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Radiological Emergency: Exposure Assessment of Livestock Carcass Management

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Exposure Assessment of Livestock Carcass Management

U.S. Environmental Protection Agency
Office of Research and Development
Homeland Security Research Program
Cincinnati, OH 45268

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Executive Summary

Proper management of livestock carcasses following large-scale mortalities protects humans, livestock, and wildlife from chemical and biological hazards; maintains air, water, and soil resources; protects ecological resources and services; and enhances food and agricultural security. In support of the National Response Framework, the U.S. Department of Homeland Security (DHS) Science and Technology Directorate funds research in collaboration with the U.S. Environmental Protection Agency's (USEPA's) Office of Research and Development, Homeland Security Research Program, and the U.S. Department of Agriculture's (USDA's) Animal and Plant Health Inspection Service (APHIS) to support the proper management of animal carcasses following major environmental incidents. Mass livestock mortalities can result from a natural disaster, foreign animal disease outbreak, chemical or radiological incident, or other large-scale emergencies. As a product of the collaborative research between USEPA and USDA, this report evaluates livestock carcass management options following a radiological emergency through a comparative exposure assessment. This assessment helps to inform a scientifically-based selection of environmentally protective methods in times of emergency. Preceding phases of this project assessed exposures following natural disasters, foreign animal disease outbreaks, and chemical emergencies.

A radiological emergency affecting livestock could be unintentional (e.g., nuclear facility or other nuclear accidents, accidental feed contamination) or intentional (e.g., criminal or terroristic acts). The radiological incident scenario for this assessment includes beef cattle that have ingested feed contaminated by fallout from a nuclear power plant accident. Four radionuclides of concern and initial contamination levels for the assessment are based on data from actual nuclear power plant accidents.

The livestock carcass management options considered in the human exposure assessment are the seven well-established methods included in the previous phases of this project: on-site open burning (pyre), on-site air-curtain burning, on-site unlined burial, on-site composting, off-site fixed-facility incineration, off-site landfilling, and off-site carcass rendering.

For the three off-site options, all environmental releases are assumed to be adequately controlled and monitored in compliance with applicable U.S. federal regulations. Because few facilities are licensed to manage radioactive wastes in the U.S., capacity, cost, and long travel-distances are likely to eliminate these from consideration for managing large volumes of radioactive carcasses. In addition, the assessment assumes that rendering would not be used because radioisotopes would remain in products and waste streams, all of which would require further management as radioactive wastes. For these reasons, radiological exposures associated with the off-site options are not quantitatively assessed.

Combustion-based carcass management options, including off-site incineration, on-site open burning, and on-site air-curtain burning, might not change the quantity, the level of radioactivity, or the rate of radioactive decay of radioisotopes significantly. These options, especially the uncontrolled on-site options, will release some quantity of radioisotopes to air causing further spread of contamination. Exposures are not assessed for the two on-site combustion options.

Exposures are quantitatively assessed for leaching to groundwater from on-site burial trenches and compost windrows, and from soil exposure pathways from compost application. Exposures are evaluated relative to one another based on ratios of estimated radionuclide activity concentrations in media to risk-based benchmarks. Potential exposures from groundwater are greater for the burial option than the composting option. This is due to the absorption of leachate by bulking material in the windrow, which reduces leaching to the ground below. For both groundwater and soil contamination, potential exposures are affected by radioactive decay rates and the amount of time before exposure occurs.

Table ES.1 summarizes rankings of the seven carcass management options. The rankings are based primarily qualitative analysis, because two of the on-site options, as well as the three off-site options, were not quantitatively assessed. Two groups of carcass management options are ranked in the first column of Table ES.1. Rank 1 (i.e., options least likely to result in exposure) applies to the three containment options: off-site landfilling, burial, and composting. These options do not destroy radioactivity; they are intended to reduce or prevent the release and dispersal of radionuclides from the carcasses. The four treatment options (i.e., off-site incineration, rendering, air-curtain burning, and open burning) receive Rank 2. They do not destroy radioactivity, but they might spread or worsen contamination at the carcass management site. In Table ES.1, the options in each ranking group are listed in descending order from least to most likely to result in radiation exposures based on the scenarios assessed in this report.

This report provides information to compare options and support decision-making in the event of actual radiological emergencies. In addition to the exposure assessment findings, it provides a scientifically based understanding of ionizing radiation and radiation exposure, conceptual models of potential radionuclide releases and exposure pathways, equations and other quantitative resources, and available mitigation options. Site managers can pair this report with site-specific information to identify possible exposure pathways, determine whether complete exposure pathways exist, and which carcass management options are compatible at their site.

Because well-informed carcass management decisions are site-specific, quantitative exposure estimates presented in this report should not be interpreted as actual exposures associated with the management options.

Table ES. 1. Qualitative Ranking of Livestock Carcass Management Options – Containment vs. Treatment Options

Management Type*	Management Option	Summary of Potential Exposures
Rank 1: Containment Options Containment options prevent or reduce the release and dispersal of contaminants, including radionuclides and radionuclide-containing particles. These options could reduce the bulk of the carcasses.	Off-site Landfilling	▪ Managing carcasses at an off-site facility authorized to accept radioactive waste would contain the radioactivity and eliminate or reduce exposures. ▪ Capacity, distance, and cost might limit feasibility.
	On-site Burial	▪ Without proper siting, on-site burial has the potential to contaminate groundwater with mobile radionuclides, particularly with longer half-lives. ▪ A thick depth of compacted cover soil will block most radiation at the surface.
	On-site Composting Windrow	▪ A properly constructed windrow would produce a minor amount of leaching, and less potential exposure, compared to burial. ▪ Bulking material absorbs most of the leachate, would block most beta particles, but provide limited blockage of gamma radiation. ▪ For radionuclides with relatively short half-lives, the windrow can be left in place until radioactivity declines to acceptable levels.
	On-site Compost Application	▪ Composting does not destroy radioactivity and most of the radionuclide contamination will be present in the finished compost. ▪ Ingestion exposure can occur if compost is applied to soil where crops or livestock are farmed or where soil can erode to surface water.
Rank 2: Treatment Options Treatment is intended to reduce the volume of the carcasses and to reduce their noxious, infectious, or toxic properties. Radioactivity is not destroyed by treatment.	Off-site Incineration	▪ Commercial waste incinerators are not licensed to accept radioactive waste. ▪ If incineration is allowed, air pollution control equipment would provide more protection than uncontrolled combustion options. ▪ Combustion ash would contain concentrated radionuclides.
	Off-site Rendering	▪ Although air and water releases are regulated, rendering facilities are not designed or permitted to process radioactive livestock, making this option unlikely. ▪ Radionuclides are not destroyed and would remain in rendering products and wastes, possibly at increased concentrations.
	On-site Open Burning and Air-curtain Burning	▪ Combustion is not effective in reducing the radioactivity levels in a waste stream, and contamination would be spread by uncontrolled air emissions. ▪ Exposure could result from contamination of air, soil, water, and biota. ▪ Combustion ash would contain concentrated radionuclides.

*Rank 1 are the options least likely to result in exposure.

Acronyms and Abbreviations

Acronym/Abbreviation	Stands For (Country or Agency Affiliation)
ac	acre(s)
APHIS	Animal and Plant Health Inspection Service (USDA)
BD	soil bulk density
Bq	becquerel(s)
Bq^{-1}	per becquerel(s)
C	coulomb(s)
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act (Superfund)
Ci	curie(s)
cm	centimeter(s)
Cs	cesium
^{134}Cs	cesium-134
^{137}Cs	cesium-137
d	day(s)
DAF	dilution attenuation factor(s)
DHS	Department of Homeland Security (U.S.)
DIL	Derived Intervention Levels (U.S. FDA)
dps	disintegrations per second
dw	dry weight
EPACMTP	EPA Composite Model for Leachate Migration with Transformation Products (EPACMTP)
esu	electrostatic unit
eV	electron volt(s)
FRPCC	Federal Radiological Preparedness Coordinating Committee (U.S.)
ft	foot (feet)
ft^2	square foot (feet)
ft^3	cubic foot (feet)
g	gram(s)
Gy	gray(s)
hr	hour(s)
ha	hectares
HHRAP	Human Health Risk Assessment Protocol (USEPA)
I	iodine
^{131}I	iodine-131
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
IND	improvised nuclear device

Acronym/Abbreviation	Stands For (Country or Agency Affiliation)
IUs	international units
J	joule(s)
kBq	kilobecquerel(s)
kg	kilogram(s)
/kg-d	per kilogram per day
/kg-hr	per kilogram per hour
km	kilometer(s)
km^2	square kilometer(s)
L	liter(s)
lb	pound(s) (weight)
LLRW	low level radioactive waste
m	meter(s)
m^2	square meter(s)
m^3	cubic meter(s)
MCL	maximum contaminant level
MCLG	maximum contaminant level goal
MeV	megaelectron volt(s)
mg	milligram(s)
mrem	millirem(s)
mSv	millisievert(s)
MT	metric ton
N_0	initial radioactivity
NHSRC	National Homeland Security Research Center (USEPA)
NNSS	Nevada Nuclear Security Site
NPP	nuclear power plant
np	radionuclide is not present
NRF	National Response Framework
ORNL	Oak Ridge National Laboratory
pCi	picocurie(s)
PAG	Protective Action Guides
PPE	personal protective equipment
PRG	Preliminary Remediation Goals for Radionuclides (USEPA)
R	roentgen(s)
Rad	roentgen absorbed dose
RCRA	Resource Conservation and Recovery Act
RDD	radiological dispersion device
Rem	radiation exposure-man
s^{-1}	per second
s	second(s)

Acronym/Abbreviation	Stands For (Country or Agency Affiliation)
^{90}Sr	strontium-90
Sv	sievert(s)
t	time
µCi	microcurie(s)
U.S.	United States (adjective)
USDA	United States Department of Agriculture
USDOE	United States Department of Energy
USEPA	United States Environmental Protection Agency
USFDA	United States Food and Drug Administration
USNRC	United States Nuclear Regulatory Commission
vDp_t	total radioactivity addition
WHO	World Health Organization
WNA	World Nuclear Association
ww	wet weight
Yr	year(s)
Zs	soil mixing zone depth
γ	gamma radiation
β	beta particle
α	alpha particle
λ	first-order decay rate constant (disintegrations per second)

1. Introduction

Established by the Department of Homeland Security (DHS), the National Response Framework (NRF) is a single comprehensive approach to domestic incident management.[1] The NRF provides the context for DHS and other federal departments and agencies to work with each other and with communities to prevent, prepare for, respond to, and recover from hazards such as natural disasters, acts of terrorism, and pandemics.

In support of the NRF, the DHS is funding research in collaboration with the United States Environmental Protection Agency's (USEPA's) National Homeland Security Research Center (NHSRC) and the United States Department of Agriculture's (USDA's) Animal and Plant Health Inspection Service (APHIS) to assure the proper management of animal carcasses following major environmental incidents such as a natural disaster, foreign animal disease outbreak, chemical or radiological contamination incident, or other large-scale emergencies. Proper management of livestock carcasses following such emergencies is needed to protect humans, livestock, wildlife, and the environment, and to enhance food and agricultural security.

1.1. Purpose and Scope

This report focuses on relative exposures and hazards for different livestock carcass management options in the event of a *radiological emergency*. Selection of radionuclides for the assessment is described in Problem Formulation in Section 2.

This exposure assessment builds on this earlier research by using consistent assumptions about the carcass management options (e.g., pyre construction and fuels), scale of mortality, and site conditions (USEPA 2017a, 2018a, 2018b). These documents are referenced in this report when previous assumptions, methods, and conclusions remain relevant to carcass management for the current assessment.

Consequences

Currently 400 nuclear reactors are in operation with 65 new ones under construction and another 165 planned around the world. Since the atomic bomb exploded at Alamogordo, New Mexico more than 70 years ago, more than 2,000 bombs have been tested, injecting radioactive materials into the atmosphere and over 200 small and large accidents have occurred at nuclear facilities. In addition, large quantities of radiological wastes are generating every year that will need to be stored for thousands of years to come. Radioactivity has seriously harmed wildlife at Chernobyl and Fukushima. The probability of future accidents or nuclear terrorism could have health and environmental consequences of radioactivity.

This report focuses on relative exposures and hazards for different livestock carcass management options in the event of a radiological emergency. Potential scenarios for a radiological contamination of livestock are similar to potential scenarios for chemical contamination in that the contamination could result from events that are unintentional (e.g., nuclear facility or other nuclear accidents, accidental feed contamination) or intentional (e.g., criminal or terroristic acts). Depending on the nature of the event, the radiological contamination could be lethal or sublethal to the livestock, and the contamination could be limited mainly to the livestock (e.g., from feed contamination) or widespread such as from radioactive fallout. This assessment assumes that

[1] Information about the National Response Framework is available at https://www.fema.gov/pdf/emergency/nrf/nrf-core.pdf

contamination does not hinder safe access to the affected livestock or implementation of carcass management activities.

1.2. Report Organization

Section 2 defines provides background information on radioactivity and radioactive hazards for the assessment. Section 3 describes how exposures might result from each of the management options and how exposures are estimated for this assessment. Section 4 presents the results of the assessment and uncertainties, and Section 5 documents quality assurance, and Section 6 identifies the literature cited. Conceptual models for livestock carcass management options are provided in Appendix A and additional radionuclide exposure information is provided in Appendix B.

2. Problem Formulation

Problem formulation for the radiological exposure assessment defines the radiological emergency scenario, radionuclides of concern, and livestock carcass management options. Aspects of the project scope and assessment scenario that are not specific to the radiological emergency or radiation exposure are consistent with the previous exposure assessments for natural disaster, foreign animal disease outbreak, and chemical emergency scenarios. These include standardized environmental settings and assumptions for specific livestock carcass management options (e.g., unit design, time requirements). These assumptions are identified in Section 3 with discussion of the management-specific approaches.

As in the previous assessments, livestock mortality is assumed to occur at a hypothetical farm. The farm's location and regional factors do not preclude the availability or feasibility of any carcass management option. In addition, impacts of the radiological emergency do not preclude access to the site or on-site carcass management activities. Humans potentially exposed include adult residents, child residents, and workers participating in carcass management. The farm includes agricultural fields and a home garden that supplies the farm residents' fruits and vegetables. The residents also produce their own livestock food products at home, including beef, dairy, pork, poultry, and eggs; fish for consumption are caught in an on-site lake. Farm residents obtain drinking water from an on-site groundwater well.

2.1. Radiological Incident Scenario

There are many possible scenarios by which radiation and radioactive materials could be released to the environment accidentally or purposely. Examples discussed in one or more previous study (e.g., Dennison 2016; USEPA 2013; USDHS and FEMA 2008; USNRC 2016) include the following:

- **Accident at nuclear power plant (NPP) or nuclear weapons facility** – Nuclear power is used to generate electricity at 99 plants in 30 states (WNA 2017). Accidents at NPP have released radioactivity into the environment. Perhaps the most well-known accident occurred at the Three-Mile Island plant in Pennsylvania in 1979. Following a technical failure, concern over a possible hydrogen explosion prompted operators to vent some gases containing radioactivity. Other well-known NPP accidents occurred at Chernobyl, Ukraine in 1986 and Fukushima, Japan in 2011.

- **Detonation of nuclear bomb** – Intentional nuclear detonations include weapons testing and the use of nuclear bombs on Hiroshima and Nagasaki in 1945. A nuclear blast releases massive amounts of energy, which dissipate as a fireball, blast forces/waves, prompt radiation, light and heat (thermal energy), and delayed ionizing radiation (i.e., fallout: nuclear fragments created in the fission process that turn into radioactive elements, which attach to vaporized debris particles from the explosion). A nuclear explosion can produce more than 300 isotopes by the fission process and other radioactivity induced by neutrons.

- **Release of a radiological dispersion device (RDD) or improvised nuclear device (IND) as an act of terrorism** – An RDD is intended to spread radioactive material with conventional explosives or by another means (USDHS and FEMA 2008; USEPA 2013). Air dispersion of radioactive materials would likely be no more than a few blocks or a few miles (USNRC 2014). An IND is a crude, yield-producing nuclear weapon fabricated from stolen fissile materials. If an IND does not result in a nuclear explosion, consequences would be similar to an RDD, but with fissile materials dispersed locally. If a nuclear explosion does occur the consequences would be similar to those from a nuclear bomb, but likely on a smaller scale.

- **Transportation accidents** – Transport of small quantities of radioactive materials occurs daily to supply materials for medical treatments and other applications and to dispose of materials with longer half-lives after use. Transportation of large quantities of radioactive materials occurs via highly protected shipments at infrequent intervals. Materials transported from uranium or thorium mining sites are not sufficiently enriched to pose a risk of a nuclear explosion. However, transport of final fuel rod assemblies to NPPs is more dangerous and is carefully guarded. In the future, there also will be transport of spent fuels from NPP holding ponds to deep storage sites (e.g., in Nevada).

Livestock could be contaminated with radioactive material by any of these events. For the purposes of comparing livestock carcass management options, it is not necessary to develop a detailed incident scenario. However, the event type is relevant to selecting radionuclides for the assessment, the way livestock are contaminated, and degree of contamination.

For carcasses to be radioactive at levels that require culling, they must have absorbed sufficient quantities of longer-lived radioactive isotopes to become radioactive themselves or be contaminated externally at high levels with no means of decontaminating their surfaces. Livestock near the damage zone of an explosion might already be dead or require humane culling. Based on a semi-quantitative assessment (USEPA 2017a), releases associated with carcass transportation are assumed to be insignificant and are not included in this assessment.

For a radiological emergency to be of sufficient magnitude and to release radioisotopes with longer half-lives, a serious NPP accident, detonation of an IND, or detonation of a nuclear bomb would be needed. Following such an event, livestock can be externally contaminated by fallout or contact with contaminated soil or other media. Internal contamination can occur via inhalation to an air-borne radioactive plume, ingestion of fallout-contaminated forage or feed, incidental ingestion of fallout-contaminated matter, and/or ingestion of contaminated surface or groundwater. Following the Fukushima incident, wild boar were found to have elevated levels of ^{137}Cs likely from ingesting mushrooms, which are cesium hyperaccumulators (Merz et al. 2015). In addition, contaminated rice straw and grass used as feed resulted in elevated cesium radioactivity in beef (Kelecom et al. 2011) and horse meat (Manabe et al. 2016).

In some cases, measures are available to decontaminate livestock that have ingested radioisotopes (Dennison 2016; Manabe et al. 2016). For example, providing clean food and water can help eliminate many isotopes from the body, and binding agents like bentonite clay or Prussian blue might prevent absorption. If the radioisotope(s) has a short half-life (e.g., ^{131}I) the passage of time might be all that is required to salvage the livestock. Similarly, milk contaminated with ^{131}I can be frozen or powdered and stored until radiation falls to an acceptable level (Dennison 2016). These options are discussed further in Appendix B. Although decontamination options should be considered in the event of an actual radiological emergency, they are not included in the scenario for this assessment of contaminated livestock management.

Considering the information above, the radiological incident scenario for this assessment includes beef cattle that have ingested feed contaminated by fallout from an NPP accident. The level of exposure is sublethal to the cattle, but sufficient to raise concerns about human exposure from beef consumption. Whether or not the beef contamination exceeds food safety standards, the beef will not enter the market and the animals are euthanized. The feed may have come from on- or off-site, but any on-site contamination from the accident (e.g., from fallout) is not so severe as to displace residents or limit the feasibility of managing carcass at the site.

2.2. Radionuclides of Concern

This section identifies the radionuclides included in the assessment and levels of contamination. Before presenting those aspects of the assessment in Section 2.2.2, Section 2.2.1 provides background information on types of radiation, and measures of radiation intensity and exposure.

2.2.1. Measures of Radiation Emissions and Exposures

Radiation covers electromagnetic energy of all wavelengths (radio waves though visible light through X-rays and higher energies). This assessment considers only "ionizing radiation," radiation with sufficient energy to knock electrons out of atoms. Ionizing radiation can be pure energy or energetic particles. There are four major types of ionizing radiation (Dennison 2016; USNRC 2014):

- **Gamma (γ) and X-rays** – pure energy (photons), very short wavelengths; penetrate most materials and require several centimeters of lead to block. However, being pure energy, gamma rays cannot be "ingested"; radionuclides that emit gamma rays can be ingested.
- **Beta (β) particles** – single negatively charged electrons (-1); high energy electrons can pass through about 1.25 centimeters of water or animal tissue, although it can be blocked by a layer of aluminum foil. Externally received beta radiation can burn skin.
- **Alpha (α) particles** – consist of 2 neutrons and 2 protons, positively charged (+2); are relatively large and easy to block (e.g., sheet of paper, clothing, skin layer).
- **Neutrons** – fast moving free neutrons (i.e., outside of an atom's nucleus); have no charge and can penetrate most materials; produced only by nuclear fission or fusion, not by natural radioactive decay.

Radionuclides have distinct first-order decay rate constants (disintegrations per second), which are denoted as λ ("lambda"). Decay constants are typically reported as half-lives, the time required for half the radionuclides to decay. Half-lives ($t_{½}$) are calculated from decay constants with using Equation 2.1.

$$t_{½} = \frac{\ln(2)}{\lambda} = \frac{0.693}{\lambda} \quad \textbf{(Eqn. 2.1)}$$

Hundreds of man-made radioactive isotopes have half-lives of a few seconds or less. Radionuclides of concern have much longer half-lives, days, years, to millions of years or more.

At least four metrics are used to measure radioactivity and exposure, as listed in Table 1. Although international units differ from units commonly used in the United States, use in the United States is evolving toward the international units (IUs). Thus, all results reported in this assessment conform to International Units (IUs). Further information is provided in Appendix B.

Table 1. Measures of Radioactivity and Exposure

Measure	International Units	United States Units	Equivalency	Equivalency
Disintegrations per second (dps)	1 Becquerel (Bq) = 1 dps	1 Curie (Ci) = decay of 1 g of radium /s	1 Ci = 3.7 E+10 Bq	1 Bq = 0.000027 µCi
Dose equivalent (net effect)	Sievert (Sv)	rem (radiation exposure-man)	1 rem = 0.01 Sv	1 Sv = 100 rem
Gamma and X-ray energy emission rates	Coulomb/kg (C/kg)	Roentgen (R)	1 R = 2.58 E-04 C/kg	1 C/kg = 3880 R
	Coulomb/ kg-hour (C/kg-h)	R/hr – measured by radiation detection equipment	1 R/hr = 2.58 E-04 C/kg-hr	1 C/kg-hr = 3880 R/hr
Amount of energy absorbed in body (gamma rays)	Gray (Gy)	Roentgen absorbed dose (Rad)	1 Rad = 0.01 Gy	1 Gy = 100 Rad

Note: One electron volt (eV) is a unit of energy equal to approximately 1.6E-19 Coulombs (C) or Joules (J). Abbreviations: Bq = Becquerel(s); C = Coulomb(s); Ci = Curie(s); dps = disintegrations per second; eV = electron volt(s); s = second; Sv = sievert(s); h = hour; g = gram; Gy = gray(s); kg = kilogram; R = roentgen(s); Rad = roentgen absorbed dose; rem = radiation exposure-man; µCi = microcurie(s).

2.2.2. Selected Radionuclides of Concern

Radionuclides of concern for the assessment are identified based on releases from NPP accidents. Table 2 lists the three most memorable NPP accidents that released radiation to the environment. In the Chernobyl and Fukushima incidents, radioactive materials in air traveled over more than half the globe, depositing in many countries. Releases from Fukushima also have contaminated groundwater in Japan and the Pacific Ocean with radioactive materials.

