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ɟamage to a pine-oak forest, Brookhaven National Laboratory, 1961. Zones delineated by vertical lines
lter and Kincaid 2009).

Gamma Radiation

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duction

tent of this chapter includes a brief history of gamma radiation, units of radiation ment, ecological importance, tables including the half life of gamma emitting , comparative sensitivity of living organisms to gamma radiation, biological :ation of radioactive and nuclear materials, and brief descriptions of case studies of ell (1962), Stalter and Kincaid 2009), and nuclear power plant disasters (Three Mile JSA, 1980, Chernobyl 1986, Japan 2011).

radiation is somewhat similar to x-rays in that both pass through living materials also referred to as "photons" they travel at the speed of light. Gamma rays have t energy to ionize matter and therefore can damage living cells. The damage d in the cell or tissue is proportional to the number of ionizing paths produced in rbing material. Isotopes of elements that are emitters are radionuclides important in roducts from nuclear testing, nuclear power plant disasters or waste.

rious affect of gamma rays depends on (1) their number (2) their energy and (3) tance from the source of radiation. Radiation intensity decreases exponentially with ng distance. Radiation damage on vascular plant species was demonstrated by ell (1962) who subjected a mature pine oak forest at Brookhaven National ory to gamma radiation from a cesium 137 source (Figure 1).

adiation dose and damage to a pine-oak forest, Brookhaven National Laboratory, nes delineated by vertical lines (Woodwell 1962, Stalter and Kincaid 2009).

; their damage to organisms is greatest when taken internally. Odum (1971) izes this concept best, "the alpha beta gamma series is one of increasing penetration easing concentration of ionization and local damage." Alpha and beta radiation, amma radiation, are corpuscular in nature. While alpha particles travel but a few ers, and can be stopped by a layer of dead skin, they are dangerous because they a large amount of local ionization which can cause mutations disrupting cell s. Beta particles are high speed electrons. While much smaller than alpha particles, able to travel up to a couple of centimeters in living tissue, giving up their energy arge path. Beta particles, like alpha particles can damage tissue, and like alpha , can cause mutations that affect the functioning of cells.

history of gamma radiation as applied to biological systems

: familiar with the discovery of x-radiation by Roentgen in 1895 and the isolation of by the Curies in 1898 (Goodspeed and Uber 1939). Researchers soon learned that ays and radioactive substances such as radium produced similar effects on al materials. Koernicke (1905) noted that cell division was delayed on x-ray and treated cells. Both Koernicke (l905) and Gager (1907) described “striking omal disruptions” after cells were dosed with x-rays or exposed to radium, a emitter. Gamma irradiated cells were also broken or fragmented by radiation it (Gager 1907, 1908). For additional historical work on radiation and plant etics the reader is directed to a review article by Goodspeed and Uber (1939). Smith ompiled a paper on the use of radiation in the production of useful mutations based rs presented in three symposia in the United States from August 1956 to January more recent review article on ionizing radiation damage to plants was prepared by d Klein (1971).

re numerous studies applying gamma radiation to biological systems. Several ations involving botanicals follow. Nuttall et al (1961) found that yellow sweet onions exposed to 4000 or 8000 rad prevented sprouting in 97% of their ental group suggesting that irradiation might be a viable method of prolonging life for onions. This study, while intriguing, has not been generally accepted by a concerned with the problems of radiation. A second article by Heeney and ord (1964) examined the effects of gamma radiation on the storage life of fresh rries. A dose of 330,000 rad prevented fungal development of the redcoat strawberry stored at 40 degrees F for 26 days. The fugal free period was sharply reduced at diation doses and/or at higher temperatures. Pritchard et al (1962) studied the effect na radiation on the utilization of wheat straw by rumen microorganisms. They ed that, “high levels of gamma radiation were needed to release nutrients trapped in raw needed by microbes. However, the levels of gamma irradiation necessary for release were well above what was practical for commercial purposes.”

ver et al (1955) investigated the use of gamma irradiation on male sterilization on rol of screw-worm flies in the southern United States while Bushland (l960) ɔ (l967) and Lawson (1967) discussed this practice as a general way of controlling nsect pests. Gambino and Lindberg (1964) examined the response of the pocket vegetation in the southeastern United States while Monk (1966) published a similar ı the effects of short-term gamma radiation on an old field. Witherspoon (1965, 1969) d radiation damage to a forest surrounding an unshielded fast reactor in l965, and l this study with a report in 1969 on radiosensitivity of forest tree species to acute tron radiation. Odum and Pigeon (1970) researched the effect of irradiation and of a tropical rain forest in Puerto Rico.

