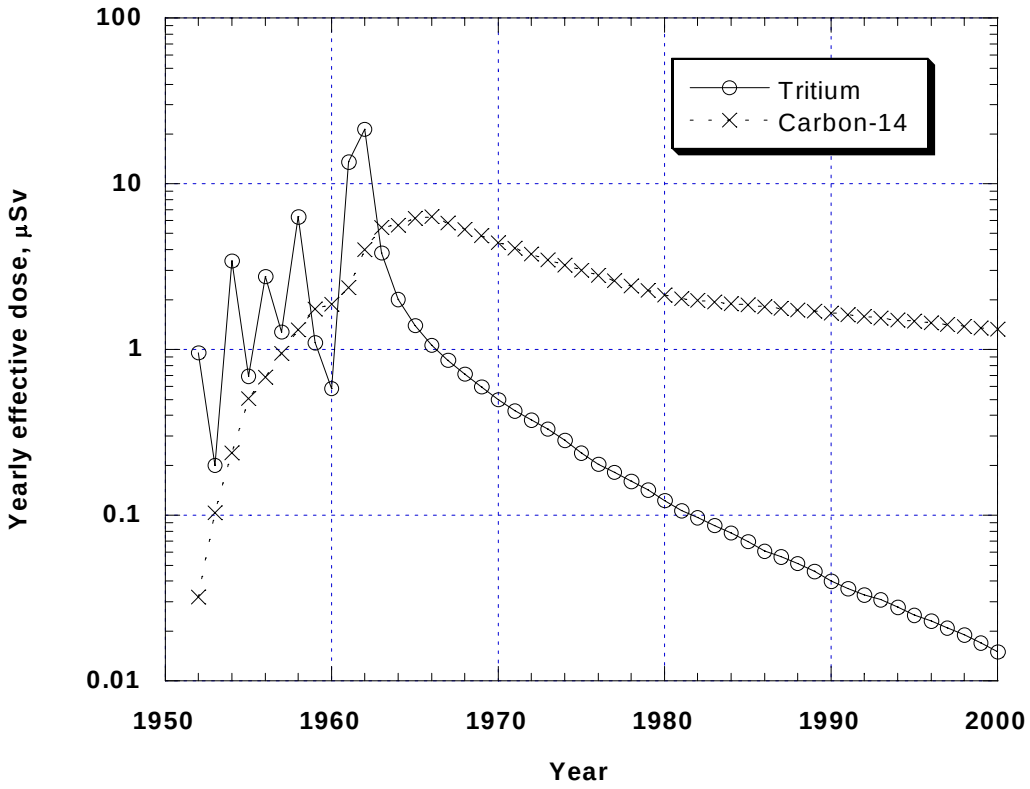

Fig. 27. Plot of the yearly doses from ^{3}H and ^{14}C calculated on the basis of specific activity models. Due to its large compartments that exchange carbon slowly and its long half life, the dose from ^{14}C tracks the injections more slowly than does the dose from ^{3}H.

Table 11. Total collective doses calculated for the 1953–1972 period from the deposition of ^{90}Sr, ^{131}I, and ^{137}Cs in global fallout and for the 1952–2000 period from ^{3}H and ^{14}C distributed throughout the Northern Hemisphere. Values are calculated for the 48 contiguous states in the U.S. The sum collective thyroid dose is estimated by summing the specifically calculated thyroid doses and adding the effective doses for ^{3}H, ^{14}C, and ^{137}Cs.