Table 2. Accidents at Nuclear Power Plant—Past Examples

Reactor	Date; Location	Area Contaminated by Release	Documented Materials Released	Estimates of Quantities Released	Reference
Three-Mile Island	March 28, 1979; outside Harrisburg, Pennsylvania	2 million people within 50 miles; however, no significant ground contamination	^{85}Kr ^{133}Xe ^{131}I	Total release = 1.0 E+15 Bq; ^{131}I release = 5.6 E+11 Bq	FRPCC 2007
Chernobyl	April 26, 1986; Ukraine	29,400 km^2 contaminated to 180 kBq/m^2; current exclusion zone =4,300 km^2	^{133}Xe ^{131}I ^{132}Te (to ^{132}I) ^{134}Cs ^{137}Cs	4% of core released total release = 8 E+18 Bq; ^{131}I release = 1.8 E+18 Bq (50% of ^{131}I in reactor); ^{137}Cs defines current exclusion zone of 37 km	FRPCC 2007; WNA 2016
Fukushima Daiichi Reactors	March 11, 2011; Japan	Releases to the air and ocean; area of 3,000 km^2 contaminated above 180 kBq/m^2	^{134}Cs ^{137}Cs ^{131}I ^{238}Po, ^{239}Po, ^{240}Po, ^{241}Po, ^{132}Te ^{90}Sr	Volume of contaminated soil in Japan estimated to exceed 1 billion cubic feet (28,300,000 m^3)	USEPA 2013; WNA 2016; Merz et al., 2015

Abbreviations: km = kilometer(s); km^2 = square kilometer(s); kBq= kilobecquerel(s); m^2 = square meter(s); m^3 = cubic meter(s); FRPCC = Federal Radiological Preparedness Coordinating Committee (U.S.); WNA = World Nuclear Association. Full references are at the end of the report.

Based on the past incidents, and a goal of including radionuclides spanning a range of half-lives, the four radioisotopes selected for the exposure assessment are listed in Table 3. Although many other isotopes might be released initially, most have very short half-lives (e.g., minutes to seconds or less), and materials remaining hours later are those listed above. Radioactive gases such as xenon and krypton can be released in large quantities but remain in gas phase where they are dispersed and diluted in air. Other long-lived radioisotopes are less likely to be released to the environment (e.g., ^{235}U, ^{238}Pu).

Table 3. Radionuclides Included in the Exposure Assessment

Radionuclide	Radiation Types	Half-life [a]	Half-life Seconds	Decay constant (s^{-1})
^{134}Cs	β, γ emitter	2.0648 Years	6.5E+07	1.1E-08
^{137}Cs	β, γ emitter	30.1671 Years	9.5E+08	7.3E-10
^{90}Sr	β emitter	28.79 Years	9.1E+08	7.6E-10
^{131}I	β, γ emitter	8.0207 Days	6.9E+05	1.0E-06

[a] Source: Prăvălie 2014.
Abbreviations: β = beta particle; γ = gamma radiation; s^{-1} = per second.

In the Fukushima incident, in which beef cattle ingested contaminated feed, the primary radionuclides of concern in beef were ^{134}Cs and ^{137}Cs. ^{131}I was not a predominant in beef but was of concern in milk and tap water (Merz et al. 2015).

2.3. Livestock Carcass Management Options

The previous exposure assessments for livestock carcass management in the event of a natural disaster, foreign animal disease outbreak, and chemical emergency all considered the seven well-established options listed in Table 4. These include three options conducted off-site at existing commercial facilities, and four options that would be conducted on site. Appendix A provides conceptual models for each of the management options and related activities.

Table 4. Livestock Carcass Management Options Considered for the Exposure Assessment

Management Type	Specific Management Option
Combustion-based Management	▪ On-site Open Burning (Pyre) ▪ On-site Air-Curtain Burning ▪ Off-site Fixed-facility Incineration
Land-based Management	▪ On-site Unlined Burial ▪ On-site Composting ▪ Off-site Lined Landfill
Materials Processing	▪ Off-site Rendering

Combustion-based waste management can be effective in reducing the toxicity of chemical contaminants, the infectivity of microbial contaminants, and the bulk of the waste. The air emissions and ash residue must be considered when evaluating the effectiveness of this type of waste management, but, if applied appropriately, combustion could reduce the hazard associated with certain waste streams. Therefore, in the previous exposure assessments in this series, for natural disaster (USEPA 2017a), foreign animal disease outbreak, (USEPA 2018a) and chemical emergency (USEPA 2018b) scenarios, combustion-based management options were fully assessed.

However, while combustion-based management would reduce the bulk of radioactive carcasses, combustion is not effective in reducing the radioactivity levels in a waste stream. "The combustion process does not destroy... radioactivity nor does it change the rate of radioactive decay, but rather it changes only the chemical and physical forms of the radionuclides. The most often encountered radionuclides, tritium, carbon, and iodine, are generally released with little or no retention in the incinerator" (USEPA 1991). Therefore, for the scenarios under consideration in this assessment, combustion-based management, which would disperse radioactive contaminants, was deemed less effective than land-based management, which could contain such contaminants.

The NRC limits carcass "treatment or disposal by incineration" to the following conditions: "A licensee may dispose of the following licensed material as if it were not radioactive" if the concentration in the material is "0.05 microcurie (1.85 kBq), or less, of hydrogen-3 or carbon-14 per gram of animal tissue, averaged over the weight of the entire animal" (10CFR § 20.2004-§ 20.2005). So, where levels of radioisotopes are extremely low, where they can be purged from living animals, or where they can decay in a short period of time, culling those animals could become unnecessary. If culling occurred, such carcasses could be treated as non-radioactive waste.

Open pyre or air-curtain burning were not ranked among the top management strategies for the scenarios considered in this assessment for several reasons. First, as noted above, NRC regulations strictly limit the treatment and disposal of radioactive waste by incineration. Also, open pyre and air-curtain burning do not reduce radioactivity or the associated hazard associated with radioactive carcasses. In addition, these combustion technologies will release radioisotopes to the air; the remaining radioisotopes would become concentrated in the bottom ash, which could necessity its (costly) management as a radioactive waste. Finally, open pyre or air-curtain combustion disperses rather than contains the hazard.

Similarly, incineration within a device such as an incinerator or industrial furnace was not ranked among the top management strategies for the scenarios considered in this assessment. The reasons are the same: NRC regulatory barriers, lack of hazard reduction, creation of radioactive ash disposal burden, and dispersal of radioactive contaminants. In addition, procedures and protocols for worker protection from radiation would be required, and the facility could need to be decontaminated after.

Mixed-waste incinerators are specially permitted by NRC to manage radioactive waste, but these are not ranked among the top waste management strategies for the scenarios considered here either. Incineration of hazardous waste mixed with radioactive waste ("mixed waste") is permitted but "these incinerators are, by their nature, expensive and difficult to design and operate" (Diederich and Atkins 2008). Also, mixed-waste incineration has fallen into disfavor; "Combinations of technical, regulatory, economic and political factors have constrained the overall use of [mixed waste] incineration. In both the Government and Private sectors, the trend is to have a limited number of larger incineration facilities that treat wastes from multiple sites. Each of these sector [*sic*] is now served by only one or two incinerators" (Diederich and Akins 2008). So, mixed-waste capacity is limited, is generally dedicated to sector-specific purposes (hospital waste, research facility waste, DOE waste), and is expensive. Mixed-waste incineration is not an available or a practical alternative in the event of a large-scale agricultural incident.

- **Rendering is also not a practical or practicable option.** Radioisotopes would remain in all products of the rendering process; none would be useful; products and contaminated waste waters would have to be treated as radioactive waste, which negates that value of rendering. NRC regulations do not permit animal tissue in which radioactive materials have been introduced to be disposed of in a manner that would permit its use as human food or as animal feed (10CFR § 20.2005), which would preclude rendering.

Thus, only three of the original seven carcass management options remain for full analysis in this assessment:

- **On-site burial.** After radiation levels have declined to levels that could be tolerated by appropriately protected workers on-site for limited durations, livestock could be buried on-site if sufficiently large areas away from water wells were suitable (e.g., sufficiently deep trenches could be dug with the bottom more than one meter above the high-water table). The best burial sites would be in areas with very deep aquifers and in areas designated as human exclusion zones due to ground-level contamination over large areas.
- **On-site composting.** After radiation levels have declined to levels that could be tolerated by appropriately protected workers on-site for limited durations, livestock could be composted on-site. Appropriate precautions to prevent runoff and infiltration would be required. Compost containing radionuclides with short half-lives might become suitable for application to an agricultural area in time. If the radionuclides have long half-lives, the windrow would require long-term monitoring of temperature and integrity (e.g., from damage by wildlife), or the finished compost could be landfilled or otherwise managed off-site. Composting the carcasses would reduce pathogens and reduce both the moisture and volume of the carcasses, which is beneficial if the compost is landfilled.
- **Off-site Landfills.** Landfilling would require transport to one of four commercially licensed low-level radioactive waste (LLRW) disposal facilities, which are licensed by states through agreements with the U.S. Nuclear Regulatory Commission (USNRC) under the Atomic Energy Act of 1954. Brandl et al. (2012) cites estimates of $8,000 per cow for disposal at LLRW facilities. The extent to which this option is even feasible depends on the number of livestock culled compared with available LLRW capacity.

High-level radioactive waste is managed primarily by the U.S. Department of Energy (USDOE) at its Nevada Nuclear Security Site (NNSS), which is on what was previously the Nevada nuclear bomb test site. USDOE is developing that facility, however, for long-term storage of spent nuclear fuels that will remain radioactive for thousands, millions, or billions of years. Thus, that facility will be used only for high-level radioactive waste from nuclear programs and reactors.

The possible limitations to off-site management in radiological disposal facilities, particularly after disposal of contaminated materials such as human clothing, worker protective clothing, contaminated soils, and other contaminated materials, means that other, ad hoc waste management options might be required. Options requiring building of new LLRW facilities (e.g., on the contaminated land, in Department of Defense lands, or Department of the Interior lands) or modifications to existing Resource Conservation and Recovery Act (RCRA) facilities would not be available soon enough to handle cattle culled in the intermediate phase of responses. These issues emphasize the importance of salvaging livestock when possible even if they are cannot provide usable products (e.g., milk that is safe to drink, meat with radioactivity levels below the United States Food and Drug Administration (USFDA) Derived Intervention Levels [DILs]) for many months after an incident.

Based on the above, exposures are quantified for the on-site burial and composting options. For burial, the trench could be constructed to include a low-permeability liner, thereby minimizing the drinking water exposure pathway. The scenario for this assessment does not include a liner. In a radiological emergency, regulators might not require a liner if the carcasses must be managed promptly or for other reasons of technical impracticability. All assumptions about the burial trench (e.g. size, cover fill, placement relative to the on-site well), including the exclusion of a liner, are consistent with the exposure assessments for a chemical emergency, foreign animal disease outbreak, and natural disaster.

Composting is assumed to occur on-site in windrows constructed outdoors and on bare earth. Design specifications and performance, including materials, dimensions, and placement relative to the on-site well are consistent with the earlier assessment scenarios. As a base case, composting is complete in eight months (based on Looper 2001), at which time the finished compost is tilled into soil on-site at an agronomic rate. The composting duration is varied in the assessment to evaluate its effect on estimated radiological exposures.

To study potential exposures, finished compost in this assessment is applied to soil on site containing varying quantities of the selected radionuclides. The amount of compost, the application rate, and tillage depth are the same as the three previous exposure assessments. Potential exposure pathways beginning with compost application include ingestion of home-grown foods produced at the compost application site and incidental soil ingestion.

3. Exposure Estimation

This section describes the data, assumptions, and methods used to assess radiological exposure following on-site carcass management in the event of a radiological emergency. Section 3.1 identifies the initial levels of radiation in the carcasses. Section 3.2 discusses estimation or radioactive material releases from the carcasses into potential exposure pathways. Section 3.3 discusses the fate and transport methods and the resulting levels of radioactivity in drinking water and soil, and Section 3.4 presents the methods used to characterize exposure doses to exposed individuals. There is an inherent challenge at considering multiple exposure pathways in this estimation due to wide-ranging exposure timelines in various media under different fate and transport scenarios. For some exposure routes such as from food consumption, advisory levels based on emergencies from shorter term exposures are used; for other exposure routes such as groundwater or drinking water, longer-term advisory levels were used, since for some exposure pathways, exposure continues long past the emergency phase.

3.1. Initial Carcass Contamination

The radiological exposure assessment begins with "base case" assumptions about the level of livestock contamination. The base case radiation level for each radionuclide is accompanied by a range of conceivable alternative levels that are also assessed for comparison. The range of radiation levels for this assessment are based on radiation levels observed in Japan following the Fukushima nuclear accident.

While chemical exposure assessments involve mass-based contaminant concentrations, radiological exposure assessments use one or more measures of radiological exposure and activity (see Table 1). For this assessment, levels of contamination are expressed in radionuclide activity concentrations, specifically Becquerels (Bq) per unit of contaminated substance (e.g., Bq/kg of soil, Bq/L of drinking water). A Becquerel is equal to 1 radioactive disintegration per second.

Radiation monitoring in foods from the Fukushima and neighboring prefectures initially focused on vegetables, which peaked shortly after the accident on March 11, 2011 (Merz et al. 2015). By August, radiation levels in vegetable were mostly below regulatory limits, with the exception of mushrooms that accumulate radiocesium (i.e., ^{134}Cs plus ^{137}Cs). Radiation in meat and dairy gradually rose following the accident, with cesium radionuclide activity concentration in beef first exceeding the provisional regulatory limit of 500 Bq/kg in early June. The highest level reported, 4,350 Bq/kg in mid-July, was in beef from Fukushima Prefecture. Exceedances were found in beef from other prefectures, possibly due to contaminated rice straw used as feed (Kelecom et al. 2013). The highest levels above the provisional standard by prefecture are presented in Table 5. In addition to beef, cesium radiation was detected in meat from wild boar, deer, and horse (Merz et al. 2015; Manabe et al. 2016). In boar, the highest detections were 14,600 and 13,300 Bq/kg, and in deer meat, 1,069 Bq/kg. Japan lowered the radiation standard applicable to meat from 500 to 100 Bq/kg on April 1, 2012. At this level, at least one sample of horse meat, at 100 Bq/kg, exceeded the standard (Manabe et al. 2016).

Table 5. Highest Radiocesium Detections by Prefecture

Prefecture	Highest Detection in Beef (Bq/kg)
Fukushima	4,350
Iwate	2,430
Tochigi	2,200
Miyagi	1,400
Akita	781
Yamagata	590

Source: Kelecom et al. (2013) (Full reference is at the end of the report.) Beef contamination by Cs-134 and Cs-137 in Japan, from the Fukushima Dai-ichi NPP accident. INAC 2013: International Nuclear Atlantic Conference, Brazil.

Based on the range of radiocesium levels detected in beef, as well as the domestic and international standards food and drinking water radiation standards, the base case level of ^{134}Cs and ^{137}Cs contamination in cattle carcasses is 500 Bq/kg. Other levels evaluated in the assessment are 50, 5000, and 50000 Bq/kg, as shown in Table 6. Beef samples can be considered representative of whole carcass concentrations because cesium is rapidly distributed throughout the body following exposure (ATSDR 2004a).

Table 6. Initial Radionuclide Activity Levels in Livestock Carcass[a]

Carcass Radionuclide Activity Levels (Bq/kg)			
^{134}Cs	^{137}Cs	^{90}Sr	^{131}I
50	50	5	100
500	**500**	**50**	**500**
5,000	5,000	500	1,000
50,000	50,000	5,000	5,000

[a] "Base case" levels are shown in bold text.

Food monitoring following the Fukushima accident generally did not measure levels of ^{90}Sr radiation directly. Radionuclides, including ^{134}Cs and ^{137}Cs which are γ and β emitters, are easily detected with γ spectrometry. As a β-emitter only, ^{90}Sr detection is more laborious (Merz et al. 2015). Based on research associated with the Chernobyl accident and nuclear weapon explosions, the Japanese government assumed that ^{137}Cs and ^{90}Sr occurs in a constant 10:1 ratio. Although Merz et al. (2015) report that this ratio is not necessarily constant over time or in different foods, the ratio is used in this assessment to set the ^{90}Sr carcass radiation levels (Table 6). Specifically, the base case level is 50 Bq/kg (i.e., 10% of the ^{137}Cs base case level), and other levels included in the assessment are 10, 100, and 1000 Bq/kg. These assumed levels might overestimate ^{90}Sr levels in leachate because it partitions to skeletal tissue (ICRP 1993 as cited in ATSDR 2004b).

^{131}I was detected in raw milk, vegetables, and potable water following the Fukushima accident. It was not found at high levels in beef (Merz et al. 2105), which is consistent with iodine partitioning being largely confined to extracellular fluid (Brown-Grant 1961 as cited in ATSDR 2004c). Levels of ^{131}I declined rapidly due to its 8-day half-life. Initially, however, levels exceeded ranged from 932 to 1510 Bq/kg, with a mean of 1210 Bq/kg (Kelecom 2013). For water, provisional advisory index values for ^{131}I were established to be 300 Bq/L for adults and 100 Bq/L for infants (WHO, 2018). Because of the partitioning behavior, the reported concentrations in raw milk, are likely to over-represent the overall concentration in cattle.

3.2. Releases to Environmental Media

The amount of contamination released from carcasses into environmental media is one the largest uncertainties in the exposure assessments of livestock management options. Release estimates for this assessment are based on the same information used to estimate chemical releases for the natural disaster and chemical emergency scenarios.

3.2.1. Burial

For the burial management option, radiological releases from the buried carcasses are contained in the liquid released from the carcasses as they decompose. Young et al. (2001) estimated that approximately 33% of the carcass mass is released as fluids during the first 2 months after burial, with half of that amount released in the first week. If the leachate has the density of water (i.e., 1 kg/L), the amount of liquid released from a single 453.6 kg (1,000 pounds [lb]) cattle carcass in the first two months is approximately 150 L. With increasing numbers of carcasses, the amount of leachate is larger. The radionuclide activity concentration of the leachate remains constant because the area of the trench increases proportionally with the number of carcasses. Table 7 shows the design assumptions for the burial trench with the base case (i.e., 100 carcasses) and larger numbers of carcasses.

Table 7. Assumptions for the Burial Management Option

Number of Carcasses	Burial Trench Design
100 (base case)	▪ 100 cattle carcasses are placed in a single trench that is 9 ft deep, 7 ft wide, and 300 ft long (2.7 by 2.1 by 91.4 m) based on guidelines provided by USDA (2005; 2017). ▪ The carcasses are covered with 6 ft (1.8 m) of soil, including 3 ft (0.9 m) mounded over the site starting at ground level (USDA 2005; 2017). ▪ An unsaturated zone of 1 m (3.3 ft) extends below the bottom of the burial trench.
500	▪ Carcasses are placed in a single trench that is 5 times as long (457 m) as the base case. ▪ All other design assumptions are equivalent to the base case.
1,000	▪ Carcasses are placed in a single trench that is 10 times as long (914 m) as the base case. ▪ All other design assumptions are equivalent to the base case.
10,000	▪ Carcasses are placed in 10 parallel trenches that are equivalent to the trench for 1,000 carcasses.

Abbreviations: ft = foot (feet); m = meter(s); USDA= United States Department of Agriculture.
Complete references are at the end of the report.

The radionuclide activity concentration of the leachate is estimated by assuming that the starting carcass radioactivity levels (Table 6) are distributed uniformly in all compartments of the carcass. With this assumption, the concentration of radioactivity in leachate equals the concentration in the muscle tissue. Assuming the leachate has the density of water (i.e., 1 kg/L), the base case ^{134}Cs radioactivity concentration is 500 Bq/L. Considering the internal partitioning behavior of the radionuclides discussed above (including considerations of the chemical form of radionuclides), this assumption is likely to overestimate the leachate radioactivity for ^{90}Sr, underestimate the leachate radioactivity for ^{131}I, and is not biased in either direction for ^{134}Cs and ^{137}Cs.

During the first few months of fluid release from the carcasses, water entering the pit from precipitation will dilute the liquid. When the fluid release declines after the first few months of degradation, however, leachate concentrations can depend on local precipitation as well as conditions in the burial trench. The contribution of precipitation is not included in the leachate modeling approach for the on-site burial option because depending on when precipitation occurred, it might or might not dilute concentrations during the most active period of leachate releases.

The leachate concentrations need to account for radioactive decay over the 2 months during which the leachate is released. The exponential decay equation, Equation 3.1, can be used to estimate the radioactivity remaining at a specified time.

$$N(t) = N_0 * e^{-\lambda * t} \qquad \textbf{(Eqn. 3.1)}$$

Where:

N(t)	=	The radioactivity remaining at time (t), e.g., Bq/L
N_0	=	The initial radioactivity, e.g., Bq/L
λ	=	The decay constant (disintegrations/sec) of the radionuclide
t	=	Time (sec)

To estimate the average leachate radioactivity during the release, the total disintegrations per L over the first two months are divided by time. The total disintegrations can be represented as in Equation 3.2, where Equation 3.1 is summed from t = 0 to t = F, the number of seconds in two months:

$$\int_{t=0}^{t=F} N_0 * e^{-\lambda * t} dt \quad \textbf{(Eqn. 3.2)}$$

In Equation 3.3, the function is integrated. N_0 is constant and thus gets pulled out of the integral.

$$\int_{t=0}^{t=F} N_0 * e^{-\lambda * t} dt = N_0 * \left(-\frac{1}{\lambda}\right) * e^{-\lambda * t} \ (from\ t = 0\ to\ t = F) \quad \textbf{(Eqn. 3.3)}$$

Finally, to find the total disintegrations, the integrated equation is evaluated across maximum and minimum bounds by subtracting the evaluation with the lower bound from the evaluation with the higher bound:

$$N_0 * \left(-\frac{1}{\lambda}\right) * e^{-\lambda * [F]} - N_0 * \left(-\frac{1}{\lambda}\right) * e^{-\lambda * [0]}) \quad \textbf{(Eqn. 3.4)}$$

The average leachate radioactivity concentrations from this approach are presented in Table 8. Considering the uncertainty in the estimated starting radioactivity levels, averaging the initial and final levels is a reasonable alternative to the approach describe above.

Table 8. Estimated Radionuclide Activity in Leachate from Burial[a]

Leachate Radionuclide Activity Levels (Bq/L)			
^{134}Cs	^{137}Cs	^{90}Sr	^{131}I
48.6	48.6	5.0	19.2
486	**486**	**49.9**	**95.9**
4,864	4,864	4,99.0	191
48,645	48,645	4,990.1	959

[a] "Base case" levels of radioactive contamination are shown in bold text. Non-bold values are conceivable alternative levels that are assessed for comparison with the base case. The ranges of alternative levels are based on radiation levels observed in Japan following the Fukushima nuclear accident.

3.2.2. Composting

Releases to the environment from composting include leaching from the windrow and application of finished compost to soil.

Leaching from the Compost Windrow

Consistent with the previous assessment scenarios, compost windrows are constructed according to specifications provided by USDA (2005; 2017). Carcasses are placed on a base layer and covered with a 2 foot (ft) (0.6 m) thick layer of bulking material (e.g., woodchips) on the top and all sides. For large animals, Glanville et al. (2006) recommends placing one U.S. ton (907 kg) of carcass, in a single layer, per 8 ft (2.4 m) of windrow. Using this recommendation, the total length of windrow for 45, 359 kg (50 U.S. tons) of large animal carcasses is 122 m (400 ft). For the base case, 100 carcasses are placed in two 16 ft (4.9 m) wide by 60 m (200 ft) long windrows. The windrow is assumed to be placed on bare earth in a well-drained area that is at least 1 m (~3 ft) above the high-water table level. Table 9 provides the windrow design assumptions for the base case and larger numbers of carcasses.

For the base case scenario, the compost windrow contains the same number of carcasses as the burial trench and the amount and rate of liquid released is the same. Therefore, the radionuclide activity concentrations are the same as for burial (Table 8). However, the bulking material surrounding the carcasses absorbs most of the liquid. Glanville et al. (2006) and Donaldson et al. (2012) both reported volumes of leachate from experimental compost windrows to not exceed 5% of the precipitation that falls on the windrows. Based on that information, the assessment assumes that only 5% of the volume of fluids released by decomposition will seep into the ground beneath the windrow. Contaminants in the remaining 95% of the leachate remain in the windrow. These assumptions have been included in each of the previous exposure assessments.