s of measurement

nits, the gigabecquerel (GBq), gray (GY), and roentgen (R) are used to measure ı. The GBq measures the number of gamma rays emitted from a source of radiation unit of radioactivity that is defined as 1.37 x 10^{-12} atomic decays each second. The of the material comprising a GBq varies. One gram of radium is 37 GBq while 10^{-7}th m of newly formed radio-sodium is also 37 GBq since both release 3.7 x 10^{-10} rations/second (Odum 1971). In dealing with biological systems, smaller units are y used such as the millicurie microcurie and picocurie which are 10^{-3}, 10^{-6} and 10^{-12} vely.

d measurement of radiation is the GY. The absorbed dose of 1 GY means the on of 1 joule of radiation energy per kg of tissue. The third, the roentgen is nearly as the GY, and is used as a unit of measurement for exposure to gamma and x rays. units of the total dose of radiation received by an organism. The dose rate is the of radiation received per unit time.

ogical importance of radionuclides

e different kinds of atoms of each element; these are referred to as isotopes. Some are radioactive, some not. Radioactive isotopes are unstable. These decay into other releasing radiation. Each radioactive isotope, radionuclide, have a specific rate of ration, its half life.

clides fall into well defined groups (Tables 1 and 2). Naturally occurring nuclides ıded in Table 1 while those from fallout produced by fission or uranium and other s are found in Table 2. Fission isotopes are produced from nuclear explosions which the most part been eliminated and from “controlled” reactions that produce nuclear While most of the aforementioned nuclides are not essential for the growth of ns, they may be incorporated in biogeochemical cycles and become concentrated in ains, especially strontium and cesium. Thus Woodwell (1962) used cesium as a radiation emitter in his well published study of an irradiated pine oak forest at ven National Laboratory, Long Island, New York. More will be said about this later in this paper.

itivity of organisms to radioactivity

a wide range of sensitivity of organisms to radioactivity. Mammals are most while bacteria are most resistant especially as spores. Moreover there is a wide tolerance to radiation during the life cycle of an organism. Radiation sickness in can be caused by as little as 0.35 Gy while a dose of 6-8 Gy is lethal to nearly 100% iduals (Donnelly et al 2010). A dose of 2 Gy may kill some insect embryos while a 100 Gy is necessary to kill all adult individuals (Odum 1971). Dividing cells are y more susceptible to radiation than resting cells. The toxicity of radionuclides on the absorption, distribution in the body, half-life, elimination half-time, type of ı emitted, and their energy.

t	Half-Life		Radiations Emitted	
n-235(^{235}U)	7×10^8	yrs.	Alpha^3	Gamma^0
ı-226 (^{226}Ra)	1620	yrs.	Alpha^3	Gamma^0
ım-40 (^{40}K)	1.3×10^9	yrs.	Beta^2	Gamma^2
-14 (See Table 3.)				

Naturally occurring gamma emitting isotopes which contribute to background ı (Odum 1971).

ıt	Half-Life	Radiations Emitted	
ium group	33 yrs.	Beta^2	Gamma
m-137 (^{137}Cs) and	2.6 min	Beta	Gamma^1
ghter barium-137 (^{137}Ba)	2.3 yrs.	Beta^1	Gamma^2
m-134 (^{134}Cs)			
ium group	285 days	Beta^1	Gamma^0
m-144 (^{144}Ce) and	17 min.	Beta^2	Gamma^2
ghter praseodymium-144	33 days	Beta^1	Gamma^1
m-141 (^{141}Ce)			
	1 yr.	Beta^2	
henium group	30 sec.	Beta^3	Gamma^2
enium-106 (^{106}Ru) and	40 days	Beta^1	Gamma^1
ghter rhodium-106 (^{106}Rh)	65 days	Beta^1	Gamma^1
enium-103 (^{103}Ru)	35 days	Beta^0	Gamma^1
nium-95 (^{95}Zr) and daughter	12.8 days	Beta^1	Gamma^1
ɔium-95(^{95}Nb)	40 hrs	Beta^2	Gamma^2
m-140 (^{140}Ba) and daughter	11.3 days	Beta^1	Gamma^1
hanium-140(^{140}La)	2.6 yrs.	Beta^1	Gamma
ymium-147 (^{147}Nd) and	61 days	Beta^2	Gamma^1
er promethium-147(^{147}Pm)	2.4×10^4 yrs.	Alpha^3	Gamma^1
ım-91 (^{91}Y)	8 days	Beta^1	Gamma^1
nium-239 (^{239}Pu)	7×10^8 yrs.	Alpha^3	Gamma^0
e-131 (^{131}I)			
ium-235 (^{235}U)			

Elements important in fission products entering the environment through fallout or sposal.