Radionuclide	Collective organ or effective committed dose, person Sv				
	Bone surface	Colon	Red marrow	Thyroid	Effective
^{3}H					11,000
^{14}C					20,000
^{90}Sr	87,000	2,800	38,000	140	5,900
^{131}I	30	56	24	160,000	7,800
^{137}Cs		25,000			22,000
Sum				210,000	66,000

Comparison of per caput effective doses

In Table 12 the doses calculated in this report are compared to similar estimates of dose from global fallout reported in UNSCEAR (1993) as doses averaged over the north temperate zone (40°–50°) of the globe and to values reported previously in Anspaugh (2000)

for doses averaged over the contiguous U.S. from atmospheric tests conducted at the Nevada Test Site. Examination of Table 12 indicates that the global fallout doses reported in UNSCEAR (1993) are higher than those reported here for ^{90}Sr, ^{131}I, and ^{137}Cs, whereas the UNSCEAR reported doses are lower for ^{3}H and ^{14}C. There are several primary reasons for this: 1) the models used in this study are somewhat different from those used by the UNSCEAR and 2) the assessment domains are different, as the U.S. covers approximately 30°–50°. In general, the agreement between the two studies is reasonable given the relatively large amount of uncertainty in both studies. The UNSCEAR will report on a revised assessment this year that has been made possible by revised information on fission and fusion yields reported for the large yield tests; the UNSCEAR assessment models have also been revised.

Comparison of the doses reported here for the high-yield tests versus those estimated previously for tests conducted at the NTS indicates that the sums of the per caput doses are roughly similar, although the importance of ^{131}I is much greater for the doses from the NTS tests. Also, other short-lived radionuclides are relatively more important for the NTS tests, notably ^{89}Sr and ^{140}Ba.

Uncertainty

It was not possible for this feasibility study for Beck (2000) to estimate uncertainty in the amounts of monthly depositions of ^{90}Sr and ^{137}Cs on a county-by-county basis or for the country-average values for the monthly deposition of ^{131}I. Thus, no attempt was made to estimate analytically the uncertainty in the estimates of internal dose reported here. Also, the models used to calculate doses from ^{3}H and ^{14}C do not at present allow for the analytical estimation of uncertainty. Based upon the author's subjective judgment, the uncertainty in doses for any individual county is a factor of three or more. The estimates of country-average per caput dose and the estimates of collective dose are likely uncertain by a factor of two or more. It is believed that a substantial amount of uncertainty is associated with estimating the amount of fallout retained by vegetation.

CONCLUSIONS

The results reported here are part of a feasibility study to determine if the external and internal doses from fallout from atmospheric tests conducted at the Nevada Test Site and from high-yield tests conducted at other locations can be estimated. Previously reported studies have determined that the internal dose from ^{131}I (NCI 1997) and other radionuclides (Anspaugh 2000) can be determined for tests at the NTS. Similarly, it has been demonstrated that it is feasible to estimate external doses from the tests at the Nevada Test Site (Beck 1999) and from the high-yield tests (Beck 2000). This report completes the individual components of this feasibility study with the demonstration that internal doses from the high-yield weapons tests can be calculated.

Except for the dose from ^{131}I and in very general terms, the dose from global fallout (or the dose from high-yield weapons) is more important than the dose from weapons tests at the Nevada Test Site. Also, the external dose tends to be higher than the dose from the ingestion of food contaminated with radionuclides. However, for ^{131}I and in particular the

dose to the thyroid, the tests conducted at the Nevada Test Site were more important contributors to dose. In fact, for the Nevada tests, ^{131}I contributed about 90% of the total effective dose. Because the variations in dose on a county-by-county basis are very large for the Nevada tests, however, there can be major local variations in this general conclusion.

Table 12. Summary of the estimates reported in this paper for per caput doses resulting from the ingestion of contaminated foods in the 48 contiguous states in the United States from fallout from high-yield tests in the atmosphere ("global fallout"). The current estimates are compared with those reported in UNSCEAR (1993) and with those previously reported for per caput doses from atmospheric tests in Nevada (Anspaugh 2000). Values in the table do not include external doses, which are reported separately by Beck (1999, 2000).