Table 9. Assumptions for the Composting Management Option

Number of Carcasses	Compost Windrow Design
100 (base case)	▪ Composting is performed on bare earth (USDA 2005, 2015) in 2 parallel windrows that are 4.9 m (16 ft) wide by 61 m (200 ft) long. ▪ An initial layer of bulking material (e.g., woodchips) 2 ft deep are placed across the entire base of the eventual windrow (USDA 2005). ▪ An additional 2 feet of bulking material are placed on the sides and top of the windrow (USDA 2005). ▪ Runoff from the windrows will be contained with hay bales.
500	▪ Carcasses are placed in 2 parallel windrows that 305 m long, 5 times the length of the 100-carcass windrows. ▪ All other design assumptions are equivalent to the base case.
1,000	▪ Carcasses are placed in 4 parallel windrows that 305 m long, 5 times the length of the 100-carcass windrows. ▪ All other design assumptions are equivalent to the base case.
10,000	▪ Carcasses are placed in 20 parallel windrows that 610 m long, 10 times the length of the 100-carcass windrows. ▪ All other design assumptions are equivalent to the base case.

Full references are at the end of the report.

Application of Finished Compost

According to Looper (2001), composting of dairy cow carcasses generally takes six to eight months, with 90% of the flesh decomposed after eight weeks. For this assessment, composting is completed in 8 months and the finished compost is applied to an on-site agricultural field in accordance with a nutrient management plan. Transport of chemicals from the compost application site can occur by runoff/erosion to the lake. The effect of composting duration on exposure is examined in the assessment.

To calculate the radionuclide activity concentration in the finished compost, the initial radioactivity levels (Table 6) in Bq/kg are multiplied by the weight per carcass (453.6 kg) and the number of carcasses in the windrow(s). From the radionuclide activity concentration in the finished compost is subtracted the 5% lost as leachate from the windrow. Radioactive decay during the 8-month composting period is accounted for using Equation 3.1 and the radionuclide decay constants in Table 3. The resulting activity levels are then divided by the total weight of the finished compost. Assuming finished livestock compost has a density of 600 kg/m^3 wet weight (NABCC 2004) and 40% moisture (Chen et al. 2012), the total weight of the finished compost of 100 cattle carcasses is 161 metric tons wet weight or 96.4 metric tons dry weight. Table 10 presents the estimated radionuclide activity concentrations in finished compost for four starting levels of contamination.

Table 10. Estimated Radionuclide Activity in Finished Compost[a] for Four Contamination Levels

Radionuclide Activity Levels in Finished Compost (Bq/kg dw)			
^{134}Cs	^{137}Cs	^{90}Sr	^{131}I
1.9E+01	2.3E+01	2.3E+00	3.5E-08
1.9E+02	**2.3E+02**	**2.3E+01**	**1.7E-07**
1.9E+03	2.3E+03	2.3E+02	3.5E-07
1.9E+04	2.3E+04	2.3E+03	1.7E-06

[a] "Base case" levels of radioactive contamination are shown in bold text.
Abbreviations: dw = dry weight.

3.3. Fate and Exposure Modeling

Fate and transport modeling for the carcass burial option begins with the radionuclide activity concentrations in leachate estimated in Section 3.2.2 and end with concentrations in well water used by residents of the site. The same methods are used to model well water contamination from the compost windrow. Fate and transport modeling for the composting option also includes calculation of surface soil concentrations at the compost application site.

3.3.1. Leaching from Burial Trenches and Composting Windrows

After seeping into the ground beneath the burial trench or composting windrow, leachate first passes downward through unsaturated soil until it reaches the water table where it is carried with the direction of the ambient groundwater flow. The leachate is diluted as it moves through these two subsurface zones, and the leached radionuclides may be affected by physical and chemical process that tend to further reduce concentrations with distance from the source (USEPA 1996). The combined effect of these processes is complex and dependent on site-specific soil and hydrodynamic properties.

Concentrations of radionuclide activity in well water are estimated by multiplying the initial concentration in leachate (i.e., Table 8) by dilution attenuation factors (DAFs) from USEPA (1996). A DAF is a ratio of a source leachate concentration to a concentration in water at a downgradient well. USEPA developed the DAFs used in this assessment to support regulatory analysis, such as soil screening level guidance for EPA's Superfund program (USEPA 1996). Modeling to develop the DAFs used the EPA Composite Model for Leachate Migration with Transformation Products (EPACMTP), which simulates physical, chemical, and biological processes in both the unsaturated and saturated zones. The unsaturated and saturated zone modules of the EPACMTP have undergone extensive verification by USEPA and have been reviewed by the USEPA Science Advisory Board, which found the model to be suitable for generic applications such as the derivation of nationwide DAFs (USEPA 1996).

In support of the soil screening level guidance, USEPA used EPACMTP and nationwide site data (e.g., soil properties at contaminated sites, well location and depth) in a series of Monte Carlo simulations for six well-placement scenarios. Distances from the source to the well in these scenarios were 100 m, 25 m, or 0 m from the source, or randomly selected from a distribution of nationwide data. The well's horizontal offset distance from the plume center line was randomly selected, either within the plume's width or half the width. Well depths were randomly selected from nationwide data for most scenarios.

The Monte Carlo analysis USEPA preformed to develop the DAFs varied parameters (e.g., depth to water table, aquifer thickness, well distance) that are independent on chemical-specific properties. The analysis assumed a non-degrading, non-sorbing contaminant. This aspect of the approach causes well-water concentrations to be overestimated, in general. As elements, radionuclides are affected by only one degradation process, radioactive decay, which is included for groundwater pathways in this exposure assessment.

Because USEPA determined that the DAF estimates are sensitive to the size of the contaminated area, it developed DAFs for sources ranging in size from 1,000 to 5,000,000 ft^2 (93 to 464,515 m^2) and presented charts of the relationships between source size and DAF for various scenarios. For this assessment, the information presented by USEPA was used to identify DAFs for burial trenches and composting windrows with 100, 500, 1,000, and 10,000 carcasses. Each of the DAFs were based on the USEPA scenario in which the well is located 100 m downgradient from the source.

Table 11 presents the base case radionuclide activity concentrations in water drawn from a well located 100 m downgradient of a 100-carcass burial trench. The well water concentrations account for radioactive decay, which is discussed further below. Table 12 shows the DAFs for burial trenches with increasing numbers of carcasses and their effect on estimated ^{134}Cs radioactivity in well water.

As in the chemical emergency exposure assessment, this assessment uses DAFs for a groundwater well 100 m downgradient from a burial trench or compost windrow. The DAF values are included in Table 12. With each order-of-magnitude increase in the number of carcasses, the estimated well water concentration increases nearly an order-of-magnitude.

Table 11. Base Case Radionuclide Activity Concentrations in Well Water with Burial of 100 Carcasses

Radionuclide	Radionuclide Activity in Carcass (Bq/kg)	Radionuclide Activity in Leachate (Bq/L)	DAF	Radionuclide Activity in in Well Water [a] (Bq/L)
^{134}Cs	500	486	878	0.51
^{137}Cs	500	499	878	0.57
^{90}Sr	50	49.9	878	0.06
^{131}I	500	95.9	878	4.6E-05

[a] Estimates include radioactive decay over 90 days of travel from the source to the well.
Abbreviations: L = liter(s); DAF = dilution attenuation factor(s).

Table 12. ^{134}Cs Radionuclide Activity Concentrations in Well Water with Burial of Increasing Numbers of Carcasses[a]

Number of Carcasses	Radionuclide Activity in Carcass (Bq/kg)	Radionuclide Activity in Leachate (Bq/L)	DAF	Radionuclide Activity in in Well Water [a] (Bq/L)
100	**500**	**486**	**878**	**0.51**
500	500	486	200	2.2
1,000	500	486	106	4.2
10,000	500	486	13	35.0

[a] "Base case" levels of radioactive contamination are shown in bold text.
Abbreviations: DAF = dilution attenuation factor(s).

The assessment assumes that 90 days elapse between leaching from the trench until well water is used. During this time, the radionuclide activity concentrations decline according to their specific half-lives. The radionuclide activity concentrations remaining after decay are calculated with Equation 3.1. Table 13 shows reductions due to decay with travel-time assumptions ranging from 0 to 365 days. Comparing the percentage reductions in radioactivity with increasing time shows that the least change occurs when the radionuclides have either short (e.g., 8 day) or long (e.g., 30 year) half-lives. The amount of change is greatest for ^{134}Cs, which has an intermediate half-life of 2.1 years. Thus, the uncertainty associated with the travel time assumption is largest for radionuclides with intermediate half-lives.

Table 13. Radionuclide Activity Concentrations in Well Water with Increasing Time Between Leaching and Water Use, Base Case Burial Option[a]

Number of Days	Radionuclide Activity in in Well Water[a] (Bq/L) (percentage reduction)			
	^{134}Cs Half-life 2.1 yr	^{137}Cs Half-life 30.2 yr	^{90}Sr Half-life 28.8 yr	^{131}I Half-life 8.0 d
0	5.5E-01 (0%)	5.7E-01 (0%)	5.7E-02 (0%)	1.1E-01 (0%)
60	5.2E-01 (5%)	5.7E-01 (0%)	5.7E-02 (0%)	6.1E-04 (>99%)
90	**5.1E-01 (8%)**	**5.7E-01 (1%)**	**5.6E-02 (1%)**	**4.6E-05 (>99%)**
120	5.0E-01 (10%)	5.6E-01 (1%)	5.6E-02 (1%)	3.4E-06 (>99%)
180	4.7E-01 (15%)	5.6E-01 (1%)	5.6E-02 (1%)	1.9E-08 (>99%)
240	4.4E-01 (20%)	5.6E-01 (1%)	5.6E-02 (2%)	1.1E-10 (>99%)
360	4.0E-01 (28%)	5.6E-01 (2%)	5.5E-02 (2%)	3.4E-15 (>99%)

[a] "Base case" levels of radioactive contamination are shown in bold text (i.e., 90 days).
Abbreviations: d = day(s); yr = year(s).

Radioactivity in well water downgradient from the compost windrow is calculated with the same methods. The DAF values differ because the area of the windrows is different from the area of the burial trench. When the windrows are built for 100, 500, 1000, and 10000 carcasses, the DAFs are 315, 72, 38, and 5, respectively.

The USEPA analysis to develop DAFs uses soil infiltration rates rather than leachate volumes as inputs to the unsaturated soil zone. The estimated radionuclide activity concentrations in the leachate from the burial trench and compost windrow are the same, but the leachate volumes are much different. As discussed in Section 3.2.2, this assessment assumes that the amount of leachate from the compost windrow is 5% of the leachate volume from burial based on Glanville et al. (2006) and Donaldson et al. (2012). To account for the difference in the well water, the concentration estimated for the compost windrow is multiplied by 5%. The resulting base case radionuclide activity concentrations for the composting option are shown in Table 14.

Table 14. Base Case Radionuclide Activity Concentrations in Well Water with Composting of 100 Carcasses

Radionuclide	Radionuclide Activity in Carcass (Bq/kg)	Radionuclide Activity in Leachate (Bq/L)	DAF	Radionuclide Activity in in Well Water [a] (Bq/L)
^{134}Cs	500	486	315	7.1E-02
^{137}Cs	500	499	315	7.9E-02
^{90}Sr	50	49.9	315	7.9E-03
^{131}I	500	95.9	315	6.4E-06

[a] Estimates include radioactive decay over 90 days of travel from the source to the well.
Abbreviations: DAF = dilution attenuation factor(s).

3.3.2. Concentrations in Surface Soil

Estimates of the radionuclide activity concentrations in finished compost were presented in Table 8. Using those values, radionuclide activity concentrations are estimated in surface soil following application of the compost at a location on site. The rate of compost application to soil is based on an agronomic nutrient addition consistent with calculations for the previous assessment scenarios. Based on those calculations, the estimated area over which the finished compost can be applied is about 4 hectares (ha) (~40,000 m^2 or 10 acres [ac]). This amounts to an application rate of about 24 dry tonnes of compost per hectare for the base case (i.e., 100 carcasses). The compost application areas with 100, 500, 1,000, and 10,000 carcasses are 3.9, 19.7, 39.5, and 395 ha, respectively.

To estimate radionuclide concentrations in soil at the compost application site, the total radionuclide activity content of the finished compost is divided by the application area for the amount added per unit area (i.e., Bq/m^2 soil). These values are then used to estimate concentrations in surface soil with Equation 3.5 (below) from USEPA's (2005) *HHRAP for Hazardous Waste Combustion Facilities*.[2] The Human Health Risk Assessment Protocol (HHRAP) is a peer-reviewed environmental modeling framework developed, refined, and used by USEPA's Office of Resource Conservation and Recovery to estimate chemical transport of chemicals released to air from a point source and their subsequent fate and transport in soil, surface water, and terrestrial plants and animals. Although developed to model chemical concentrations, the equations used here are valid for radionuclide activity concentrations. In Equation 3.5, the total radioactivity addition with compost is mixed with the surface soil layer. The resulting estimate, *Cs*, is the concentration radio activity in Bq per kg bulk soil at the application location.

$$Cs = (vDp_t) / (Zs * BD) \qquad \textbf{(Eqn. 3.5)}$$

where:

Cs	=	Radionuclide activity concentration in surface soil, Bq/kg
vDp_t	=	Total radioactivity addition, Bq/m^2
Zs	=	Soil mixing zone depth (m)
BD	=	Soil bulk density, kg/m^3

Soil parameter values used in these calculations are HHRAP default assumptions. Specifically, HHRAP provides default assumptions for bulk-soil density at 1500 kg per m^3 (93.6 pounds [lb] per ft^3) (surface soil, unsaturated) and mixing depth assumptions. The compost is assumed to be tilled into the soil to a depth of 20 cm. Table 15 presents the estimated base case radionuclide activity concentration in soil.

[2] Further information on HHRAP is available at: https://archive.epa.gov/epawaste/hazard/tsd/td/web/html/risk.html.

Table 15. Estimated Radionuclide Activity in Finished Compost, Base Case

Radionuclide	Radionuclide Activity Levels in Finished Compost (Bq/kg dw)	Chemical Application Rate (Bq/m^2)	Concentration in Soil After Application (Bq/kg)
^{134}Cs	1.9E+02	4.5E+02	1.5
^{137}Cs	2.3E+02	5.6E+02	1.9
^{90}Sr	2.3E+01	5.6E+01	0.2
^{131}I	1.7E-07	4.2E-07	1.4E-09

Abbreviations: dw = dry weight; m^2 = square meter(s).

With larger numbers of carcasses, the radioactivity in soil is the same as the base case if the amount of finished compost and the area of compost application increase in direct proportion. Radioactivity in soil does change when the initial level of radioactivity changes. For example, with a 10-time increase in the ^{134}Cs radioactivity, the concentration in soil will increase 10 times as well, assuming that the application rate is still determined from the nutrient content of the compost.

3.4. Exposure Estimation

With the goal of comparing exposures among carcass management options, exposure pathways, and radionuclides, all exposures are normalized to human health benchmarks. Health-based benchmarks are concentration- or dose-based estimates of the exposure level below which adverse health effects are not expected. This section identifies the benchmark chosen for the assessment and describes how the radionuclide activity concentration estimated in Section 3.3 are compared with them.

3.4.1. Human Health Benchmarks

Exposure-limiting benchmarks for radiation have been issued by many countries and by international organizations for nuclear safety. Table 16 shows relevant standards issued by U.S. and international agencies. In this assessment, radiation exposure can occur via the use of contaminated groundwater in the home or pathways associated with contamination in on-site soil.

Table 16. Overall Limits (Emergency and Non-emergency) for Human Exposures to Radiation

Exposure Medium	Benchmark	Radioactive Material	*Level of Exposure*	*Reference*
Drinking Water	Maximum Contaminant Level (MCL)	Beta/photon emitters	4 mrem/year over 70-year lifetime	USEPA 2001
	WHO Guidelines for Drinking Water	^{137}Cs, ^{131}I, ^{90}Sr	10 Bq/L	IAEA 2016
Foods	Derived Intervention Levels (DILs)	^{90}Sr	160 Bq/kg food	USFDA 2004, USFDA 2015
		^{137}Cs, ^{134}Cs	1,200 Bq/kg food	
		^{131}I	170 Bq/kg food	
	FAO/WHO *Codex Alimentarius* Guidelines	^{131}I, ^{90}Sr	1,000 Bq/kg food	IAEA 2016
		^{137}Cs, ^{134}Cs	100 Bq/kg food	
Soil	[no names]	Gamma radiation	No more than 2 times background	USEPA 2013
All	Annual Occupational limit	All	50 mSv	Dennison 2016

Full references are at the end of the report. Abbreviations: FAO = Food and Agriculture Organization of the United Nations; IAEA = International Atomic Energy Agency; MCL = maximum contaminant level; mrem = millirem(s); mSv = millisievert(s); USEPA = U.S. Environmental Protection Agency; USFDA = U.S. Food and Drug Administration; WHO = World Health Organization.

Benchmarks for Groundwater

Table 16 includes two benchmarks for radionuclides in drinking water. For a radiological emergency in the US, the most relevant of these is the Maximum Contaminant Level (MCL) established by USEPA as a legal limit applicable to public water systems. The MCL value shown, 4 mrem/year, applies to radiation exposure from beta- and gamma-emitting radionuclides, which include all four of the radionuclides included in the assessment. USEPA has issued a separate MCL for alpha-emitting radionuclides, and MCLs specific to uranium and radium.

The MCL for beta- and gamma-emitters is an effective dose of radiation to the whole body or any organ from radionuclides ingested in the course of a single year. Because the ingested radionuclides may stay in the body, the dose is based on the radiation that will be received by an adult over the next 50 years. If multiple emitters are present, the sum of their doses must not exceed the MCL. USEPA first identified 4 mrem/yr as a regulatory level for beta- and gamma-emitters in 1976 and retained it as the MCL under later rules, most recently in 2000 (USEPA 2000). The MCL is in millirem, a unit commonly used in the U.S. The equivalent level in international units is 0.04 millisieverts (mSv) or 4.0E-5 Sv.

To help public water systems and state regulators monitor compliance with the MCL, the USEPA calculated radionuclide activity concentrations equating to 4 mrem/yr for 179 man-made individual beta particle and photon emitters (USEPA 2002). Table 17 lists the radioactivity concentrations for the four radionuclides in this assessment. Also shown in Table 17 are USEPA's estimates of the cancer risks associated with drinking water exposure for each of the 179 radionuclides at 4 mrem/yr.

Table 17. Radionuclide Activity Concentrations for Maximum Contaminant Level (MCL) Compliance (USEPA 2002)

Radionuclide	Radionuclide Activity Concentration		Estimated Risk
	pCi/L	Bq/L	
^{134}Cs	20,000	740	1.29E-4
^{137}Cs	200	7.4	2.14E-04
^{90}Sr	8	0.30	2.03E-05
^{131}I	3	0.11	3.91E-06

Full reference at the end of the report. Abbreviation: pCi = picocurie(s).

In addition to the MCL, exposures from groundwater are evaluated relative to benchmarks calculated for this assessment with USEPA's Preliminary Remediation Goals for Radionuclides (PRG) Calculator.[3] USEPA developed the PRG Calculator as an online tool to aid decision-making at CERCLA (Comprehensive Environmental Response, Compensation, and Liability Act [Superfund]) sites. PRGs can be used as initial cleanup levels for radiation, especially where there are appropriate government cleanup levels already. The tool estimates PRGs as radionuclide activity levels in abiotic or biotic media for several radionuclide exposure scenarios (e.g., outdoor worker, home residents). Users can enter a target risk level (e.g., 1.0E-4) and site-specific exposure factors or use EPA default values.

For this assessment, the PRG Calculator's farmer scenario is used to calculate benchmarks, in Bq/L, for water exposure pathways. The PRGs are based on a target risk level of 1.0E-04, which is consistent with both the MCL and risk specific doses for chemical exposure in the natural disaster and chemical emergency assessments.

The farmer scenario includes four exposure routes that begin with contaminated water: ingestion of drinking water, inhalation of aerosolized water, immersion (e.g., bathing), and ingestion of irrigated produce, livestock, and fish. All water for farm products comes from contaminated water on site, whether it be groundwater or surface water, and fish tissue concentrations are estimated from the same water contamination. Fish ingestion is not included in this assessment because the pathway must begin with surface water, not groundwater. All home-grown farm products are either irrigated (produce) or watered (livestock) with contaminated well water.

Although the farmer scenario includes inhalation activities, such as showering and laundering, the PRG Calculator includes these activities only for radon and certain other volatile radionuclides (USEPA 2016). The PRG Calculator does not include inhalation exposure for the radionuclides in this assessment.

The PRGs for this assessment are calculated for one-year of exposure to adults and children age 1 to 2. Drinking water ingestion rates are 1.219 L/d and 0.332 L/d for adults and children, respectively, the same values used in the natural disaster and chemical emergency assessments.

[3] The PRG Calculator is an on-line tool available at: https://epa-prgs.ornl.gov/radionuclides/

All other exposure factors (e.g., inhalation rates, food ingestion rates) are default values, which are documented in the PRG User's Guide (USEPA undated).

PRG calculations also require slope factors that are specific to each radionuclide and exposure source. This assessment uses slope factors prepared by the Center for Radiation Protection Knowledge at Oak Ridge National Laboratory (USEPA 2016),[4] which are built into PRG calculator. The slope factors for this assessment are shown in Table 18.

Based on the information describe above, groundwater PRGs calculated for this assessment are presented in Table 19.

Table 18. Slope Factors for Radionuclide Ingestion

Radionuclide	Ingestion Slope Factor (Bq^{-1})		
	Tap Water	Diet	Soil
^{134}Cs	1.14E-09	1.40E-09	1.55E-09
^{137}Cs	8.24E-10	1.01E-09	1.15E-09
^{90}Sr	1.51E-09	1.86E-09	2.33E-09
^{131}I	1.23E-09	1.75E-09	3.31E-09

Abbreviations: Bq^{-1} = per becquerel(s).

Table 19. Preliminary Remediation Goals for Radionuclides (PRGs) Calculated for Groundwater Exposure

Radionuclide	PRG (Bq/L)			
	Drinking Water Ingestion Only		All Pathways	
	Adult	Child 1-2	Adult	Child 1-2
^{134}Cs	2.0E+02	7.2E+02	2.7E+01	5.0E+01
^{137}Cs	2.7E+02	1.0E+03	3.3E+01	6.3E+01
^{90}Sr	1.8E+02	6.7E+02	4.5E+01	8.1E+01
^{131}I	1.5E+02	5.5E+02	7.5E+00	1.7E+01

Benchmarks for Soil

Benchmarks for soil are calculated with the PRG Calculator, described above for groundwater. The PRGs for soil are calculated with the farmer scenario, which includes exposure from incidental soil ingestion, external radiation from contaminants in soil, inhalation of fugitive dust, and consumption of homegrown foods grown in contaminated soil. Ingestion of home-caught fish is not included because the exposure route begins with sediment rather than surface soil (i.e., where compost has been applied). All exposure factors are the same as described above for the calculating the groundwater PRGs, and the target risk is 1.0E-04.

A required input for calculating the soil PRGs is the area of soil contamination. As described in Section 3.3.2, compost application areas are calculated for composting 100, 500, 1000, and 10000 cattle carcasses. The PRG calculator provides a list of areas to enter but does not allow the

[4] A compendium of radionuclide dose coefficients prepared by the Oak Ridge National Laboratory is available at: https://epa-dccs.ornl.gov/documents/SlopesandDosesMasterTableFinal.pdf

custom areas to be entered. The areas entered in the PRG calculator were the available values closest to the calculated compost application areas, as shown in Table 20.

PRGs calculated with the information discussed above are presented in Table 21. The PGRs are not very sensitive to the area of soil contamination. The two largest contamination areas have the same PRG values, and because they are the lowest (i.e., most conservative) values they are selected to be the soil exposure benchmarks in this assessment.