(1962), Sparrow and Evans (1961), Sparrow and Woodwell (1962), and Sparrow et have demonstrated that sensitivity of ionizing radiation is directly proportional to of the cell nucleus or chromosome volume. The larger the chromosome volume the nsitive the material is to radiation. There are also differences in radiation tolerance wild and laboratory rodent populations. Gambino and Lindberg (1964) and Golley 65) have reported that the lethal dose for 50% of some wild rodent populations is twice that of laboratory white mice or white rats, likely due to the reduced variation tter.

tivity has been successfully used to sterilize certain male insect pests. Sterile males duced to natural populations in large numbers which mate with females. A female nly once, and once mated with a sterile male produces no young. Introducing sterile male screw-worm flies in areas where they occur successfully reduced the of screw-worm flies, a major pest in the southern United States. For those seeking eneral information on this topic see Baumhover et al (1955) Bushland (1960), o (1967), Knipling (1960,1964, 1965, 1967) and Lawson (1967).

ation effects on ecosystems

e early 1960's there have been numerous studies on the effect of gamma radiation on ms. These studies were fueled by the arms race between the Soviet Union and the States (Stalter and Kincaid 2009). After lengthy negotiations between the two powers T (Strategic Arms Limitation Treaty) was signed in 1971 and extended in 1977. With ing of the treaty, less funding for irradiation studies was available (Stalter and 2009). Thus most studies cited in this paper are those conducted prior to the SALT nt of 1971. The gamma source that has been used has been either cesium 137 or 0. These include the studies of Woodwell (1962, 1965a) at Brookhaven National ory, Long Island, New York, a tropical rain forest , Puerto Rico (Odum and Pigeon d the desert of Nevada (French 1965). Additional studies have been conducted in s and forests of Georgia (Odum and Kuenzler 1963) (Platt 1965), and Oak Ridge, ee (Witherspoon 1965, 1969). Much additional work involving a portable gamma n plant communities has been conducted at the Savanna River Ecology Laboratory, outh Carolina (McCormick and Platt 1962, McCormick and Golly 1966, Monk 1966, nick 1969).

and Kincaid (2009) investigated community development following gamma n at a pine-oak forest, Brookhaven National Laboratory, Long Island, New York. The e of this study was to compare vascular plant community change at five vegetation e site of Woodwell's (1962) gamma irradiated forest (Figure 1). The zones were: the ne where all vegetation was killed; a gramminoid *Carex pensylvanica* zone; an us zone; an oak dominated zone; and a control, the original oak pine forest. n greater than 63,000 roentgens killed all vegetation. *Carex* dominated the zone g 27,000 to 63,000 roentgens, ericaceous shrubs, *Vaccinium* spp. and *Gaylussacia* vere dominant at the zone receiving 11,000 to 27,000 roentgens while oaks survived one receiving 3600 to 11,000 roentgens. Upon completion of the Woodwell study in 's, pitch pine (*Pinus rigida*) has invaded the total kill zone as bare mineral soil favors generation (Stalter and Kincaid 2009). *Carex* remained the dominant taxon in the

Carex zone demonstrating again that different plant species vary in their tolerance ion.

ous plant communities may be more resistant to radiation than mature forests many early successional species have small nuclei (Sparrow and Evans 1961) and ause herbaceous taxa like *Carex pensylvanica* have more below ground plant material shielded from gamma radiation. Sparrow (1962), Sparrow and Evans (1961), and et al (1963) present detailed information on the relationship between nuclear , chromosome numbers and relative radiosensitivity.

ogical magnification of radioactive material

tive material may become concentrated or "biologically magnified" during food nsfer. Numerous biology and ecology text books include information on how living ns take up nutrients pesticides and radioactive material and concentrate them. this concept is well known, we direct the reader to several early studies involving entration of radioactive material (See the work of Foster and Rostenbach, 1954; and Kornberg 1956; Davis and Foster 1958). Ophel (1963) reported a concentration ium 90 in perch flesh as 5x that of lake water while that in perch bone was 3000x! al information on radioecological concentration can be found in Auberg and (1958), Auberg and Hungate (1967) and Polikarpov (1966).

oactive fallout

tive particles that fall to the earth after above ground nuclear tests and nuclear lant accidents are called radioactive fallout. Radioactive particles mix with the dust tmosphere and eventually fall to earth often thousands of miles from the initial n.