Radionuclide	Per caput effective dose commitment, μSv		
	This project		UNSCEAR (1993)
	Nevada Test Site	Global fallout[a]	Global fallout[b]
^{3}H	-	66[c]	48
^{14}C	-	120[c]	78[d]
^{55}Fe			14
^{89}Sr	17		2.3
^{90}Sr	3.7	37	170
^{91}Sr	0.0065		
^{97}Zr	0.15		
^{99}Mo	1.0		
^{103}Ru	3.8		
^{106}Ru	7.2		
^{105}Rh	0.086		
^{132}Te	7.8		
^{131}I	610[e]	48	79
^{133}I	1.9		
^{136}Cs	3.6		
^{137}Cs	10	130	280
^{140}Ba	12		0.42
^{143}Ce	0.40		
^{144}Ce	5.3		
^{147}Nd	1.1		
^{238}Pu			0.0009
$^{239+240}Pu$	1.2		0.50
^{241}Pu	0.087		0.004
^{241}Am			1.5
Sum	680[e]	400[f]	670[d]

[a] Averaged over the U.S.
[b] North temperate zone (40°–50°).
[c] To the year 2000.
[d] The UNSCEAR (1993) value of 2600 μSv was multiplied by a factor of 0.03, the portion estimated to be delivered in 50 y.
[e] Age corrected.
[f] Incomplete sum for the radionuclides considered.

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Radiation Dose to the Population of the Continental United States from the Ingestion of Food Contaminated with Radionuclides from High-yield Weapons Tests Conducted by the U.S., U.K., and U.S.S.R. between 1952 and 1963

Part II. Reference and Subsidiary Information

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Report to the National Cancer Institute
Purchase Order No. 263-MQ-912901

COMPARISON OF CALCULATED DOSES WITH THOSE DERIVED FROM MEASUREMENTS IN FOODSTUFFS

One of the specified tasks was to compare the internal dose estimates calculated for ^{90}Sr, ^{131}I, and ^{137}Cs with those derived from the measurements of fallout radionuclides in foods. Extensive measurements of fallout radionuclides in foods started in 1960 with the establishment of the Pasteurized Milk Network (PMN) of the Public Health Service. Additional data were also taken on a limited and/or sporadic basis by many organizations [see PHS (1960)[5] for a summary of early measurement efforts], but many of the more sophisticated measurements were not well organized until after the end of the period of testing of high-yield weapons in the atmosphere.

A full-scale comparison of the measurements with the dose estimates provided in Part I of this report would be a major undertaking well beyond the limited funds made available for the present study.

One of the key issues, of course, is whether the model used in Part I of this study is a reasonable qualitative and quantitative description of the movement of fallout radionuclides to man. The model used for Part I of this study is the PATHWAY model of Whicker and Kirchner (1987).[6] During the development of this model it was extensively tested against several data sets, including the measured amounts of global fallout radionuclides in foodstuffs; in addition other data sets were used such as concentrations measured following tests at the Nevada Test Site and following the reactor accident at Windscale, UK. A major report on this subject was published (Kirchner and Whicker 1984).[7] This article gives several graphs of long-term comparisons of ^{90}Sr and ^{137}Cs from global fallout in beef and milk. Many additional data sets are provided. The following is an excerpt from the abstract in Kirchner and Whicker (1984):

> "The statistical tests used to compare the predictions of PATHWAY to the observations include a correlation analysis, a paired t-test, and a binomial test. We use the correlation coefficient between observations and predictions through time to compare the dynamics of the simulated and real world system. Plots of the residuals from regression are then examined for bias between the predictions and observations. The significance of any trends in the residuals is evaluated using a runs test. The paired t-test and the binomial test are used to evaluate the accuracy of PATHWAY's predictions. The hypothesis for the paired t-test is that the ratio of predictions to observations is 1. The paired t-test can be used to test hypotheses about ratios because the distributions of observations and predictions appear to be lognormal. However, the paired t-test does not consider uncertainty in the predictions of the model. We use a binomial test to compare the observed

[5] Public Health Service. Radiological Health Data Vol. 1, No. 1; April 1960.
[6] See Part I References for citation.
[7] Kirchner, T. B.; Whicker, F. W. Validation of PATHWAY, a simulation model of the transport of radionuclides through agroecosystems. Ecological Modeling 22:21–44; 1984.

data to an interval estimate from PATHWAY. The interval corresponds to a 95% confidence interval on the prediction, and is derived from uncertainty analyses that have been conducted on PATHWAY.