Table 20. Compost Application Areas for Calculating Soil Preliminary Remediation Goals for Radionuclides (PRGs)

Number of Carcasses	Compost Application Area		Modeled Area of Contamination (m^2)
	Ha	m^2	
100	3.9	39,500	50,000
500	19.7	197,000	200,000
1,000	39.5	395,000	500,000
10,000	395	3,950,000	1,000,000

Abbreviations: Ha = hectares; m^2= square meter(s).

Table 21. Preliminary Remediation Goals for Radionuclides (PRGs) Calculated for Soil Exposure

Radionuclide	PRG (Bq/kg)							
	50,000 m^2		200,000 m^2		500,000 m^2		1,000,000 m^2	
	Adult	Child* 1-2	Adult	Child 1-2	Adult	Child 1-2	Adult	Child 1-2
^{134}Cs	1.3E+03	1.9E+03	1.1E+03	1.8E+03	1.1E+03	1.7E+03	1.1E+03	1.5E+03
^{137}Cs	2.2E+03	3.9E+03	2.2E+03	3.9E+03	2.2E+03	3.9E+03	2.2E+03	3.9E+03
^{90}Sr	2.9E+02	7.2E+02	2.9E+02	7.2E+02	2.9E+02	7.2E+02	2.9E+02	7.2E+02
^{131}I	4.0E+04	5.7E+04	3.8E+04	5.6E+04	3.8E+04	5.6E+04	3.8E+04	5.4E+04

*Child age 1-2 years

3.4.2. Exposure Metrics

In many health-based exposure and risk assessments, contaminant concentrations in exposure media (e.g., drinking water, food) are used to calculate amount of contaminant ingested based on ingestion rates, exposure durations, and other exposure factors. The resulting estimates (e.g., doses in mg/kg-d), are then evaluated relative to health benchmarks that reflect the inherent toxicity of the contaminant.

In this exposure assessment, it is not necessary to estimate ingestion exposure doses, because the all of the benchmarks discussed above are in environmental media concentration units (e.g., Bq/L). These benchmarks can be compared directly to the radionuclide activity concentrations in water or soil presented in Section 3.3. The concentration-based benchmarks already account for ingestion rates as well as the inherent cancer-causing potential of the radionuclides.

4. Results and Discussion

This section presents the results of the radiological exposure assessment. Section 4.1 discusses exposures with the base case assumptions. Section 4.2 examines how the exposure estimates change with variation of the base case assumptions. Section 4.3 compares all seven off-site and on-site carcass management options in terms of their utility and potential for radiological exposures. Section 4.4 identifies the major sources of uncertainty in the assessment and evaluates how they affect the quantitative exposure estimates.

4.1. Base Case Exposure Assessment

Base case exposures are evaluated on a relative basis, comparing estimates among management options, exposure pathways, and radionuclides. To facilitate these comparisons, the estimated radionuclide activity concentrations in groundwater and soil presented in Section 3.3 are divided by radionuclide-specific, risk-based media concentration benchmarks identified in Section 3.4. These ratios are referred to as "ranking ratios."

4.1.1. Groundwater Pathways

The base case for this assessment radiological exposure following burial or composting 100 cattle carcasses under the site and carcass management scenario assumptions are identified in Section 3.2. Base case levels of radionuclide contamination are based on contamination observed in beef and dairy following the Fukushima accident, as described in Section 3.1.

The base case results are presented in Table 22. The results are ranking ratios calculated by dividing estimated radionuclide activity concentrations by health-based benchmark concentrations. The exposure concentrations are normalized to benchmarks in this way for risk-based comparisons (e.g., among management options, radionuclides). However, the results should not be interpreted as actual levels of risk because the comparative assessment is based on several assumptions (e.g., distance to the well) that are likely to differ from actual sites.

Ranking ratios for groundwater exposures are consistently higher with burial than composting, as shown in Table 22 and Figure 1. This is because the burial trench releases much more leachate than the compost windrow. Estimates for the two options begin with the same leachate concentrations and well placement relative to the source. However, dilution attenuation in soil and groundwater differs between the options owing to the DAF approach from USEPA (1996) used to estimate well water concentrations. In the EPACMTP modeling to develop the DAFs, increasing the source area increased the infiltration rate, which lowered the DAF, but also increased the mixing zone depth, which increased the DAF (USEPA 1996). The Monte Carlo modeling that produced the DAFs determined the balance of these relationships.

Table 22. Ranking Ratios with the Base Case[a]

Radionuclide	Base Case Contamination (Bq/L)	Groundwater					Soil	
		Ranking Ratio with MCL	Ranking Ratio with PRG				Ranking Ratio with PRG	
			Water Ingestion Only		All Water Pathways			
			Adult	Child[b] 1-2	Adult	Child 1-2	Adult	Child 1-2
Burial								
^{134}Cs	500	6.9E-04	2.6E-03	7.0E-04	1.9E-02	1.0E-02	np	np
^{137}Cs	500	7.6E-02	2.1E-03	5.7E-04	1.7E-02	8.9E-03	np	np
^{90}Sr	50	1.9E-01	3.8E-04	1.0E-04	7.5E-03	3.2E-03	np	np
^{131}I	500	4.1E-04	2.5E-07	6.8E-08	1.0E-06	5.7E-07	np	np
Composting								
^{134}Cs	500	9.6E-05	3.6E-04	9.8E-05	2.7E-03	1.4E-03	1.2E-03	8.1E-04
^{137}Cs	500	1.1E-02	2.9E-04	7.9E-05	2.4E-03	1.2E-03	8.6E-04	4.7E-04
^{90}Sr	50	2.7E-02	5.3E-05	1.4E-05	1.1E-03	4.5E-04	6.4E-04	2.6E-04
^{131}I	500	5.8E-05	3.5E-08	9.5E-09	1.4E-07	7.9E-08	3.5E-14	2.5E-14

Acronyms: MCL = Maximum Contaminant Level, np = radionuclide is not present, PRG = Preliminary Remediation Goals for Radionuclides.

[a] The base case includes 100 cattle carcasses and carcass contamination levels that vary by radionuclide. Contamination levels are discussed in Section 2.2.

[b] Child age 1-2 years.

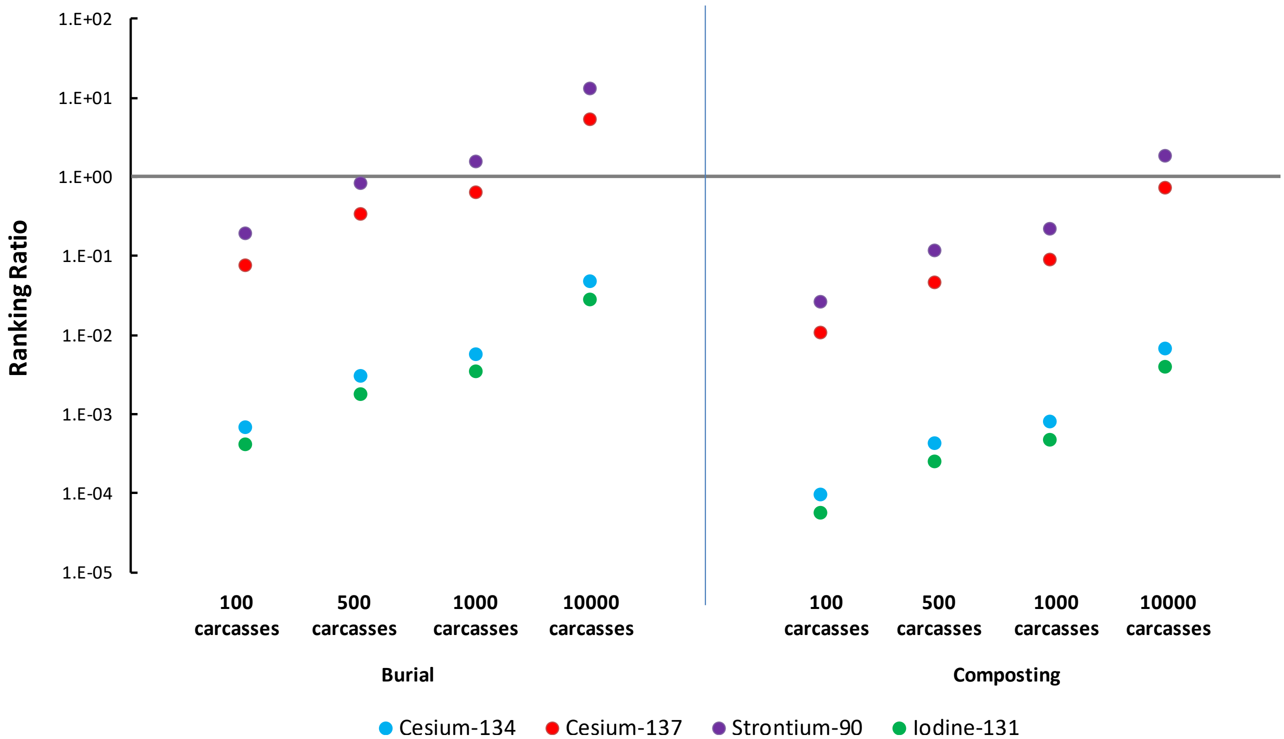

Figure 1. Groundwater exposure ranking ratios for burial and composting by scale of mortality, with Maximum Contaminant Level (MCL) benchmark.

Ranking ratios for groundwater exposure are calculated for two types of benchmark, the MCL and PRGs calculated for this assessment (see Section 3.4.1). While there is a single set of constituent-specific regulatory benchmarks for the MCL, PRGs are calculated separately for adults and children and separately for with or without pathways other than drinking water ingestion. The PRGs with the exposure basis most directly comparable to the MCL is water ingestion only by an adult. As shown in Table 22, the base case activity concentrations in groundwater estimated for all four radionuclides are below (i.e., have ranking ratios below 1) both types of benchmark. With the exception of ^{134}Cs, each of the radionuclides is closer to exceeding the MCL than the PRG. Differences between the benchmarks, and the estimated radioactivity concentrations relative to the benchmarks, are explained by differences in how the benchmarks were derived. For example, while the PRGs all represent a target risk level of 1.0E-04, the MCLs all represent the same effective (i.e., 4 mrem/yr) dose but different levels of risk (see Table 17). In addition, the MCL is based on a water ingestion rate of 2 L/d and PRGs are based on more recent age-specific ingestion rates.

Considering the ranking ratios with MCLs, ^{137}Cs and ^{90}Sr are about two orders of magnitude closer to the benchmark than ^{134}Cs and ^{131}I. This pattern roughly corresponds to differences in half-lives; ^{137}Cs and ^{90}Sr have half-lives of 30.2 and 28.8 years, respectively, and ^{134}Cs and ^{131}I have much shorter half-lives (2.1 years and 8 days, respectively). When internally absorbed (e.g., from ingestion), radionuclides with longer half-lives will remain active longer in the body. However, the pattern among the radionuclides may be affected by other factors including differences in the methods used to calculate the benchmarks. This might explain why the position of ^{134}Cs differs among the four radionuclides when compared to the MCL and PRG benchmarks, as seen by comparing Figures 1 and 2.

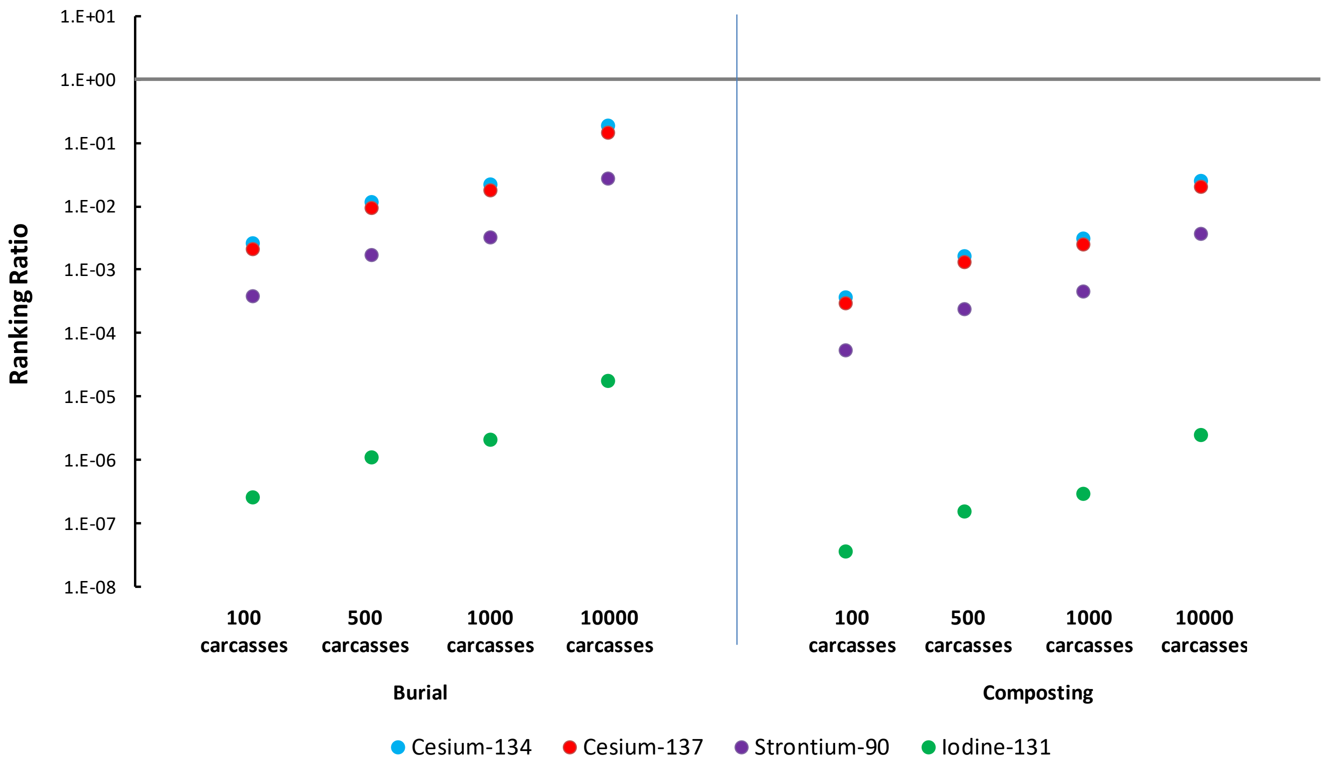

Figure 2. Groundwater exposure ranking ratios for burial and composting by scale of mortality, with Preliminary Remediation Goals for Radionuclides (PRG) benchmark (adult, drinking water only).

Calculation of the PRG benchmarks includes chemical-specific properties, such as biotransfer factors and partitioning coefficients. Estimation of groundwater concentrations include radioactive decay constants, but no other chemical-specific properties. Significantly, the DAFs that relate radionuclide activity concentrations in leachate to concentrations in well water, are not chemicals specific. For this reason, exposure to cesium radionuclides is likely to be overestimated because cesium has a low mobility in surface soil compared to other metals and usually does not migrate below a depth of 40 cm (ATSDR 2004a). However, groundwater contamination with cesium could occur if, for example, cracks or macro-pores in the soil provide a pathway to groundwater.

As discussed in Section 3.4.1, the PRG benchmarks were calculated with the USEPA's online PRG Calculator. The tool provides options to create site-specific PRG values by choosing receptor and setting scenarios, exposure pathways, radionuclides of concern and other factors. This assessment uses PRGs for two scenarios, which are labeled as "Water Ingestion Only" and "All Groundwater Pathways" in Table 22 and Figure 3. The "Water Ingestion Only" PRGs are based on exposure to farm residents who drink well water with radionuclide contamination and receive no other radiation from carcass management activities. This scenario is included for comparisons with MCLs, which are based only on drinking water ingestion. The "All Groundwater Pathways" PRGs are calculated for farm residents who drink contaminated well water, and are also exposed by immersion (e.g., bathing, dishwashing), and ingesting home-grown foods irrigated or watered with the groundwater.

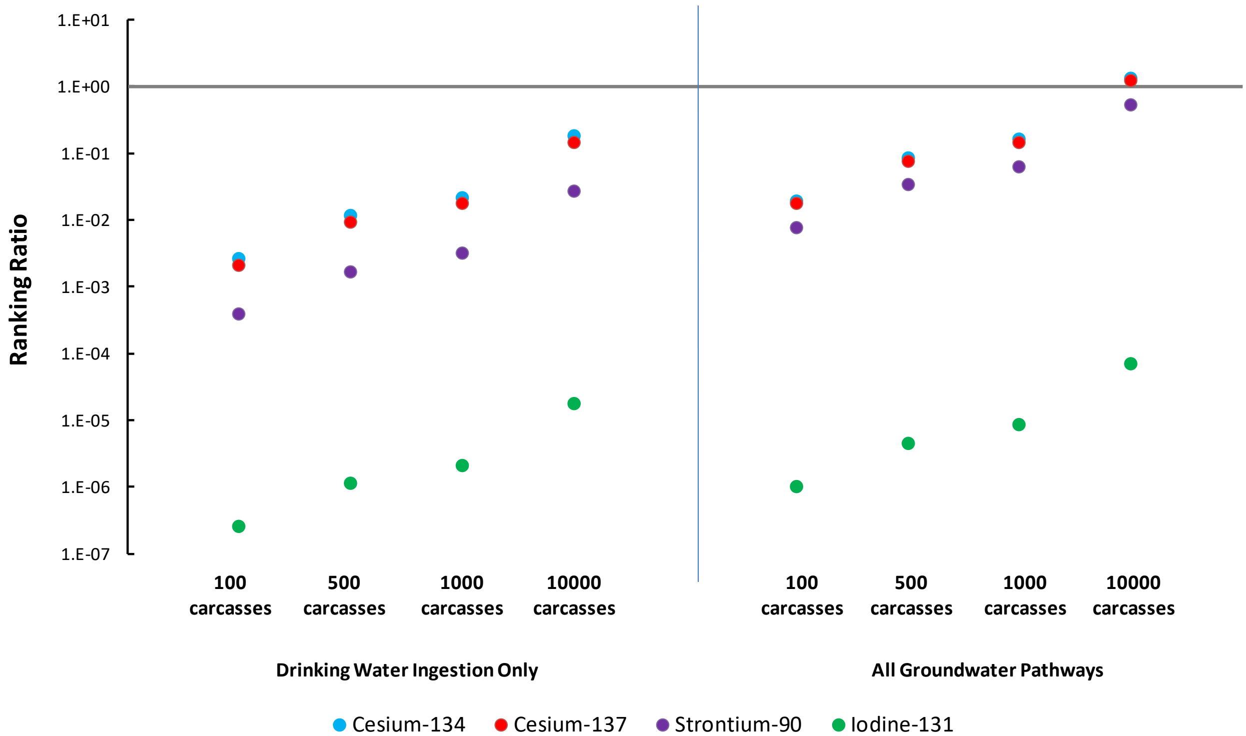

Figure 3. Groundwater exposure ranking ratios for burial by scale of mortality, with Preliminary Remediation Goals for Radionuclides (PRG) benchmark.

As expected ranking ratios based on water ingestion only PRGs are higher than ranking ratios based on PRGs for water ingestion and additional pathways. The ranking ratios differ by about an order of magnitude or less, as seen in Figure 3. Table 23 shows the relative contributions of the groundwater exposure pathways for each radionuclide, and for adults and children. For all four radionuclides, ingestion of homegrown produce is the largest source of exposure for both adults and children. Variations between pathways, radionuclides, and age groups in Table 23 are attributable to differences in chemical fate properties and age-specific ingestion rates.

Table 22 shows that ranking ratios groundwater exposure are higher for adults than children. In contrast, in chemical exposure assessment, children often are more highly exposed than adults because they tend to ingest more (e.g., food, soil) per unit body weight. Chemical exposure doses are typically normalized to body weight (e.g., mg chemical per kilogram body weight per day). For radiation exposures, a dose estimate is an amount of energy not an amount of radioactive material (ATSDR 1999), and exposures are not normalized to body weight. The radiation exposure estimates are higher for adults because adults have higher ingestion rates (e.g., L/day) than children, and thus receive more internal radiation from a year's worth of ingestion.

Table 23. Contribution of Groundwater Exposure Pathways to Preliminary Remediation Goals for Radionuclides (PRGs)

Radionuclide	Drinking Water	Homegrown Produce	Homegrown Livestock	Immersion
Adult				
^{134}Cs	14%	75%	11%	<1%
^{137}Cs	12%	78%	10%	<1%
^{90}Sr	5%	94%	1%	<1%
^{131}I	25%	61%	14%	<1%
Child Age 1-2 Years				
^{134}Cs	7%	77%	16%	<1%
^{137}Cs	6%	79%	14%	<1%
^{90}Sr	3%	95%	1%	<1%
^{131}I	12%	59%	28%	<1%

4.1.2. Soil Pathways

Exposure to radionuclides in soil is evaluated only for the composting option, and specifically to surface soil where finished compost is amended. It is possible that the soil in the footprint of the compost windrows might have higher levels of radionuclides, but this was not included in the exposure assessment. The ranking ratios for the soil exposure pathways are calculated by dividing the estimated radionuclide activity concentrations in soil by PRGs. As discussed in section 3.4.1, the PRGs are based on a target risk level of 1.0E-04 and exposure from incidental soil ingestion, external radiation from contaminants in soil, inhalation of fugitive dust, and consumption of homegrown foods grown in contaminated soil.

Table 24 presents the base case ranking ratios, along with the estimated radionuclide activity levels in finished compost and soil. All ranking ratios are below 1. Differences among the radionuclides result from chemical-specific fate inherent health risk properties included in the PRG calculator, as well as differing radioactive decay rates. ^{131}I radioactivity in compost and soil is much lower than estimated for the other three radionuclides because of its much shorter half-life of eight days.

4.2. Uncertainty Analysis

The uncertainty analysis for the radiological emergency exposure assessment examines two factors that, in the event of an actual emergency, could vary greatly from the base case. These are the scale of mortality (i.e., the number of carcasses to be managed) and the level of contamination. Section 4.4 discusses how the exposure assessment is affected by a number of other scenario assumptions and uncertainties in the data and methods.

4.2.1. Scale of Mortality

In the base case scenario, the radiological emergency results in 100 contaminated carcasses that must be managed. This section shows how the radionuclide exposures, as indicated by ranking ratios, would change with 500, 1,000, and 10,000 carcasses.

Figures 1 and 2 show the ranking ratios for groundwater pathways using the MCL and PRGs, respectively, as benchmarks. Results for burial and composting are included in the site-by-side charts. The ranking ratios increase with the scale of mortality, but less than proportionally. For example, with 5, 10 and 100 times more carcasses, the ranking ratios for all radionuclides and both management options increase approximately 4.4, 8.3, and 69 times, respectively. The proportionality is a function of the DAFs used to estimate radionuclide activity concentrations in well water relative to leachate, and as discussed in Section 3.3.1. The DAFs reflect variables that are independent of chemical-specific properties. For example, USEPA determined that the DAFs are sensitive to the size of the leachate source and thus used source area as a basis for identifying site-specific DAFs (USEPA 1996). The development of that approach is discussed in Section 3.3.1 and further in Soil Screening Guidance: Technical Background Document (USEPA 1996).

Table 24. Base Case Ranking Ratios for Soil Exposure Pathways Following Compost Application

Radionuclide	Amount of Finished Compost (MT dw)	Total Radioactivity at End of Composting (Bq)	Radioactivity in Finished Compost (Bq/kg dw)	Compost Application Area (m^2)	Radioactivity Application Rate (Bq/m^2)	Concentration in Soil After Application (Bq/kg)	Ranking Ratio with PRG, Adult	Ranking Ratio with PRG, Child
^{134}Cs	96	1.8E+07	1.9E+02	39,498	452	1.5	1.2E-03	8.1E-04
^{137}Cs	96	2.2E+07	2.3E+02	39,498	556	1.9	8.6E-04	4.7E-04
^{90}Sr	96	2.2E+06	2.3E+01	39,498	56	0.2	6.4E-04	2.6E-04
^{131}I	96	1.7E-02	1.7E-07	39,498	4.24E-07	1.4E-09	3.5E-14	2.5E-14

Abbreviation: dw = dry weight, MT = metric tons, PRG = Preliminary Remediation Goals for Radionuclides. Child age 1-2 years.