re two types of nuclear weapons, the fission bomb and fusion bomb or uclear weapon. In thermonuclear devices, deuterium fuses to form a heavier with the release of energy and neutrons. A fission bomb is needed to trigger the reaction. The thermonuclear weapon produces more neutrons which induce ivity in the environment than a fission device per unit of energy released. Roughly ent of the energy of a nuclear weapon is in residual radiation which may become d in the atmosphere (Glasstone 1957). The amount of fallout produced depends on of weapon, size of the weapon and also on the amount of naturally occurring that is mixed with the radioactive material released in the explosion. Fallout and intensity depend upon the direction of the wind, speed and direction of the jet presence and amount of precipitation.

explosions carry radioactive material high in the atmosphere where the radioactive becomes fused with silica dust and other material present in the vicinity of the n. These particles are largely insoluble. The fallout particles may adhere to on where they enter food chains at the primary consumer level. Fallout from yl in 1986 was deposited in Lappland (Sweden) where caribou consumed nated vegetation. Shifting winds also carried Chernobyl radiation particles to Italy where rabbit growers fed their rabbits vegetation contaminated with ive fallout from Chernobyl. Ultimately the rabbits were destroyed because of the ıcentration of radioactive material in their flesh.

:e differences in the kind of radionuclides that enter terrestrial and marine food ›oluble fission products, strontium 90 and cesium 137, are generally found in the amounts in land plants and animals. In marine systems fallout that forms strong :es with organic matter such as cobalt 60, iron 59, zinc 65, and manganese 54 are ely to be concentrated in marine organisms. In addition, those found in colloidal :h as cesium 134 and zirconium 95 are also found in high concentration in marine ns. Cesium 134 is mostly from the fission products of a power reactor whereas l37 can be formed during atomic power plant accidents or as a product of nuclear :plosions.

re additional considerations/problems associated with concentrating radioactive entering food chains as the concentration of radioactivity is also a function of richness, and the exchange and storage capacity of soils. Nutrient poor soils and s such as those found on granite outcrops act as a nutrient trap providing more :lides to the vegetation. For example, sheep grazing on hill pastures in England ated 20x as much strontium 90 in their bones than sheep pastured in deep valleys ılcium content of the soil was higher and the grasses taller (Bryant et al 1957). For al radiological work on tracers in food chains and trophic levels see Odum and 1963), Odum and Kuenzler (1963), de la Cruz (1963), Ball and Hooper (1963), Foster ıd Foster and Davis (1956).

ear power plant accidents

›criptions of three power plant accidents in the United States the Soviet Union and llow. The first nuclear power plant accident occurred at 4 am on March 28, 1979, :risburg, Pennsylvania, USA, the state's capital. A malfunction in the cooling system in a portion of the core to melt in the Number 2 reactor. The approximately 2 people who lived near the plant had an average dose of 0.14 Gy (Rogovin 1980). h some radioactive gas was released from the plant on the 29th and 30th of March as, "not enough to cause any radiation dose above background levels in the rhood of the accident "(http://www.world-nuclear.org/info/info/info/inf36.html). :ely, there were no reported injuries or health issues emanating from the Three Mile :cident.

serious nuclear accident occurred at the Chernobyl power plant located 80 miles the city of Chernobyl in the Ukraine, one of the original Soviet Republics. A " shut down and test that began on the 25th of April, 1986, led to this disaster. At he morning, 26 April, the reactor's power source dropped and when the backup ›stem failed, the reactor, Reactor Four, exploded. Shortly after the initial explosion at ›yl, the Swedish government reported high levels of radiation at their Forsmark power plant at Stockholm. When additional European nuclear power plants also ıced higher than normal levels of radiation, they contacted the USSR for an :ion. Although initially denying the nuclear disaster, on the 28th of April the USSR edged that one of their reactors had been compromised.

ı. Naturally occurring isotopes which contribute to background radiation.