"PATHWAY's predictions are significantly correlated with observed levels of ^{137}Cs and ^{90}Sr in pasture and alfalfa. PATHWAY also simulates the dynamics of ^{131}I, ^{140}Ba, and ^{137}Cs in milk well, but fails to predict what appears to be a long term accumulation of ^{90}Sr in the agro-ecosystem. PATHWAY predicts the absolute concentrations of ^{131}I in milk quite well, but tends to predict levels of ^{140}Ba, ^{90}Sr, ^{137}Cs in milk that are different from those observed by factors of 2 to 7. PATHWAY predicts levels of ^{137}Cs and ^{90}Sr in pasture and beef within a factor of 2 of those observed."

Thus, while the PATHWAY model has been tested extensively and performs quite well, it is not perfect and has been noted to both underpredict and overpredict real world situations. In order to examine some important data sets that pertain directly to global fallout, the data presented to the U.S. Congress by Terrill (1963)[8] are used here. The data pertain to the PMN mentioned above. Although data from 62 different locations are available, it is not easy to associate these milkshed data with counties. In addition deposition values for ^{131}I and dose estimates are not available on a county-by-county basis. Therefore, a comparison has been made only for the population-weighted average dose calculated for the 48 states with network-average concentrations, C_m, measured in milk. The relevant milk data are shown in Table 1.

The reported concentrations for ^{90}Sr, ^{131}I, and ^{137}Cs have been used as the starting point to calculate effective doses for adults according to the following equation:

$$E = C_m \times L \times T \times F_g \times \mathrm{K}$$

where E = Effective dose, Sv;
L = Consumption rate of milk, L day^{-1};
T = Number of days in time period, days period^{-1};
F_g = Ingestion-dose coefficient for the radionuclide, Sv Bq^{-1}; and
K = Units conversion constant, 0.037 Bq pCi^{-1}.

Values of F_g are the same as those used in Part I of this report. A value for L was taken to be 0.42 L day^{-1}, which is consistent with the PATHWAY model values (Whicker and Kirchner 1987). T is either 365 days per year or one fourth of that per quarter. The results of these calculations and the comparisons to the values estimated and reported in Part I of this report are shown in Table 2. A comparison of the values indicates that the dose values for ^{90}Sr and ^{131}I agree quite well, certainly within the expected uncertainties of the values. Dose values for ^{137}Cs do not agree as well, with the model results from Part I being substantially higher. However, a significant amount of the calculated dose from ^{137}Cs would be expected to have occurred from the consumption of contaminated meat; thus, the difference is reasonable.

[8] See following list of documents for citation.

Table 1. Daily average concentration of radionuclides in milk from the 62 stations in the U.S. Public Health Service's Pasteurized Milk Network, 1960 through the first quarter of 1963. From Terrill (1963).

Time period or parameter	Concentration in milk, pCi L^{-1}				
	^{89}Sr	^{90}Sr	^{131}I	^{137}Cs	^{140}Ba
1960					
12-month average level	<5	8	0	10	0
12-month low station	<5	4	0	<5	0
12-month high station	<5	13	0	75	0
1961					
12-month average level	10	8	20	10	<10
12-month low station	<5	4	<10	<5	<10
12-month high station	30	16	70	65	10
1962					
12-month average level	50	13	32	45	12
12-month low station	17	3	<10	12	<10
12-month high station	170	30	104	108	29
1^{st} Quarter 1963					
3-month average level	35	16	<10	70	<10
3-month low station	<5	4	<10	20	<10
3-month high station	265	37	20	135	30

Table 2. Calculated doses according to the measured concentrations of global fallout radionuclides in milk from Table 1 compared to the estimates of dose reported in Part I of this report. Estimates in the last three columns include doses calculated to arise from additional pathways.