4.2.2. Level of Contamination

The base case radionuclide activity concentrations in the carcasses are based on the upper ranges of contamination observed following the Fukushima accident. The scale of contamination resulting from the Fukushima accident was affected by the amount of radionuclide released, the manner in which the releases occurred, and many site-specific factors (e.g., meteorology, proximity of potentially affected livestock). In the event of a similar accident in the future, changes in any of these factors could result in higher or lower levels of contamination.

To examine how exposure estimates change with varying levels of contamination, this assessment includes four starting contamination levels for each radionuclide. Four levels of contamination include one that is below the base case level, and two levels that are higher. For the cesium and strontium radionuclides, the higher levels are 10 and 100 times greater than the base case, and for ^{131}I the higher levels are 2 and 10 times greater. The rationales for the base case, lower, and higher contamination levels are discussed in Section 3.3.1.

Tables 25 through 28 show the ranking ratios with increasing levels of contamination for groundwater exposure from the burial or composting of 100 carcasses. The results for the four radionuclides are presented in separate tables because the levels of contamination differ. For all four radionuclides and both management options, the estimated exposures, and therefore ranking ratios increase in equal proportion to the level of contamination (i.e., a 100 times increase in the initial contamination level results in 100 times greater exposure).

The PRG ranking ratios in Tables 25 through 28 are based on the "All Groundwater Pathways" estimates. The development of these benchmarks includes pathways and processes, such as uptake by plants and livestock, which are not addressed by the MCLs. Because both types of benchmarks increase in the same proportional rate with the level of contamination, it is evident that the fate and transport algorithms used in USEPA's PRG Calculator are not concentration dependent.

Although not shown, the relationship above between level of contamination and ranking ratios for groundwater exposure also applies to soil exposure pathways associated with compost application.

Table 25. Ranking Ratios with Increasing ^{134}Cs Contamination

Carcass Contamination, ^{134}Cs (Bq/kg)	Ranking Ratio with MCL	Ranking Ratio with PRG	
		Adult	Child
Burial			
50	6.9E-05	1.9E-03	1.0E-03
500	6.9E-04	1.9E-02	1.0E-02
5,000	6.9E-03	1.9E-01	1.0E-01
50,000	6.9E-02	1.9E+00	1.0E+00
Composting			
50	9.6E-06	2.7E-04	1.4E-04
500	9.6E-05	2.7E-03	1.4E-03
5,000	9.6E-04	2.7E-02	1.4E-02
50,000	9.6E-03	2.7E-01	1.4E-01

Abbreviation: MCL = Maximum Contaminant Level, PRG = Preliminary Remediation Goals for Radionuclides.

Table 26. Ranking Ratios with Increasing ^{137}Cs Contamination

Carcass Contamination, ^{137}Cs (Bq/kg)	Ranking Ratio with MCL	Ranking Ratio with PRG	
		Adult	Child
Burial			
50	7.6E-03	1.7E-03	8.9E-04
500	7.6E-02	1.7E-02	8.9E-03
5,000	7.6E-01	1.7E-01	8.9E-02
50,000	7.6E+00	1.7E+00	8.9E-01
Composting			
50	1.1E-03	2.4E-04	1.2E-04
500	1.1E-02	2.4E-03	1.2E-03
5,000	1.1E-01	2.4E-02	1.2E-02
50,000	1.1E+00	2.4E-01	1.2E-01

Abbreviation: MCL = Maximum Contaminant Level, PRG = Preliminary Remediation Goals for Radionuclides.

Table 27. Ranking Ratios with Increasing ^{90}Sr Contamination

Carcass Contamination, ^{90}Sr (Bq/kg)	Ranking Ratio with MCL	Ranking Ratio with PRG	
		Adult	Child
Burial			
5	1.9E-02	7.5E-04	3.2E-04
50	1.9E-01	7.5E-03	3.2E-03
500	1.9E+00	7.5E-02	3.2E-02
5,000	1.9E+01	7.5E-01	3.2E-01
Composting			
5	2.7E-03	1.1E-04	4.5E-05
50	2.7E-02	1.1E-03	4.5E-04
500	2.7E-01	1.1E-02	4.5E-03
5,000	2.7E+00	1.1E-01	4.5E-02

Abbreviations: MCL = Maximum Contaminant Level, PRG = Preliminary Remediation Goals for Radionuclides.

Table 28. Ranking Ratios with Increasing ^{131}I Contamination

Carcass Contamination, ^{131}I (Bq/kg)	Ranking Ratio with MCL	Ranking Ratio with PRG	
		Adult	Child
Burial			
100	8.3E-05	2.0E-07	1.1E-07
500	4.1E-04	1.0E-06	5.7E-07
1,000	8.3E-04	2.0E-06	1.1E-06
5,000	4.1E-03	1.0E-05	5.7E-06
Composting			
100	1.2E-05	2.8E-08	1.6E-08
500	5.8E-05	1.4E-07	7.9E-08
1,000	1.2E-04	2.8E-07	1.6E-07
5,000	5.8E-04	1.4E-06	7.9E-07

Abbreviation: MCL = Maximum Contaminant Level, PRG = Preliminary Remediation Goals for Radionuclides.

In this assessment, the four radionuclides are evaluated independently of each. However, if multiple radionuclides were present, the total beta/gamma radiation would determine compliance with the MCL. It should be noted that an MCL applies to public water systems, not private wells as included in this assessment scenario. The MCL is included in the assessment to serve as a basis of comparison and evaluation of the findings.

The cesium monitoring data from the Fukushima accident measured total cesium radiation (i.e., the total of all radioisotopes). Those data were used to select the base case radioactivity level that is used for each of the two cesium radioisotopes.

4.3. Exposure Assessment Summary

The exposure assessment of livestock carcass management options in the event of a radiological emergency follows related assessments for carcass management following natural disasters, foreign animal disease outbreaks, and chemical emergencies. Each of those assessments concluded with a two-tiered ranking of the seven on-site and off-site management options. The Tier 1 assessments compared the off-site to the on-site options qualitatively, because only the off-site options were not included in the quantitative exposure assessments. The Tier 1 assessments concluded that, in general, off-site management options are more protective of human health and the environment than on-site option, because all releases to the environment (e.g., incinerator emissions to air, rendering facility discharge to surface water) are restricted by, and are assumed to comply with, applicable environmental regulations. The quantitative Tier 2 rankings showed that the potential exposures from on-site options depend on the type of hazardous agent and site-specific exposure pathways.

The ranking of management options in the event of a radiological emergency is primarily qualitative, because two of the on-site options, as well as the three off-site options, were not quantitatively assessed. As in the previous assessments, exposures from the off-site options were not modeled, because all releases to the environment from those options are controlled and regulated under federal environmental laws (e.g., the Clean Air Act, the Atomic Energy Act). As discussed in Section 2.3, the two on-site options excluded from the radiological exposure assessment are open burning and air-curtain burning, the two combustion-based options.

Table 29 presents the qualitative ranking of the seven management options. Composting is divided to distinguish exposures associated with the compost windrow and application of finished compost. The carcass management options are divided into two groups, containment and treatment options. The containment options limit the release and dispersal of, and exposure to, chemical or biological hazards posed by the carcasses. The treatment options are intended to reduce the volume of the carcasses and to reduce their noxious, infectious, or toxic properties. Composting is listed with the containment options in Table 29 but can be considered a treatment option since most microbes are inactivated.

Radioactivity is not reduced by the carcass treatment options included in Table 29. In each case, treatment might spread or worsen contamination at the carcass management site. Containment options control the release of radionuclides to environmental media and human health exposure pathways. Based on this difference, the containment options, as a group, are ranked higher (i.e., more protective) than the treatment options.

The containment options are listed in Table 29 in descending order of their effectiveness. Off-site facilities designed and permitted to manage radioactive waste include features (e.g., impervious liners, overpacking in containers) that would not be included in the on-site options if designed as described in Section 3. Although off-site containment would be the most effective containment option, it is likely to be impractical, particularly for a very large volume of contaminated carcasses. For example, decomposition progresses rapidly in the first week after death and the deteriorating condition of the carcasses would make them increasingly difficult to transport and manage at a distant facility. Currently, there are only four licensed low-level radioactive waste landfills in the U.S., in Barnwell, South Carolina; Richland, Washington; Clive, Utah; and Andrews, Texas (USNRC 2016).

Table 29. Qualitative Ranking of Livestock Carcass Management Options – Containment vs. Treatment Options

Management Type*	Management Option	Summary of Potential Exposures	Controls and Limits to Environmental Releases
Rank 1: Containment Options Containment options prevent or reduce the release and dispersal of contaminants, including radionuclides and particles containing radionuclides. These options could reduce the bulk of the carcasses.	Off-site Landfilling	▪ Managing carcasses at an off-site facility authorized to accept radioactive waste would contain the radioactivity and eliminate or reduce exposures. ▪ Capacity, distance, and cost might limit feasibility.	▪ Facilities authorized to manage radioactive wastes are designed and operated with regulatory oversight to effectively contain radioactivity.
	On-site Burial	▪ Without proper siting, on-site burial has the potential to contaminate groundwater with mobile radionuclides, particularly with longer half-lives. ▪ A thick depth of compacted cover soil will block most radiation at the surface.	▪ Compliance with regulatory siting limitations (e.g., minimal depth to groundwater) will limit exposures. ▪ Lining the burial trench protects groundwater from contamination but might be infeasible in the time available to before carcasses begin to decompose.
	On-site Composting Windrow	▪ A properly constructed windrow would produce a minor amount of leaching, and less potential exposure, compared to burial. ▪ Bulking material absorbs most of the leachate, would block most beta particles, but provide limited blockage of gamma radiation.	▪ Groundwater contamination can be reduced or eliminated by building the windrow on an impervious surface and containing runoff. ▪ For radionuclides with relatively short half-lives, the windrow can be left in place until radioactivity declines to acceptable levels. ▪ Composting can be used to reduce the moisture of radioactive materials before further management. ▪ External exposure to radioactivity from the windrow can be reduced by limiting time near it.
	On-site Compost Application	▪ Composting does not destroy radioactivity and most of the radionuclide contamination will be present in the finished compost.	▪ Compost can be buried, landfilled, or otherwise contained to avoid surface exposure pathways.

Management Type*	Management Option	Summary of Potential Exposures	Controls and Limits to Environmental Releases
		▪ Ingestion exposure can occur if compost is applied to soil where crops or livestock are farmed or where soil can erode to surface water.	
Rank 2: Treatment Options Treatment is intended to reduce the volume of the carcasses and to reduce their noxious, infectious, or toxic properties. Radioactivity is not destroyed by treatment.	Off-site Incineration	▪ Commercial waste incinerators are not licensed to accept radioactive waste. ▪ If incineration is allowed, air pollution control equipment would provide more protection than uncontrolled combustion options.	▪ Incineration of radioactive carcasses is unlikely due to unavailability.
	Off-site Rendering	▪ Although air and water releases are regulated, rendering facilities are not designed or permitted to process radioactive livestock, making this option unlikely. ▪ Radionuclides are not destroyed and would remain in rendering products and wastes.	▪ If approved, rendering could be used to reduce the moisture, weight, and volume of radioactive materials before further management.
	On-site Open Burning and Air-curtain Burning	▪ Combustion is not effective in reducing the radioactivity levels in a waste stream, and contamination would be spread by uncontrolled air emissions. ▪ Exposure could result from contamination of air, soil, water, and biota. ▪ Combustion ash would contain concentrated radiation.	▪ Open burning and air-curtain burning include no pollution control. ▪ Off-site disposal might be required for combustion ash.

*Rank 1 are the options least likely to result in exposure.

With on-site burial, the carcasses are isolated from exposure pathways on the land surface and the most likely exposure pathways begin with leaching to soil and groundwater. Leaching from the compost windrow also has the potential to contaminate groundwater, but the amount of leachate released, and the resulting exposure, is much lower from composting than from burial (Section 4.2 are lower). Above ground, the carcasses in the windrow are more vulnerable to disturbance (e.g., by animals) than when they are buried, although carcasses are rarely disturbed by animals in well-constructed windrows.

While burial is intended to be a final and permanent destination for the carcasses, the compost windrow is a temporary management location. Depending on its radioactivity, the finished compost might be buried on-site, sent to an off-site landfill, amended to soil, or some other option. If a radionuclide contained in the compost has a lengthy half live (e.g., years), then further containment will be needed.

The quantitative exposure assessment for the burial and composting options included a number of conservative assumptions that are likely to overestimate drinking water exposure. For example, a complete drinking water exposure pathway would require a domestic water-supply located down gradient from the source in the direction of groundwater flow. In addition, the DAF approach developed by USEPA to estimate contaminant concentrations at a nearby well does not account for chemical-specific properties and thus overestimates exposures for relatively immobile radionuclides (e.g., ^{134}Cs and ^{137}Cs). Despite these conservative aspects of the approach, the exposures estimated for both options were below benchmarks except with the management of 10,000 carcasses or carcasses with the highest assessed levels of contamination.

A significant radiological emergency in the United States would be largely unprecedented, and carcass management might be subsumed in a broader and unprecedented response plan (see Appendix B). For example, it is possible a specialized radioactive waste disposal unit or immobilization treatment system would be constructed at the site, or that the site would be designated as an exclusion zone and carcasses would be left unmanaged. These outcomes are outside the scope of this assessment.

While the findings above can inform decision-making in the event of an actual radiological emergency, managers should compare the scenarios and assumptions of this assessment to site-specific circumstances. In doing so, decision-making can be aided further by the following information provided in this report:

- **Radiation facts** – Section 2.2 describes the different types of radioactivity and identifies the U.S. and international units used to characterize radiation and radiation doses. The report also describes concepts in radiological exposure assessment (e.g., internal and external doses) that differ from chemical exposure assessment.
- **Conceptual models** – Conceptual models for each management option, which are included in Appendix A, identify the possible pathways by which humans might be exposed to contamination.
- **Environmental fate concepts** – The description of radionuclide releases and environmental fate estimation in Sections 3.2 and 3.2 identify factors (e.g., aquifer and well characteristics) determine whether a complete exposure pathway actually exists at a particular site.
- **Management option assumptions** – Sections 3.2 and 3.3 identify assumptions to (e.g., compost burial trench dimensions, volume of finished compost) used to estimate

environmental releases and exposures. These assumptions are from cited literature and can be used for calculations for actual sites.

- **Radioactive decay equations** – The report provides equations to calculate radioactive decay and describes how decay relates to the management options.
- **Information and computational resources** – Sections 3.3 and 3.4 identify information resources and tools (e.g., USEPA DAFs, Oak Ridge National Laboratory (ORNL) radiation dose conversion factors, the PRG Calculator) that can be useful for site-specific studies.
- **Variability relationships** – Section 4.2, as well as topics discussed throughout the report, describe how exposures might differ at sites where scenarios and assumptions differ from those assumed for this assessment.
- **Mitigation** – By describing the environmental releases and exposure pathways for the management options, the report can be used to identify effective mitigation measures to prevent or reduce radiation exposure.

To fully understand the findings of this exposure assessment, it important to understand how the assessment approach addresses unavoidable and inherent uncertainties. Section 4.4 identifies three types of uncertainties in the assessment and describes how the findings are influenced by the approaches and assumptions used to address them.

4.4. Uncertainty Summary

Tables 30 through 32 summarize three types of uncertainties in the exposure assessment:

- **Parameters with Moderate to High Natural Variation (Table 30)** – These uncertainties pertain to parameters for which substantial variation exists across the United States, and the assessment uses value selected either to be nationally representative, to be health protective (i.e., overestimate exposure), or for another reason. The table lists the magnitude (low, medium, high) and direction (under- or overestimate) of bias in the exposure estimates for each one.
- **Uncertain Parameter Values or Models (Table 31)** – These include parameters for which limited data were available to calculate a central tendency value or to estimate likely variation across conditions possible in the country. Uncertainty is characterized as low, medium, or high. By definition, the direction of bias is unknown.
- **Simplifying Assumptions (Table 32)** – The assessment requires a number of "simplifying assumptions" to compare management options relative to each other within a reasonable level of effort. The table identifies the magnitude (low, medium, or high) and direction (under- or overestimate) of bias introduced by the assumptions.

Table 30. Moderate to High Natural Variation in Parameter—Potential Bias from Selected Values

Key Topic	Selected Parameter Value	Bias	Rationale
Radiological Emergency Scenario			
Scale of Mortality	▪ The assessment assumes a "base case" mortality of 100 cattle at one farm with a total weight of 50 short tons. ▪ The base case mortality matches the earlier assessments for the natural disaster and foreign animal disease outbreak scenarios. ▪ Larger scale losses of 500, 1,000, and 10,000 are also evaluated.	Possibly High Underestimate	▪ The base case scale of mortality could be "small" relative to mass mortality or euthanasia (e.g., in the event of wide-spread feed contamination). ▪ Larger scale losses could make some management options technically infeasible (e.g., due to resource availability) ▪ Large-scale mortalities could exceed the capacity of off-site management facilities. ▪ Large scale mortality might require periods of temporary carcass storage due to capacity or resource limitations, which increases the potential for exposures.
Site Setting and Environmental Conditions			
Groundwater	▪ The assessment assumes that radionuclides leached from the burial trench and compost windrow can reach groundwater. ▪ The groundwater is assumed to supply domestic water well 100 m downgradient from the source of leachate.	Variable Overestimate	▪ In the event of a radiological emergency, it is unlikely that carcass management would be sited 100 m from a domestic water well. ▪ Although the domestic well exposure pathway is possible, the domestic well would have to be shallow enough to directly intersect leachate from surface sources. In addition, well contamination would require the well to be located down gradient (in the direction of groundwater flow) from the source.
Dilution Attenuation Factors	▪ The assessment uses DAFs developed by the USEPA using a Monte Carlo analysis of a nationwide database of aquifer and well data. The DAFs and the groundwater transport methods do not include radionuclide-specific mobility properties.	High Overestimate	▪ Exposure through groundwater pathways is likely to be overestimated, particularly for cesium, which has a low mobility in surface soil.

Key Topic	Selected Parameter Value	Bias	Rationale
Exposure Receptors and Estimation			
Human Receptors	▪ Exposures are assessed for two types of farm residents: young children (age 1-2 years old) and adults.	Moderate Overestimate	▪ In the event of a radiological emergency that causes contamination throughout the site, residents might be prohibited from or might voluntarily avoid living on-site.
Exposure Factors	▪ Exposure factors (e.g., ingestion rates, body weights) are mean values from USEPA's (2011) *Exposure Factors Handbook* and related guidance.	Neutral	▪ Means are used so that exposure is not over- or under-estimated by this aspect of the approach.

Abbreviations: DAF = dilution attenuation factor(s). Full references are found at the end of the report.

Table 31. Uncertainty in Parameter Value(s) Selected

Parameter	Description	Uncertainty	Rationale for Uncertainty Category
Radiological Emergency Scenario			
Radionuclides Included	▪ Radionuclides included in the assessment were identified from food monitoring following the Fukushima accident.	Moderate	▪ The assessment does not include several other radionuclides that could be released by the potential emergency scenarios discussed in Section 2. ▪ The radionuclides include ones with short (8 day) and long (30 year) half-lives.
Releases and Release Rates			
Releases Estimates	▪ Each exposure pathway in the assessment begins with a release of radioactive leachate from a carcass management unit. Data to characterize amount and rate of leaching from leachate released following death is uncertain and very limited.	High	▪ Although release estimates were based on the best available information, releases might be over or underestimated. In addition, actual releases can vary significantly due to many factors (e.g., unit design, environmental conditions).

Parameter	Description	Uncertainty	Rationale for Uncertainty Category
Radioactive Decay in Soil and Groundwater	▪ Radioactivity concentrations in well water account for radioactive decay during travel from the source to the well. The assumed duration is 90 days. This assumption has a low impact on estimates for radionuclides with long half-lives (e.g., in years).	Moderate	▪ The effect of this assumption on well water concentrations was evaluated for a series of durations from 0 to 365 days as shown in Table 13.
Radionuclide Partitioning and Mobility	▪ Data on radionuclide leaching from livestock carcasses is not available. The assessment assumes that radionuclides are leached in proportion to decomposition fluids released over the first two months after death as estimated by Young et al. (2001). This approach does not account for radionuclide-specific partitioning in tissue compartments and the associated effect on mobility.	Moderate	▪ As discussed in Section 3.1, cesium radioisotopes distribute throughout the carcass, while strontium partitions preferentially to skeletal tissue and iodine partitions to extracellular fluid. This leaching is likely to be overestimated for ^{90}Sr.
Fate and Transport Modeling			
Models	▪ The assessment uses utilizes two models previously developed by USEPA: the PRG Calculator and an analysis using the EPACMTP leaching model.	Moderate	▪ The uncertainties associated with the existing models, data, and methods can individually contribute to under-or over-estimation of exposures.

Abbreviations: EPACMTP = EPA Composite Model for Leachate Migration with Transformation Products; PRG = Preliminary Remediation Goals for Radionuclides

Table 32. Simplifying Assumptions—Effects on Exposure Estimates

Key Topic	Simplifying Assumption	Effect	Rationale for Effect
Radiological Emergency Scenario			
Type of Livestock Affected	▪ The assessment scenario includes management of cattle carcass. Livestock species differ somewhat in terms of body composition (e.g., percent fat vs. muscle; feathers vs. fur), which can affect the rate of and amount of leaching.	Moderate Over- or Underestimate	▪ Although cattle are larger than most other livestock species, smaller animals (e.g., poultry) can die in large numbers resulting in a comparable mass of carcasses to manage. Body composition varies among species, but variability is limited by the general similarity in warm-blooded vertebrate bodies.
Effect of the Radiological Emergency on Management Activities	▪ Some radiological emergency scenarios include personal injuries, property damage, or environmental contamination. This assessment assumes that the radiological emergency does not impede, preclude, or otherwise affect any of the carcass management options. In reality, a radiological emergency might hinder access to the site or work in the affected area.	Moderate Underestimate	▪ A disruptive radiological emergency (e.g., nuclear power plant accident) might underestimate exposure if the effects of the emergency interfere with timely and effective carcass management.
Site Setting and Environmental Conditions			
Site Layout	▪ A goal of this assessment is designed to assess exposure for reasonably anticipated exposure pathways from carcass management. Therefore, the conceptual models and site layout were intentionally designed to include all feasible complete exposure pathways. For example, residents are assumed to eat home-grown foods from the radiological emergency site.	High Overestimate	▪ The assessment is likely to overestimate exposure because the scenario assumes a worst-case exposure for each possible pathway, which is unlikely in the event of a radiological emergency.

Carcass Management Options			
Design of On-site Management Units	▪ Basic assumptions about the design of on-site management options (e.g., burial trench dimensions) are based USDA guidance and other relevant sources and an assumed 50 short tons of carcasses. For larger mortalities, the spatial pattern and nature of environmental releases could be different.	Moderate Over- or Underestimates	▪ Assumptions about many aspects of carcass management units could lead to over- or underestimation of exposure.
Composting Duration	▪ The compost is assumed to be finished in 8 months. The duration, along with radionuclide half-lives, affects the amount of radioactivity remaining in the finished compost	Low Over- or Underestimate	▪ The assumed duration is based estimates from the literature. This uncertainty has the greatest effect for radionuclides with short half-lives (e.g., on the order of months or less).
Carcass Handling Before Management	▪ Workers who handle contaminated livestock carcasses are assumed to use recommended personal protective equipment (PPE).	Moderate Underestimate	▪ Exposure to workers is underestimated if protective equipment is inadequate.
Temporary Storage	▪ In an actual emergency, circumstances might require temporary storage (e.g., piling) of carcasses until management options are readied. ▪ This assessment does not include temporary carcass storage.	Moderate Under- or Overestimates	▪ Exposures might be underestimated if carcass management is delayed, especially long enough for the carcasses to begin to release liquid from decomposition.