)E HALF-LIFE RADIATIONS EMITTED

ı-235 (^{235}U) 7 x 10^8 yrs. Alpha[3] Gamma[0]
-226 (^{226}Ra) 1620 yrs. Alpha[3] Gamma[0]
m-40 (^{40}K) 1.3 x 10^9 yrs. Beta[2] Gamma[2]
14 (^{14}C) 5568 yrs. Beta[0]
ıw energy, less than 0.2 Mev; [1] relatively low energy, 0.2-1 Mev; [2] high energy, 1-3
ery high energy, over 3 Mev.
. Gamma emitting nuclides of elements which are essential constituents of organisms.
d from Odum (1971).
)E HALF-LIFE RADIATIONS EMITTED

0 (^{60}Co) 5.27 yrs. Beta[1] Gamma[2]
64 (^{64}Cu) 12.8 hrs. Beta [1] Gamma[2]
31 (^{131}I) 8 days Beta [1] Gamma
^{59}Fe) 45 days Beta[1] Gamma[2]
ese-54 (^{54}Mn) 300 days Beta[2] Gamma[2]
m-42 (^{42}K) 12.4 hrs. Beta[3] Gamma[2]
22 (^{22}Na) 2.6 yrs. Beta [1] Gamma[2]
24 (^{24}Na) 15.1 hrs. Beta [2] Gamma[2]
(^{65}Zn) 250 days Beta[1] Gamma[2]
ium-140 (^{140}Ba), bromine-82 (^{82}Br), molybdenum-99 (^{99}Mo) and other trace
s.
:. Nuclides important in fission products entering the environment through fallout
disposal.
)E HALF-LIFE RADIATIONS EMITTED
ntium group
Strontium-90 (^{90}Sr) and 28 yrs. Beta[1]
daughter yttrium-90 (^{90}Y) 2.5 days Beta[2]
Strontium-89 (^{89}Sr) 53 days Beta[2]
ım group
Cesium-137 (^{137}Cs) and 33 yrs. Beta[2] Gamma
daughter barium-137 (^{137}Ba) 2.6 min. Beta Gamma[1]
Cesium-134 (^{134}Cs) 2.3 yrs. Beta[1] Gamma[2]
ım group
Cerium-144 (^{144}Ce) and 285 days Beta[1] Gamma[0]
daughter praseodymium-144 (^{144}Pr) 17 min. Beta[2] Gamma[2]
Cerium-141 (^{141}Ce) 33 da ys Beta[1] Gamma[1]
ıenium g roup
Ruthenium-106 (^{106}Ru) and 1 yr. Beta[0]
dau ghter rhodium-106 (^{106}Rh) 30 sec. Beta[3] Gamma[2]
Ruthenium-103 (^{103}Ru) 40 da ys Beta[1] Gamma[1]
Zirconium-95 (^{95}Zr) and dau ghter 65 da ys Beta[1] Gamma[1]
niobium-95 (^{95}Nb) 35 da ys Beta[0] Gamma[1]
Barium-140 (^{140}Ba) and daughter 12.8 days Beta[1] Gamma[1]

lanthanum-140 (^{140}La)	40 hrs.	Beta[2]	Gamma[2]
Neodymium-147 (^{147}Nd) and	11.3 days	Beta[1]	Gamma[1]
daughter promethium-147 (^{147}Pm)	2.6 yrs.	Beta[1]	Gamma
Yttrium-91 (^{91}Y)	61 days	Beta[2]	Gamma
Plutonium-239 (^{239}Pu)	2.4 x 10^4 yrs.	Alpha[3]	Gamma[1]

131 (see Group B)
m (see Group A)

Radionuclides of Ecological Importance

s estimate that the radiation from the Chernobyl accident was 100x that of the two ɔmbs dropped on Hiroshima and Nagasaki. It is estimated that the total ɩheric release was 5200 PBq (petabecquerel, 10^{15} Bq). The immediate death toll was iduals though many more may die from the long term effects of radiation. The ɔattled blazes at the Chernobyl power plant for two weeks. Those battling the fires roes in this author's eyes because they knew they were exposing themselves to us levels of radiation. Ultimately the Soviet authorities encased the Chernobyl n concrete. A second more stable sarcophagus is currently being constructed over nal; its scheduled completion date is 2013.

ɩay have been additional unreported nuclear power plant accidents in the Soviet ʀadioactive monitoring stations in Europe have picked up higher levels of radiation us times which may have been the result of other Soviet nuclear power plant s.

d and most recent nuclear power plant crisis occurred at the Fukushima Daiichi lant in Japan. The cause of this disaster was a severe earthquake and tsunami on the ɩarch, 2011. The earth quake, which registered approximately 9 on the Richter Scale, event that set this tragedy in motion. The earthquake and resulting tsunami ɖ the power plant compromising the cooling systems to the reactors causing the fuel ɔverheat. This disaster was rated greater than that at Three Mile Island. As of June e Fukushima disaster has released approximately one tenth the total amount of ɩ as was released at Chernobyl. Unfortunately, the damaged Japanese reactor s to spew forth radiation so the ultimate amount of radiation released from the ɩnot be determined with certainty.

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