Time period	Effective dose to adults, μSv					
	From milk concentration			From results in Part I		
	^{90}Sr	^{131}I	^{137}Cs	^{90}Sr	^{131}I	^{137}Cs
1960	1.3	0	0.74	0.81	0	3.0
1961	1.3	2.5	0.74	0.84	1.2	3.6
1962	2.1	4.0	3.3	4.4	6.8	17
1963, first quarter	0.64	<0.31	1.3	0.69	0.034	0.48

In general the results of this comparison are considered to be satisfactory and indicate that there are no gross errors in the assumptions used in the modeling process. Comparisons such as this can never be perfect and agreement within a factor or two or so is considered excellent.

LIST OF SIGNIFICANT REFERENCES

Congressional Hearings

Over the years Congress has held several hearings on fallout, and the records of the major hearings listed below are major sources of information on fallout. Most of the material is concerned with global fallout, but significant amounts of information pertaining to the Nevada Test Site are also included, particularly in the 1957, 1959, and 1963 hearings.

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LIMITATIONS OF PRESENT CALCULATIONS OF DOSE FROM ^{131}I IN GLOBAL FALLOUT

Problems in calculating doses from ^{131}I contained in global fallout were mentioned in Part I. It is instructive to remember that by definition global fallout consists of debris that is injected into the upper regions of the atmosphere, from which it devolves slowly with time. A normal expectation would be that this material comes down so slowly that all of the ^{131}I contained in the debris would have decayed before it reached the earth. However, it was noted on many occasions that ^{131}I from global fallout did occur in milk, but mainly through the occurrence of uncommon atmospheric events such as the large-scale subsidence of air masses and from the penetration of large thunder storms into the upper troposphere and even into the stratosphere (Machta 1963).

In general these unusual occurrences were not predictable. Also, the networks that were established to monitor global fallout were not generally designed and equipped to monitor the presence of radionuclides as short-lived as ^{131}I. Thus, although some data exist and have been used by Beck (2000) to calculate country-average values of deposition of ^{131}I, it has not yet been possible to use such data to provide county-by-county estimates of the deposition of ^{131}I.

An alternate method of improving the estimates of dose from ^{131}I and in achieving much better resolution is to use the actual data on the measurements of the concentration of ^{131}I in milk. A summary of such measurements for the 1960–1963 (first quarter only) were presented earlier. Briefly, the history of such measurements is that the Public Health Service established the Raw Milk Network in 1957 to develop sampling and radiochemical analytical proficiencies (Terrill 1963). The Pasteurized Milk Network was established later and was used to monitor and report levels of radionuclides in milk from 1960 through 1974. The milksheds sampled through the PMN covered essentially all of the contiguous U.S. plus Alaska and Hawaii.

A proposed method to reconstruct radiation dose from ^{131}I in global fallout is to use the actual data reported from the PMN. This could cover at least the major periods of fallout from 1960 through 1963. Monthly summaries of such data are available in *Radiological Health Data,* a publication of the U.S. Public Health Service. It is hoped that the unsummarized data can be located and used for dose-reconstruction purposes.

An improved dose reconstruction for the important 1956–1958 years is more problematic, as very few measurements of radionuclides in milk were made. Perhaps additional work with the gummed-film data (Beck 2000) could be useful, and additional work could be done with the cattle-thyroid data collected by Van Middlesworth (1954, 1956, 1958,1960, 1963). There are also many measurements of concentrations of radionuclides in air that might be processed to derive useful information on the occurrence of ^{131}I in air; the deposition to ground and vegetation could then be estimated.