Carcass Transportation	▪ Based on a semi-quantitative assessment (USEPA 2017a), releases associated with carcass transportation are assumed to be insignificant and are not included in this assessment.	Low Underestimate	▪ If carcass transportation results in a significant exposure, the assessment underestimates overall exposure. ▪ Transportation-related exposures could occur with any of the management options but have a slightly greater likelihood with off-site management options.
Compost Application	▪ The assessment assumes that finished compost is tilled into soil on site at an application rate based on an assumed nutrient content.	Low Over- or Underestimate	▪ Radionuclide activity concentrations may be over- or underestimated depending on the actual application rate (e.g., kg compost per acre) and tillage depth.
	▪ The assessment assumes that finished compost is tilled into soil on-site and the compost application site is used to for home grown food production.	High Overestimate	▪ Depending on the radioactivity of the finished compost, it might be unsuitable for food production.
Exposure Receptors and Estimation			
Homegrown farm Products	▪ Farm residents are assumed to consume only home-grown fruits, vegetables, and livestock products.	Moderate Overestimate	▪ Exposure from home-grown foods is estimated using EPA methods and assumptions; however, most farm residents also rely on store-bought foods.

Abbreviations: PPE = personal protective equipment.

5. Quality Assurance

This report used scientific information extracted from sources of secondary data including journal articles, publications in the open literature, and government reports both published and non-published, including distribution limited reports. Data and information were gathered from published reports to identify the significant pathways by which pathogens might reach individuals and estimate how many microorganisms an individual is likely to be exposed to through each pathway. A targeted literature review was performed to identify the most highly relevant data to inform an exposure assessment. Scientific and technical information from various sources were evaluated using the assessment factors below:

- Focus: The work not only addresses the area of inquiry under consideration, but also contributes to its understanding. The source is germane to the issue at hand.
- Verity: The data are consistent with accepted knowledge in the field, or if not, the new or varying data are explained within the work. The data fit within the context of the literature and are intellectually honest and authentic.
- Integrity: The data are structurally sound and present a cohesive story. The design or research rationale is logical and appropriate.
- Rigor: The work is important, meaningful, and non-trivial relative to the field. It exhibits sufficient depth of intellect rather than superficial or simplistic reasoning.
- Soundness: The scientific and technical procedures, measures, methods, or models employed to generate the information are reasonable for, and consistent with, the intended application.
- Applicability and Utility: The information is relevant for the intended use.
- Clarity and Completeness: The clarity and completeness with which the data, assumptions, methods, QA, and analyses employed to generate the information are documented.
- Uncertainty and Variability: The variability and uncertainty (quantitative and qualitative) related to results, procedures, measures, methods, or models are evaluated and characterized.

6. Literature Cited

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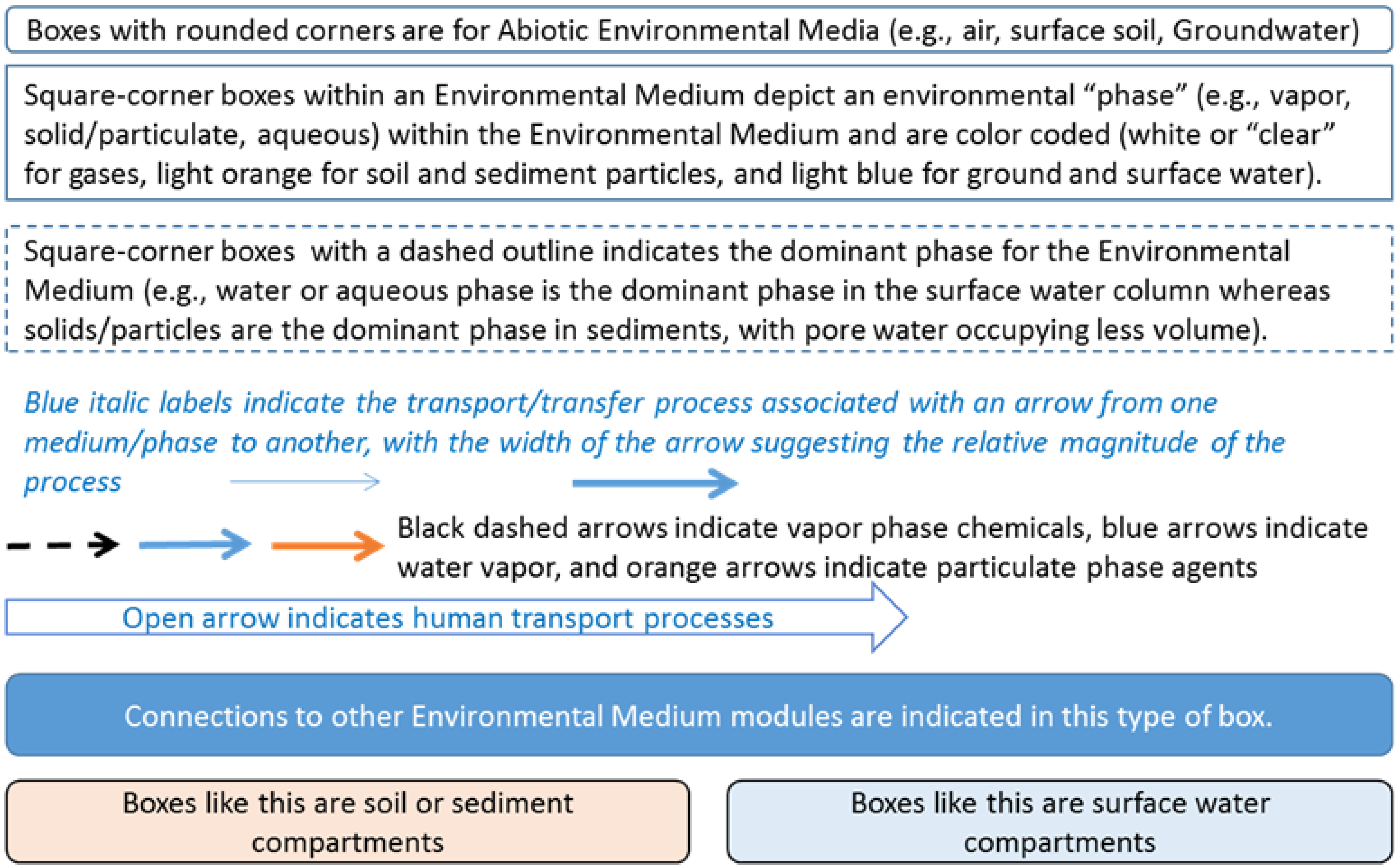
Appendix A: Conceptual Models

Conceptual Models Outline

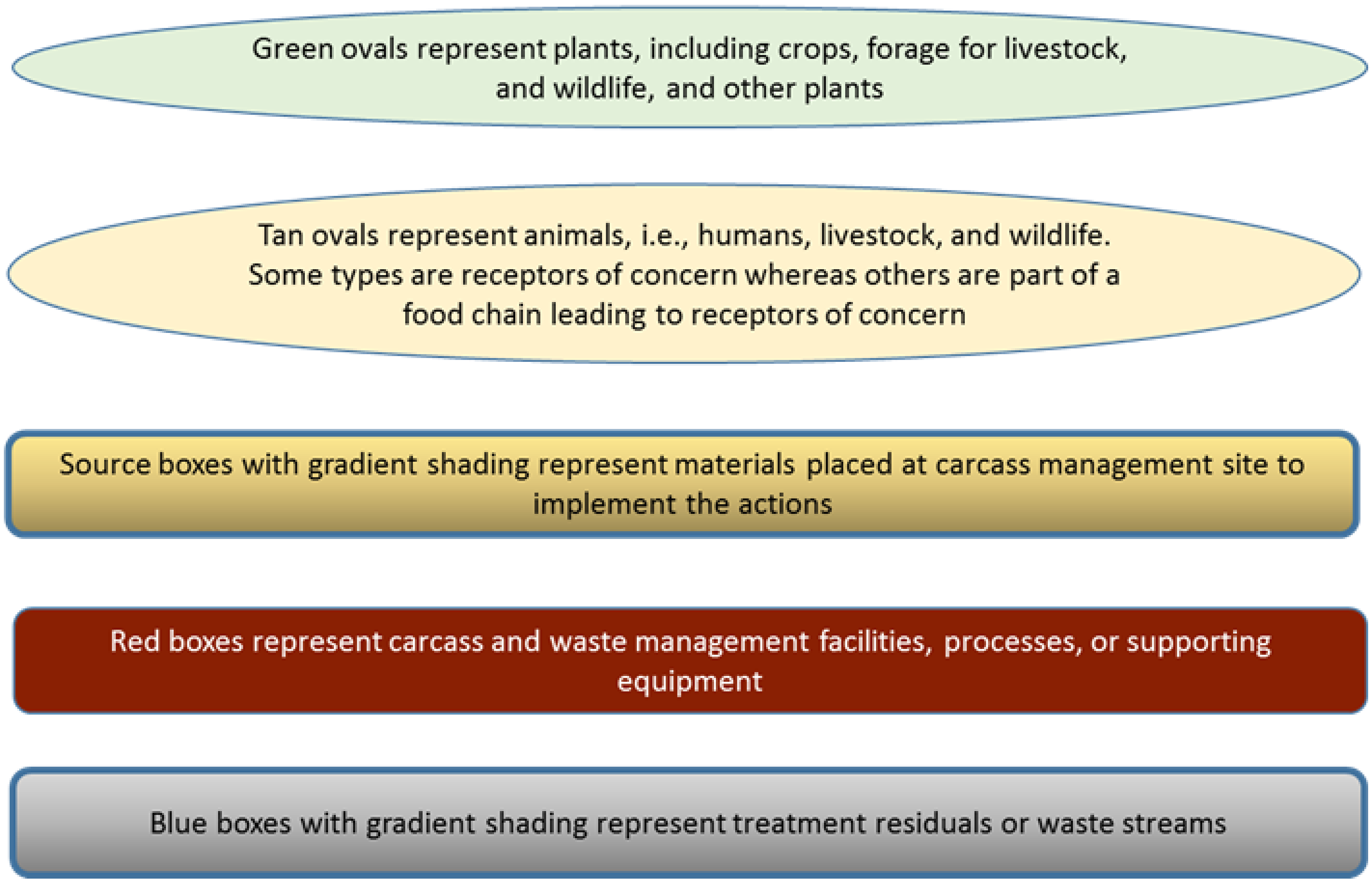
This section provides various conceptual models for each of the management options and related activities

Following sub-sections in Appendix A provide the development and clarifications of conceptual models for livestock carcass management options:

A.1. Legend to Module Diagrams



A.1. Legend to Module Diagrams (Continued)



A.1. Legend to Module Diagrams (Continued)

Abbreviations Used in the Figures

CAA	Clean Air Act
CWA	Clean Water Act
MBM	meat and bone meal
NPDES	National Pollutant Discharge Elimination System
PM2.5	atmospheric particulate matter that have a diameter of less than 2.5 micrometers
PM10	atmospheric particulate matter that have a diameter of less than 10 micrometers
RCRA	Resource Conservation and Recovery Act

A.2. Conceptual Model Overviews

Livestock Carcass Management Option	Figure
On-site Open Burning (pyre)	A.1
On-site Air-curtain Burning	A.2
Off-site Fixed-facility Incineration	A.3
On-site Unlined Burial	A.4
On-site Composting	A.5
Off-site Lined Landfill	A.6
Rendering	A.7
Temporary Carcass Storage	A.8
Carcass Handling	A.9
Carcass Transportation	A.10

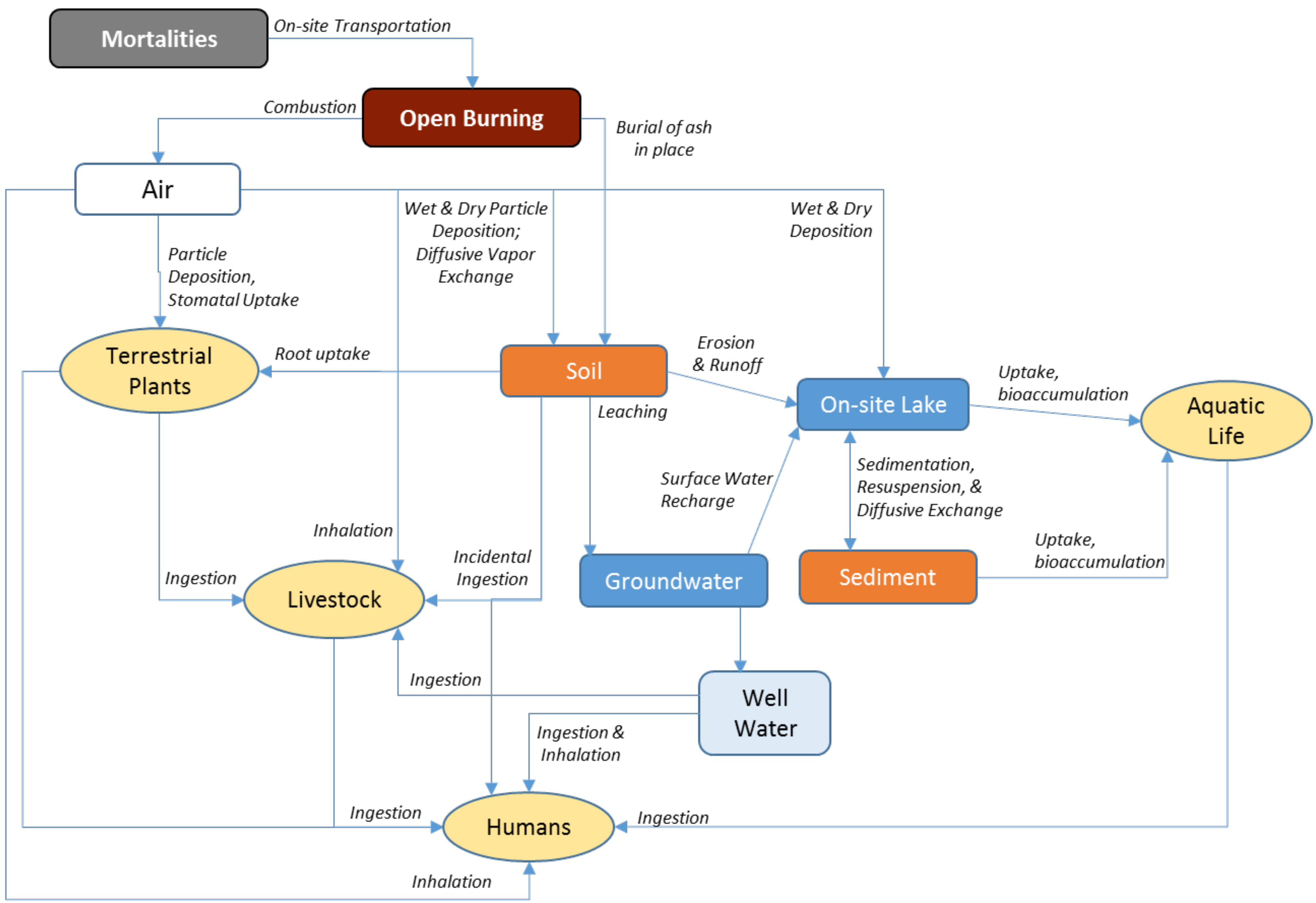


Figure A.1. On-site open burning.

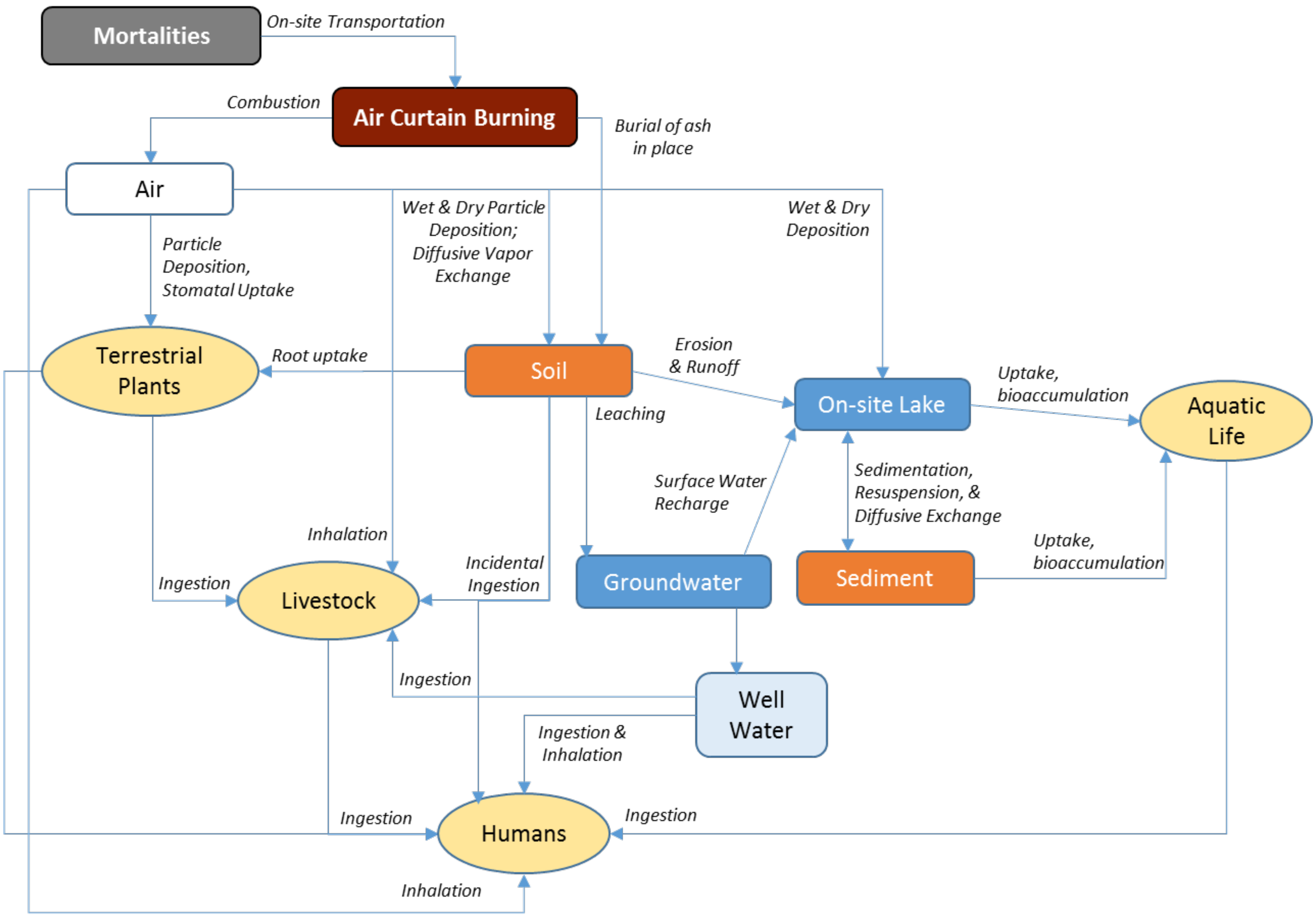


Figure A.2. On-site air-curtain burning.

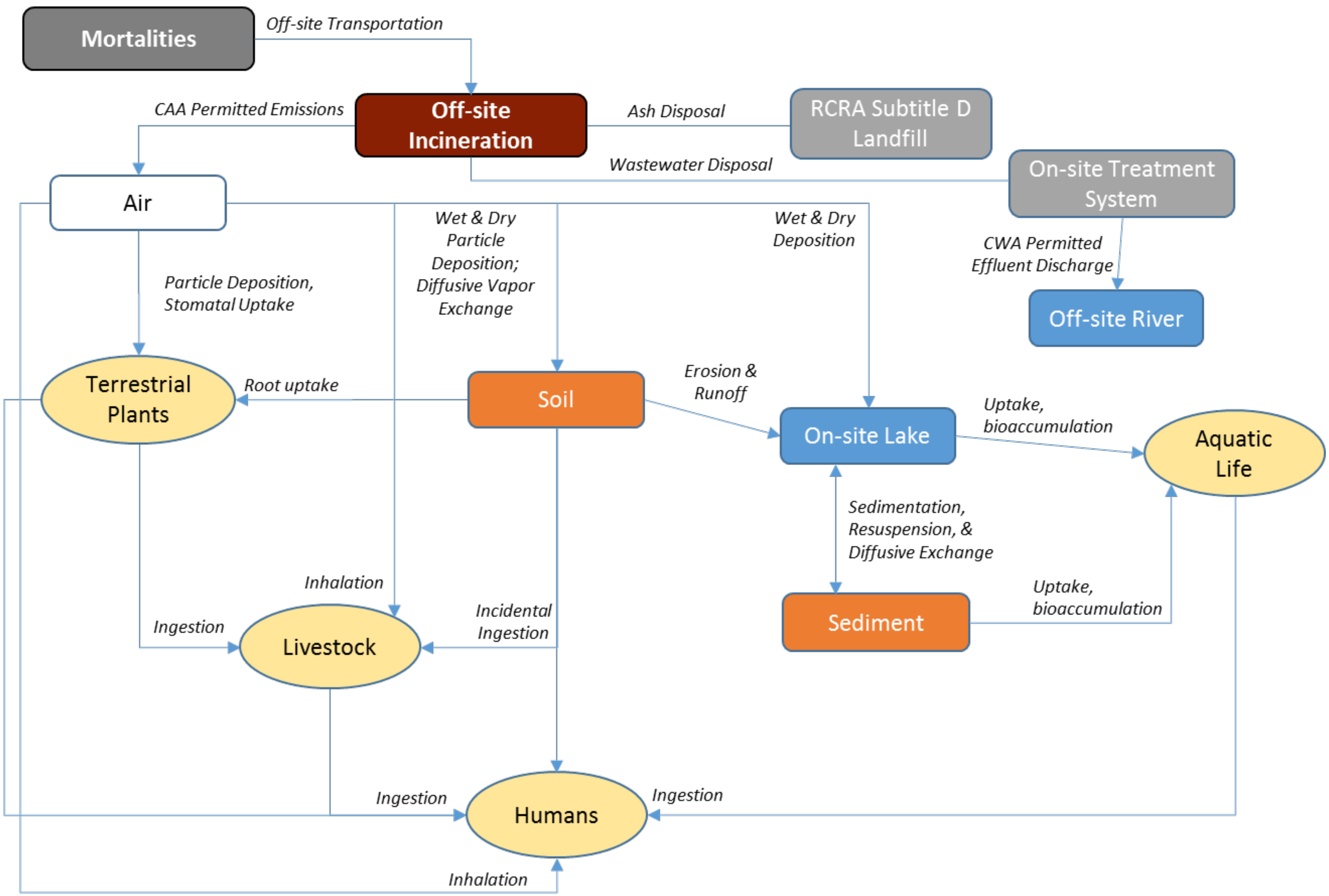


Figure A.3. Off-site incineration.

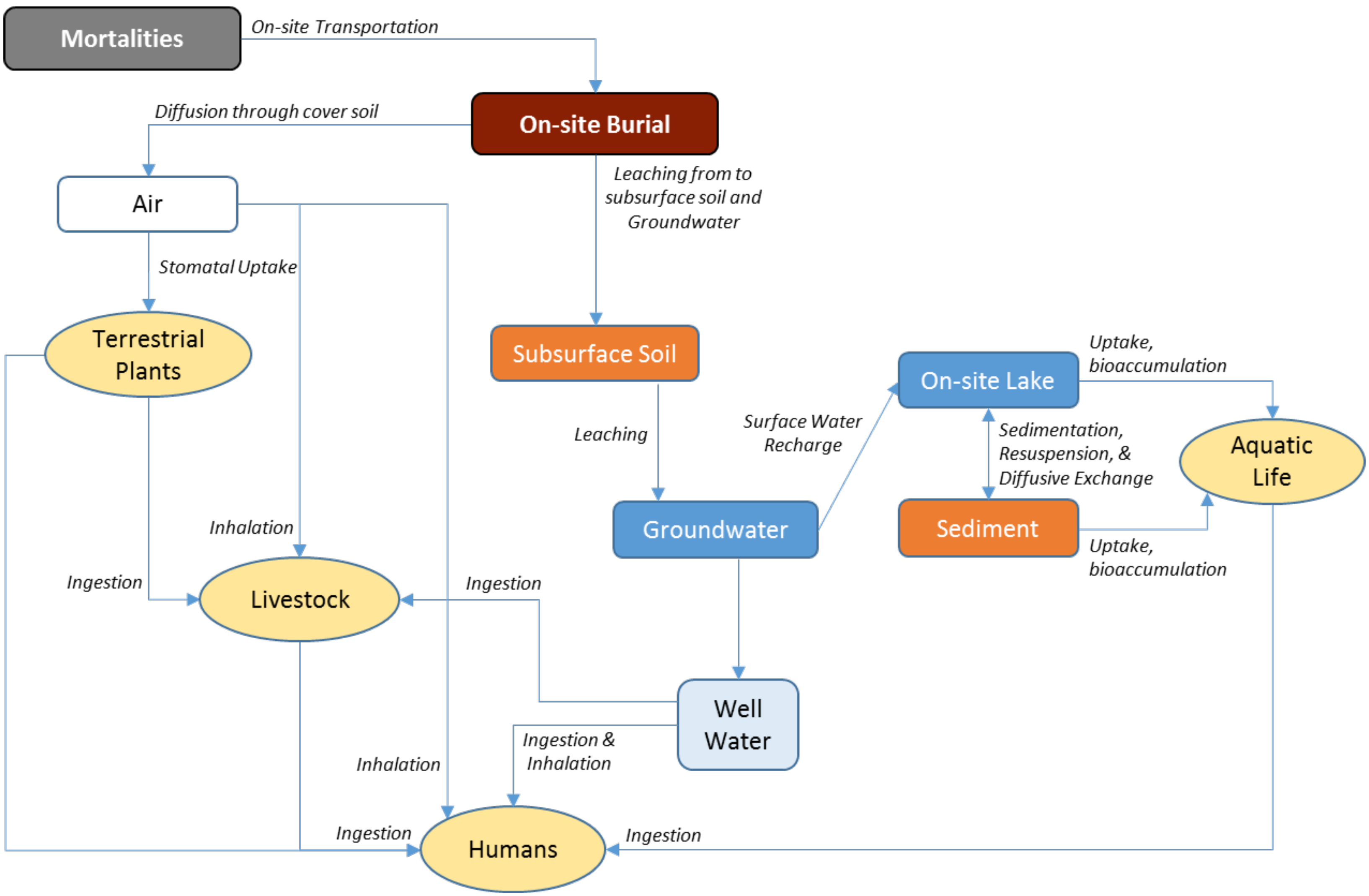


Figure A.4. On-site unlined burial.

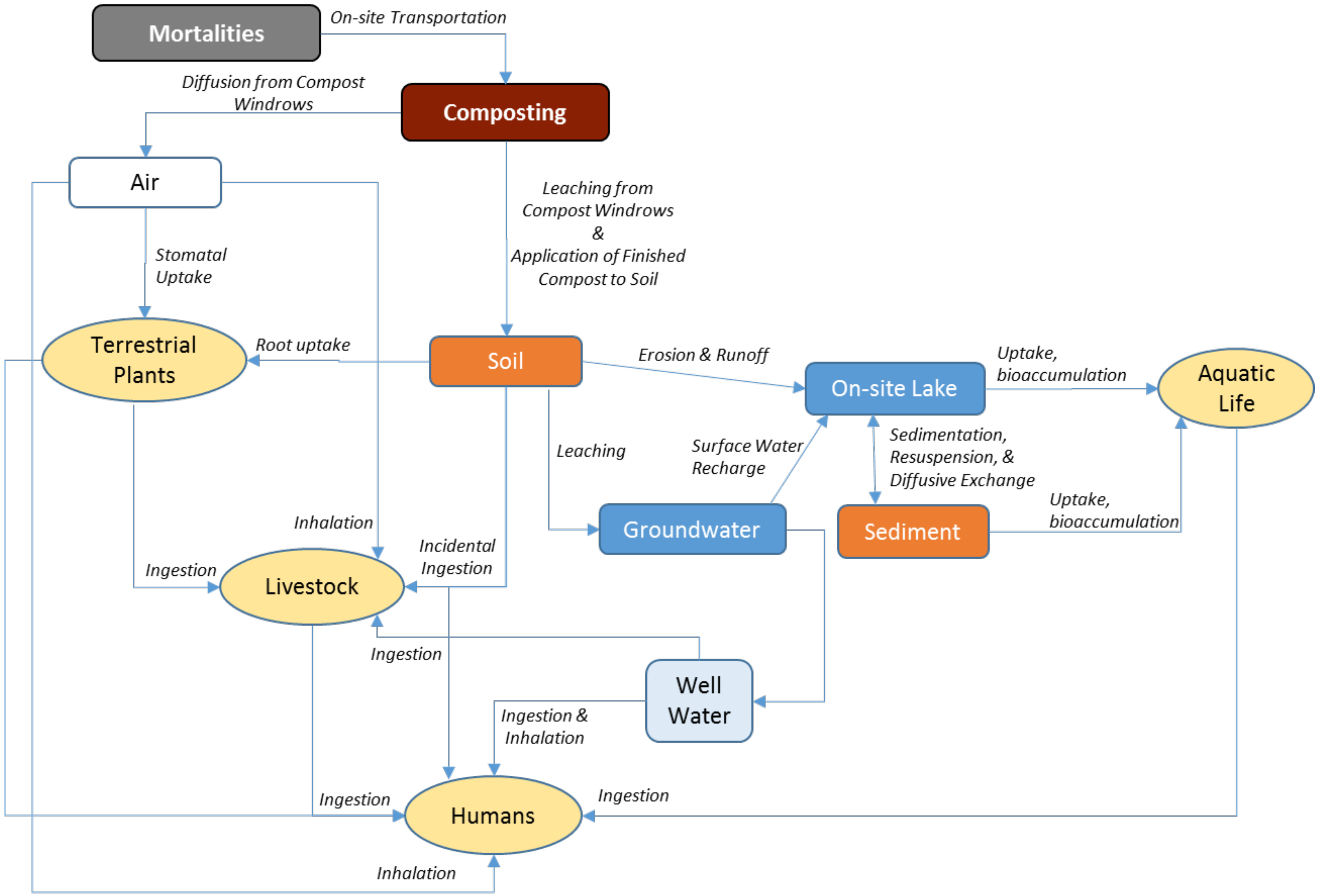


Figure A.5. On-site composting.

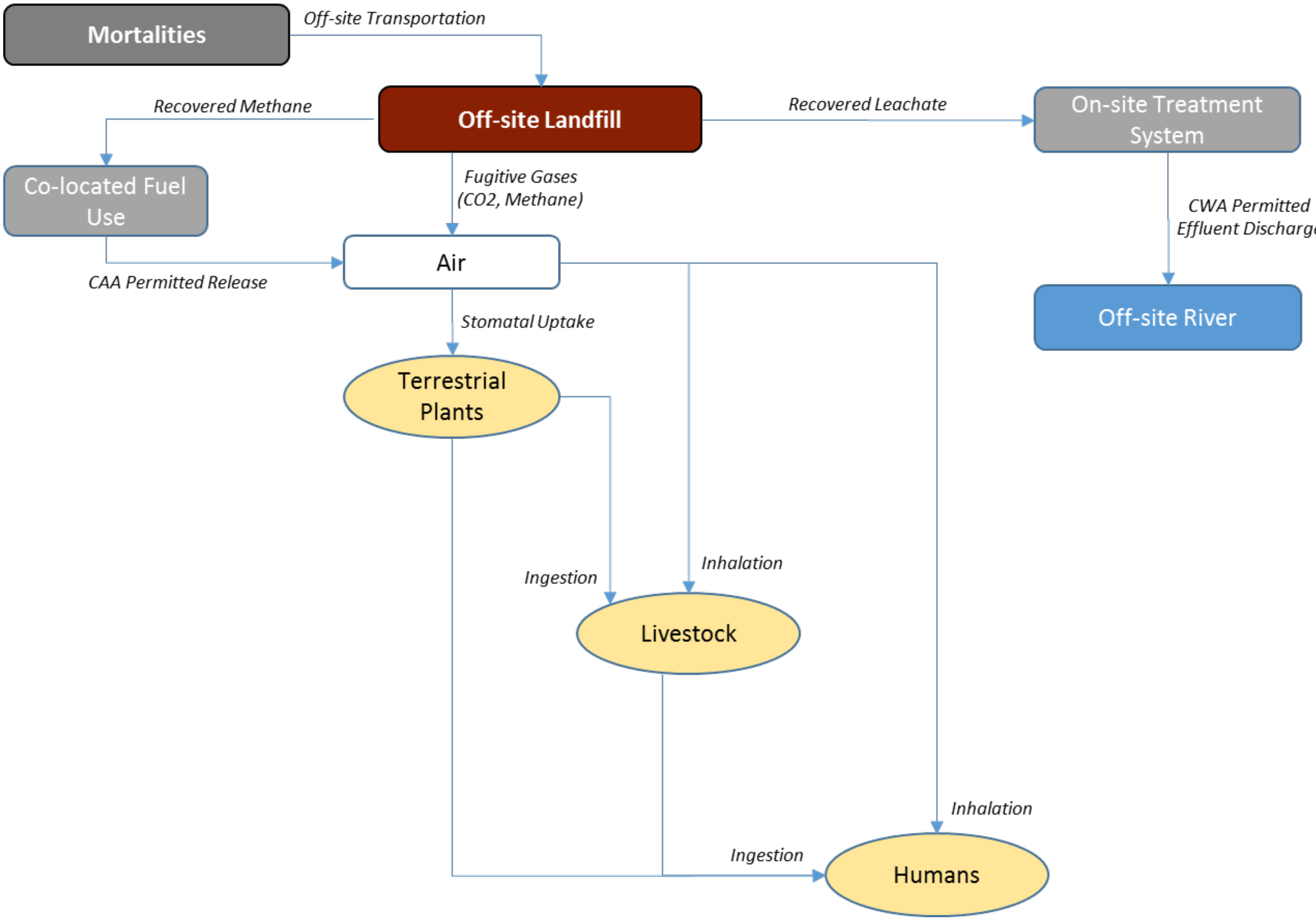


Figure A.6. Off-site landfilling.

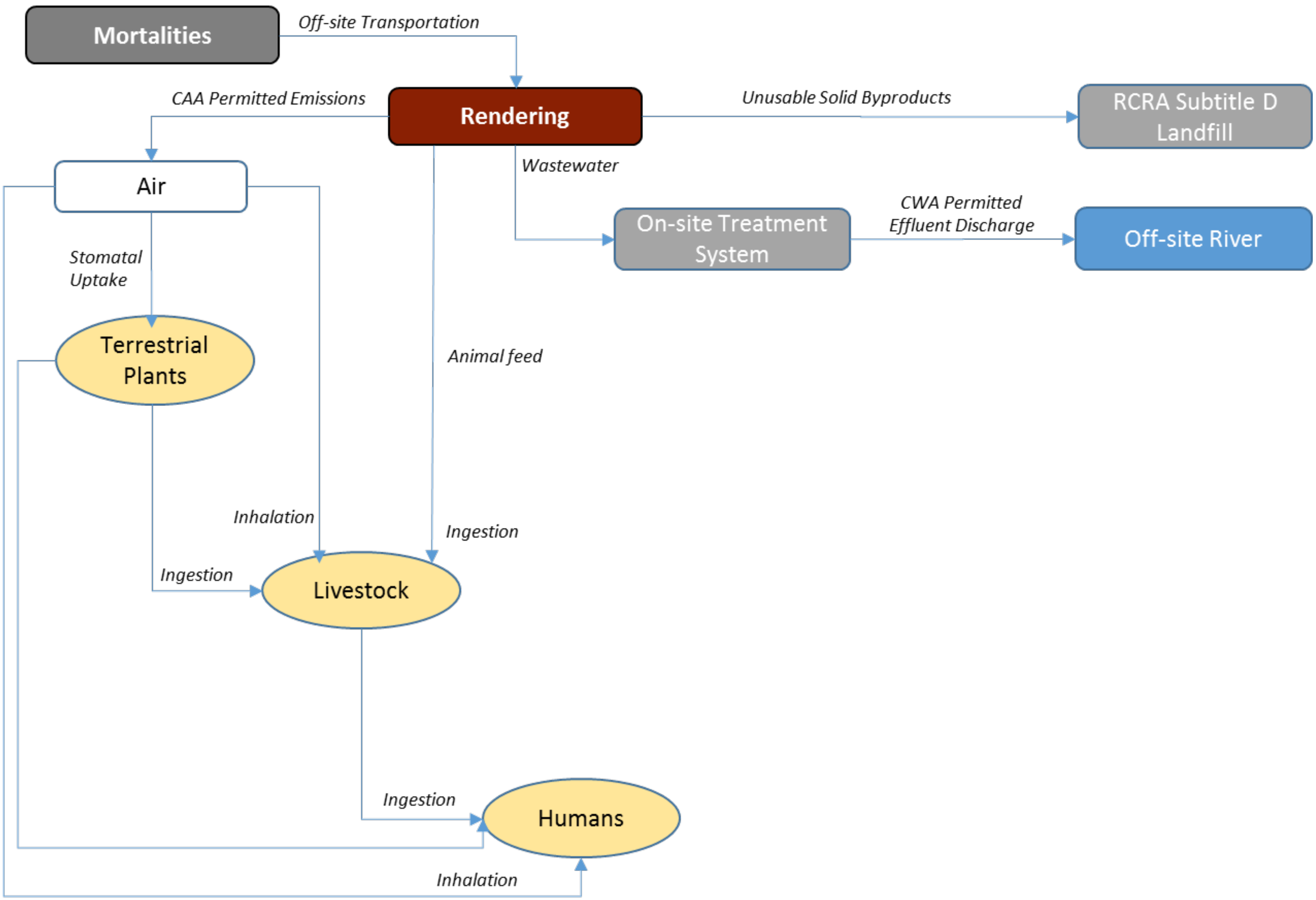


Figure A.7. Rendering.

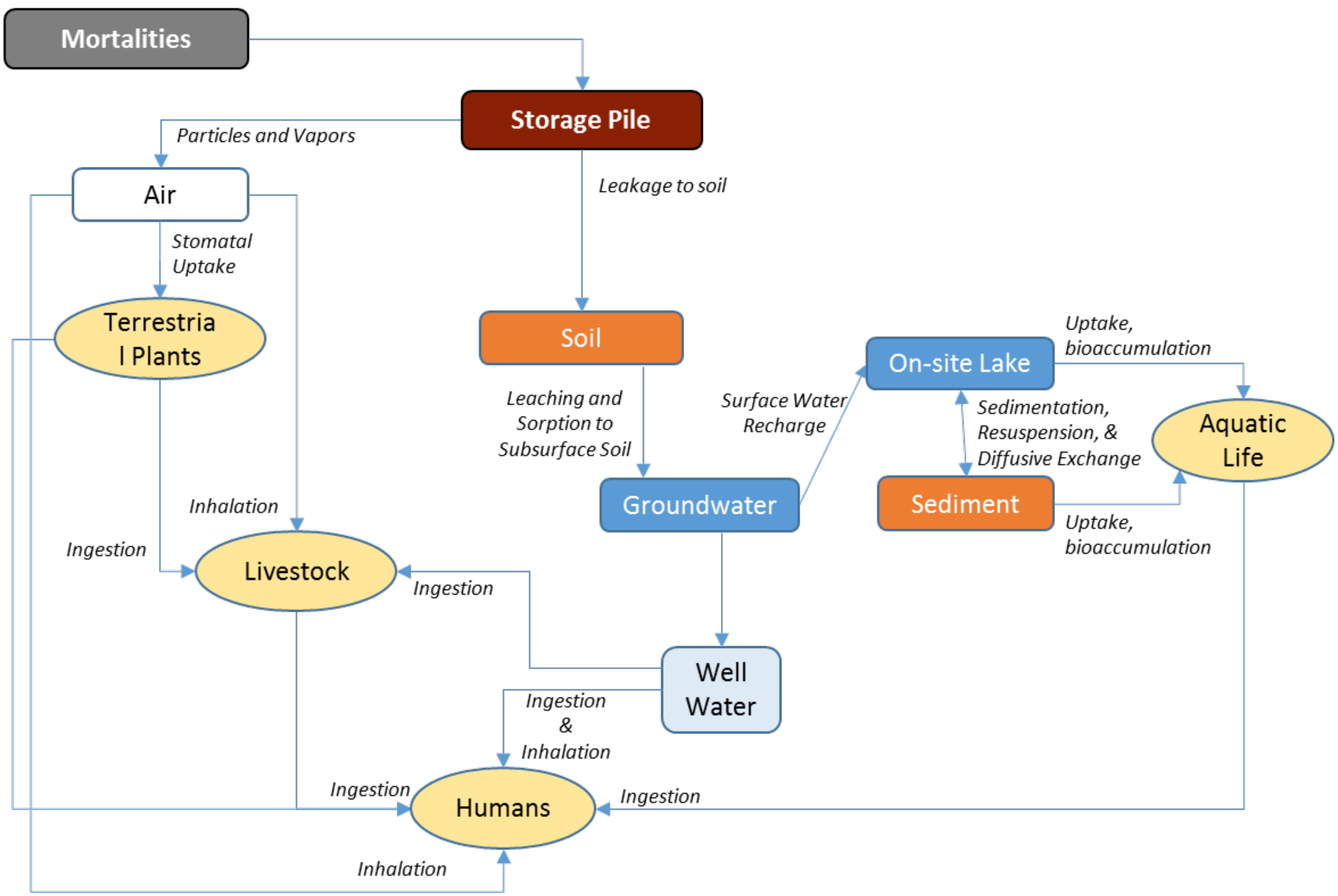


Figure A.8. Temporary carcass storage pile.

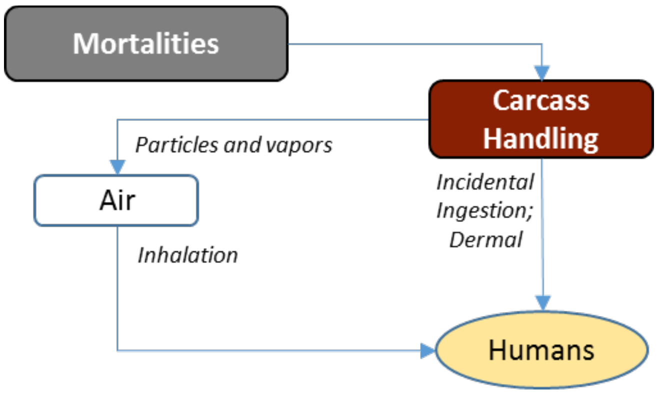


Figure A.9. Carcass handling.

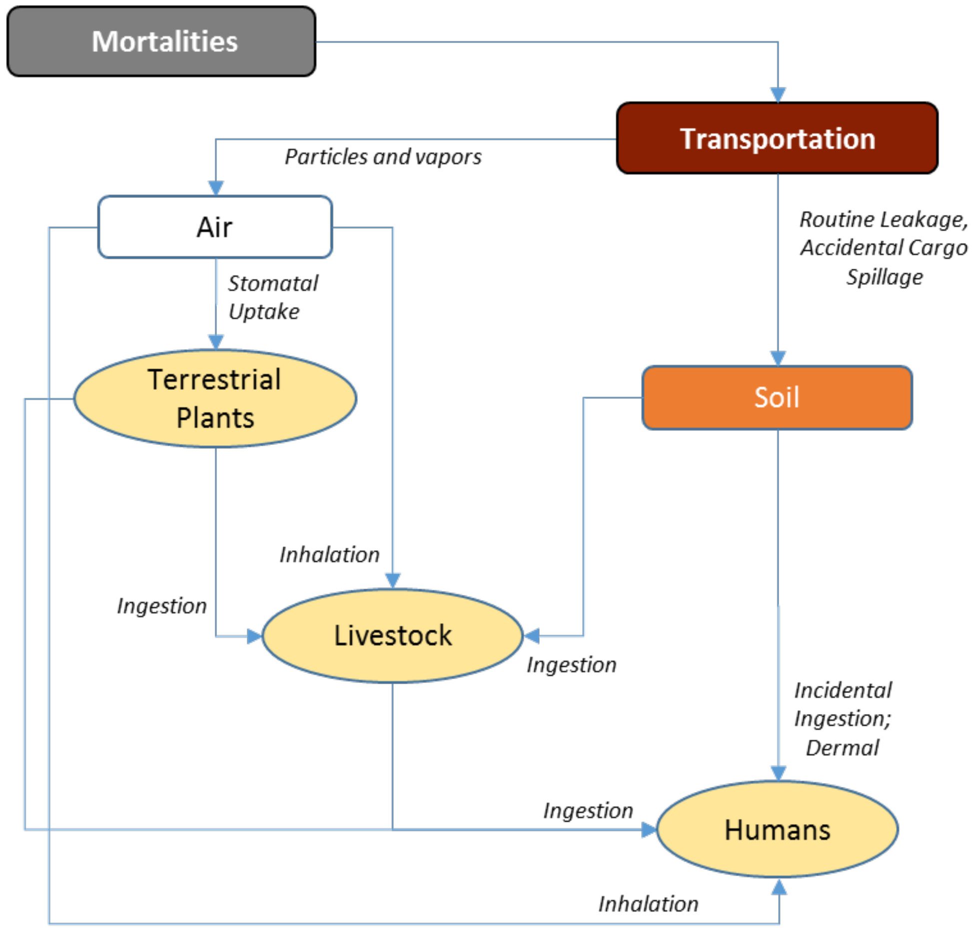


Figure A.10. Carcass transportation.

A.3. Carcass Management Source Modules

Livestock Carcass Management Option	Figure
On-site Open Burning (pyre)	A.11
On-site Air-curtain Burning	A.12
Off-site Fixed-facility Incineration	A.13
On-site Unlined Burial	A.14
On-site Composting	A.15
Off-site Lined Landfill	A.16
Rendering	A.17

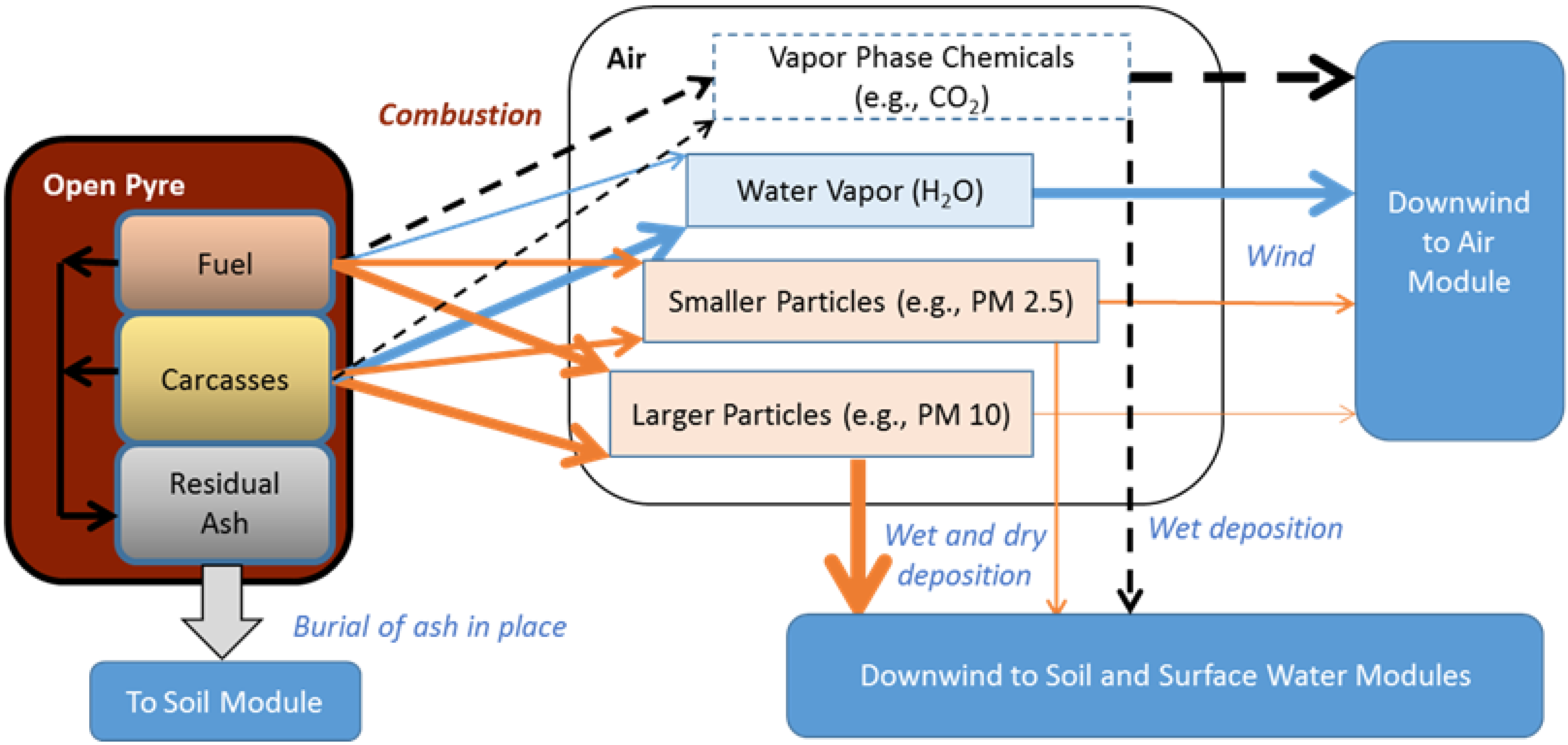


Figure A.11. Combustion-based management: On-site open burning module.

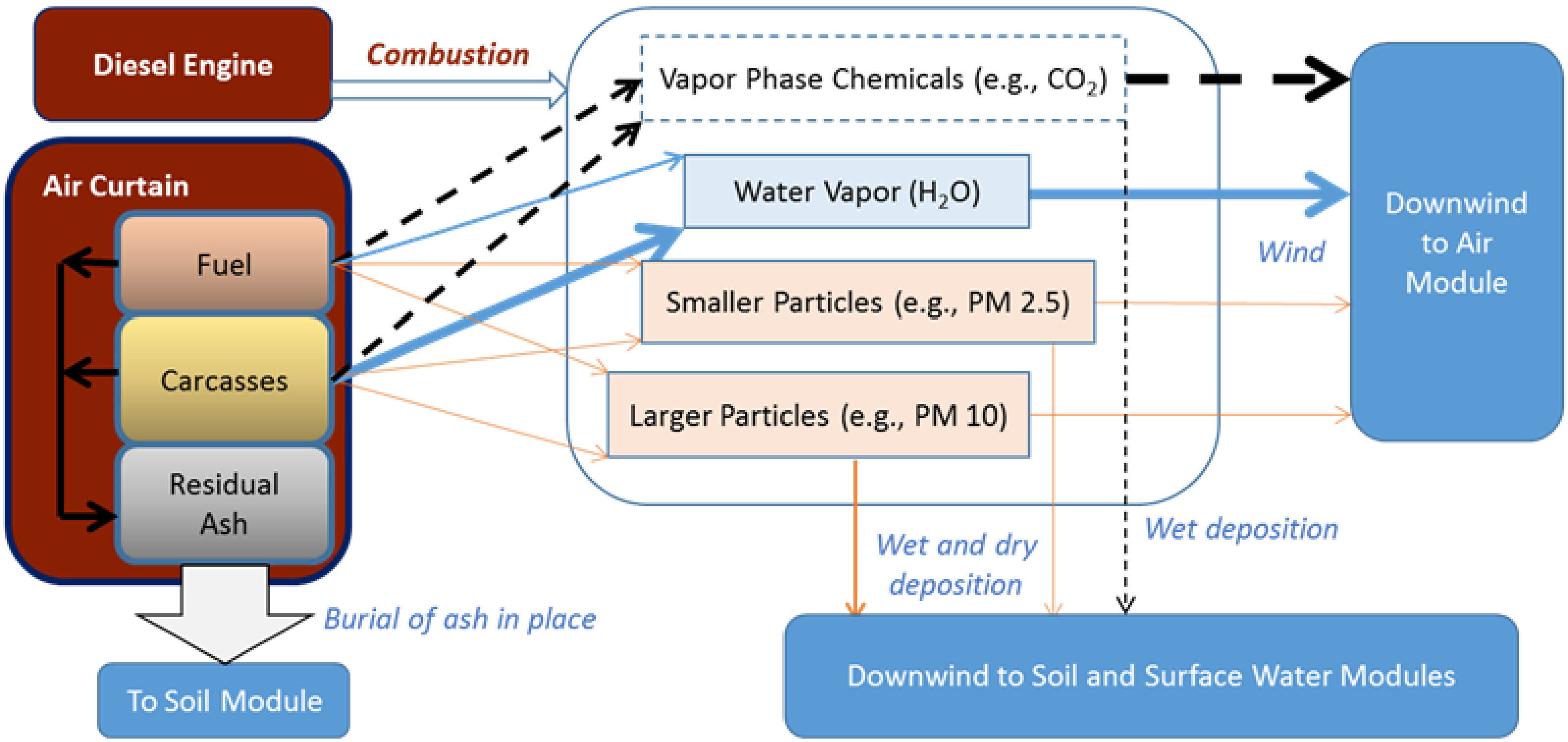


Figure A.12. Combustion-based management: Air-curtain burning module.

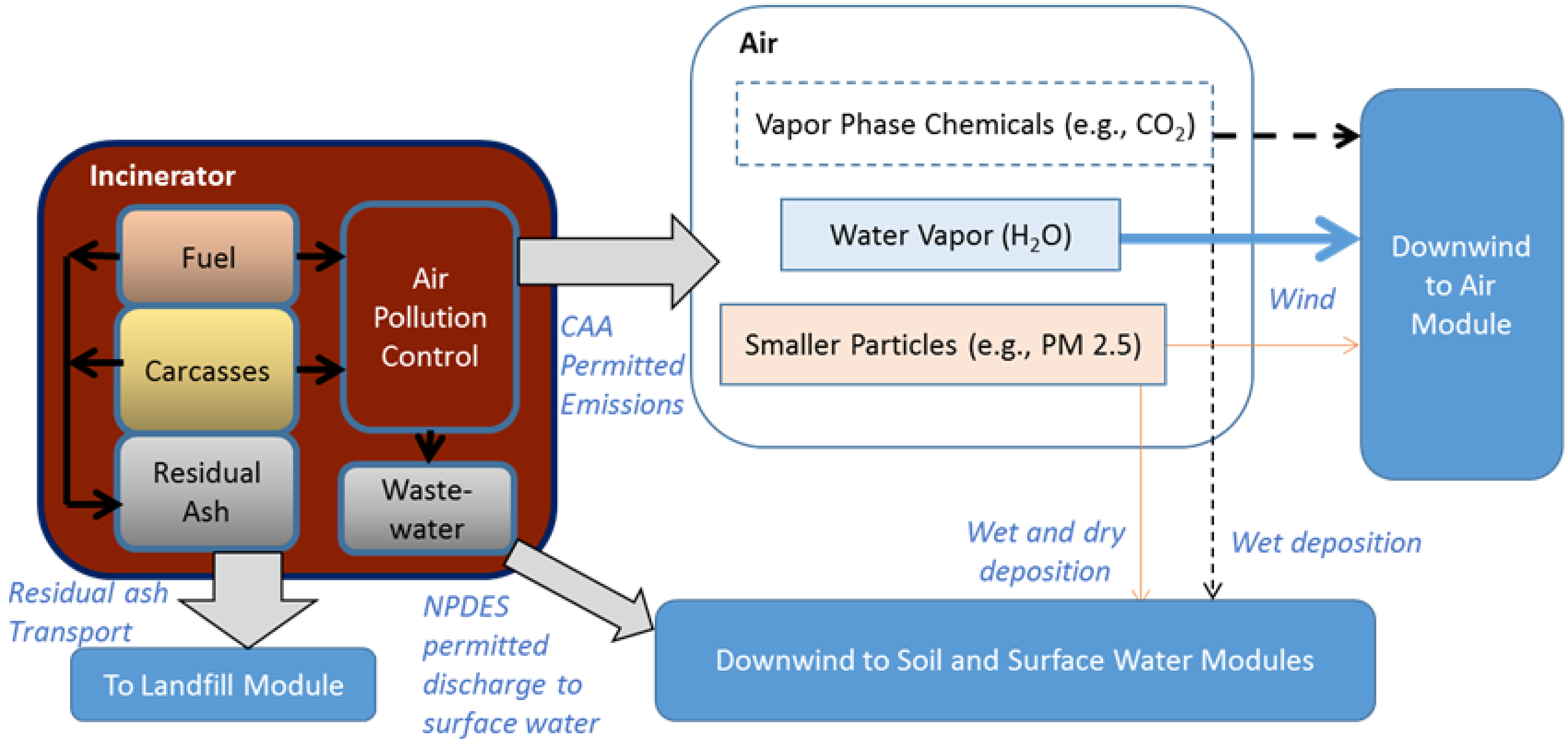


Figure A.13. Combustion-based management: Fixed-facility incineration module.

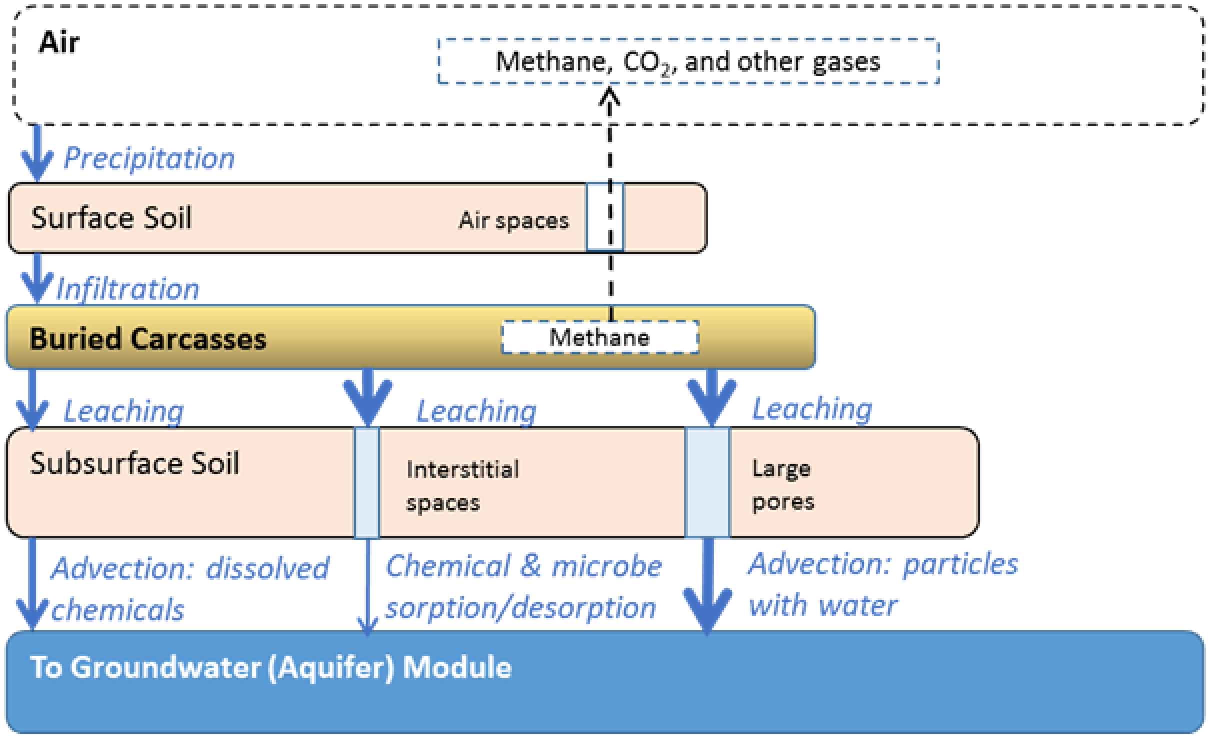


Figure A.14. Land-based management: On-site burial module.

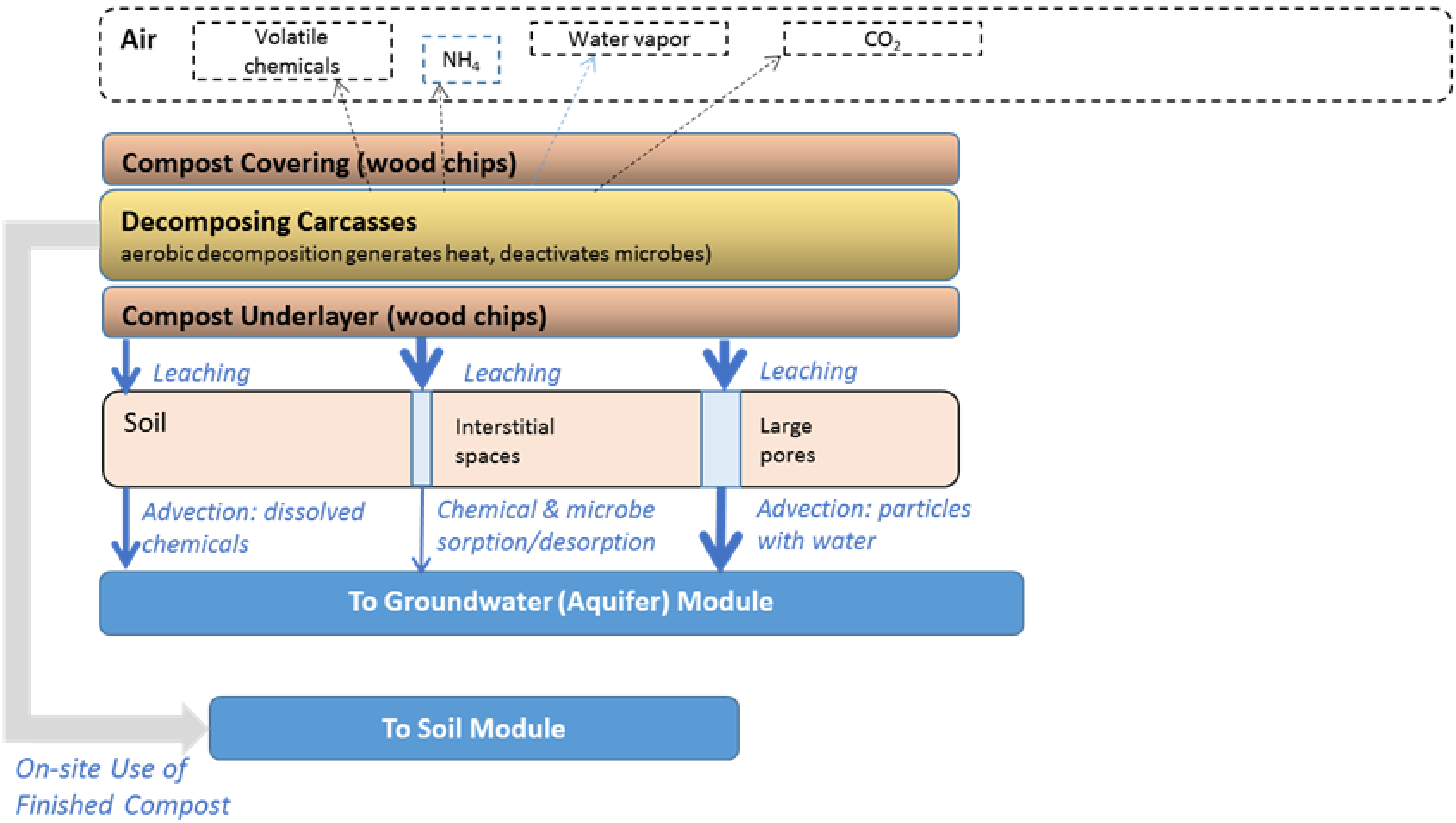


Figure A.15. Land-based management: Composting module.

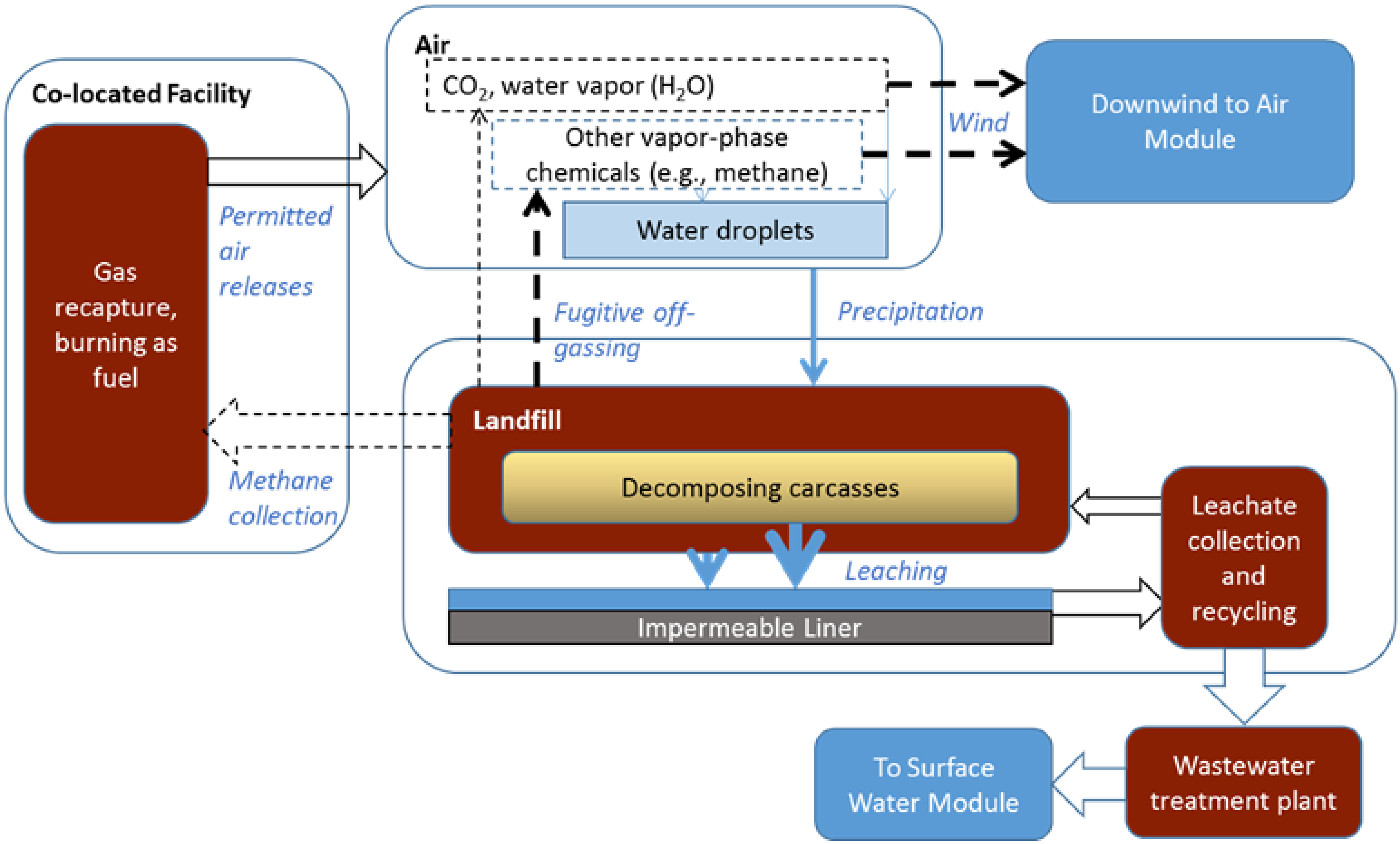
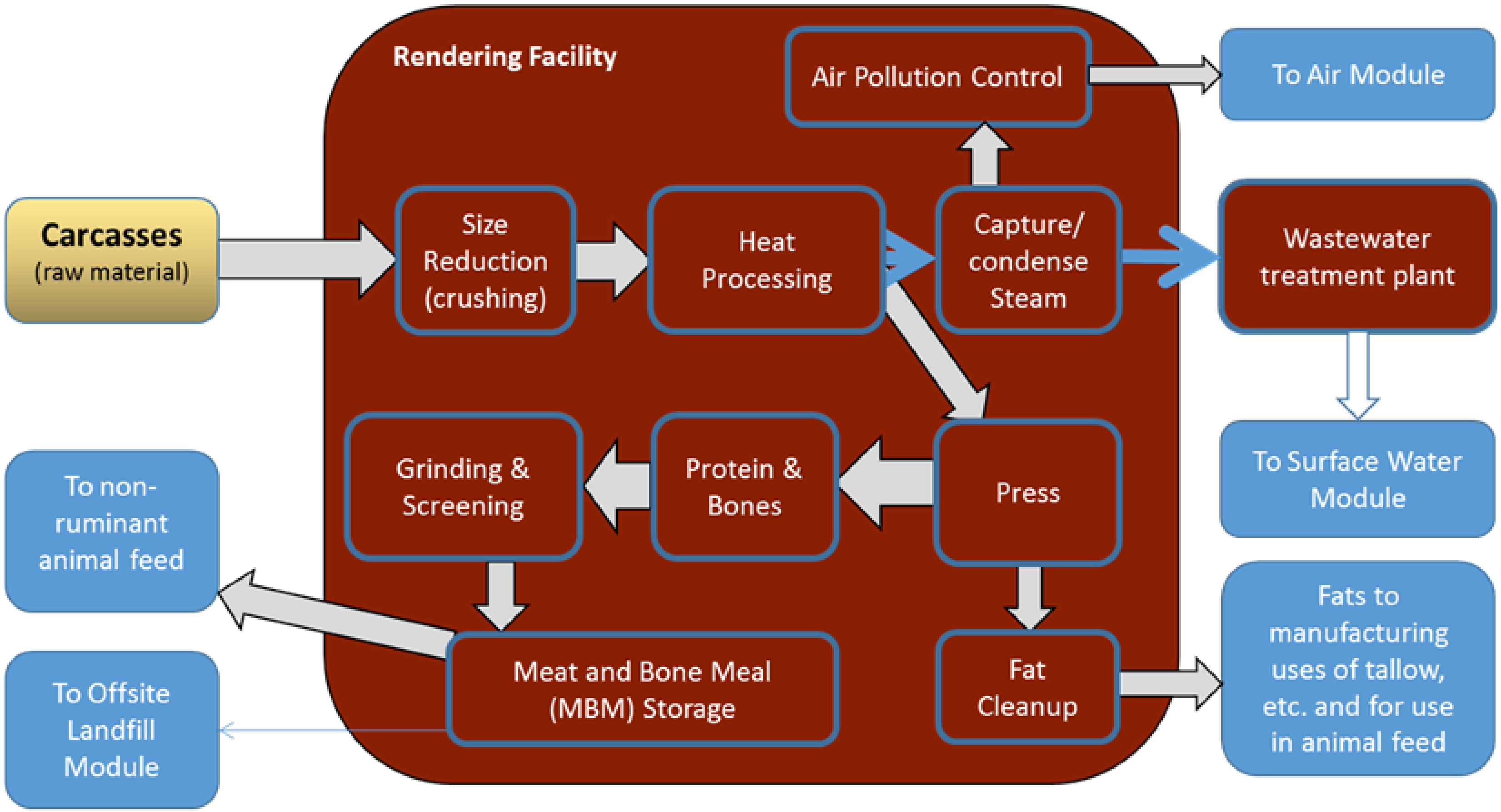


Figure A.16. Land-based management: Off-site landfill module.



[(a)] Adapted from Meeker & Hamilton 2006 and from Bisplinghoff 2006

Figure A.17. Rendering module.

A.3.1. Abiotic Compartment Modules

Livestock Carcass Management Option	Figure
Air	A.18
Soil	A.19
Surface Water and Sediment	A.20
Groundwater	A.21

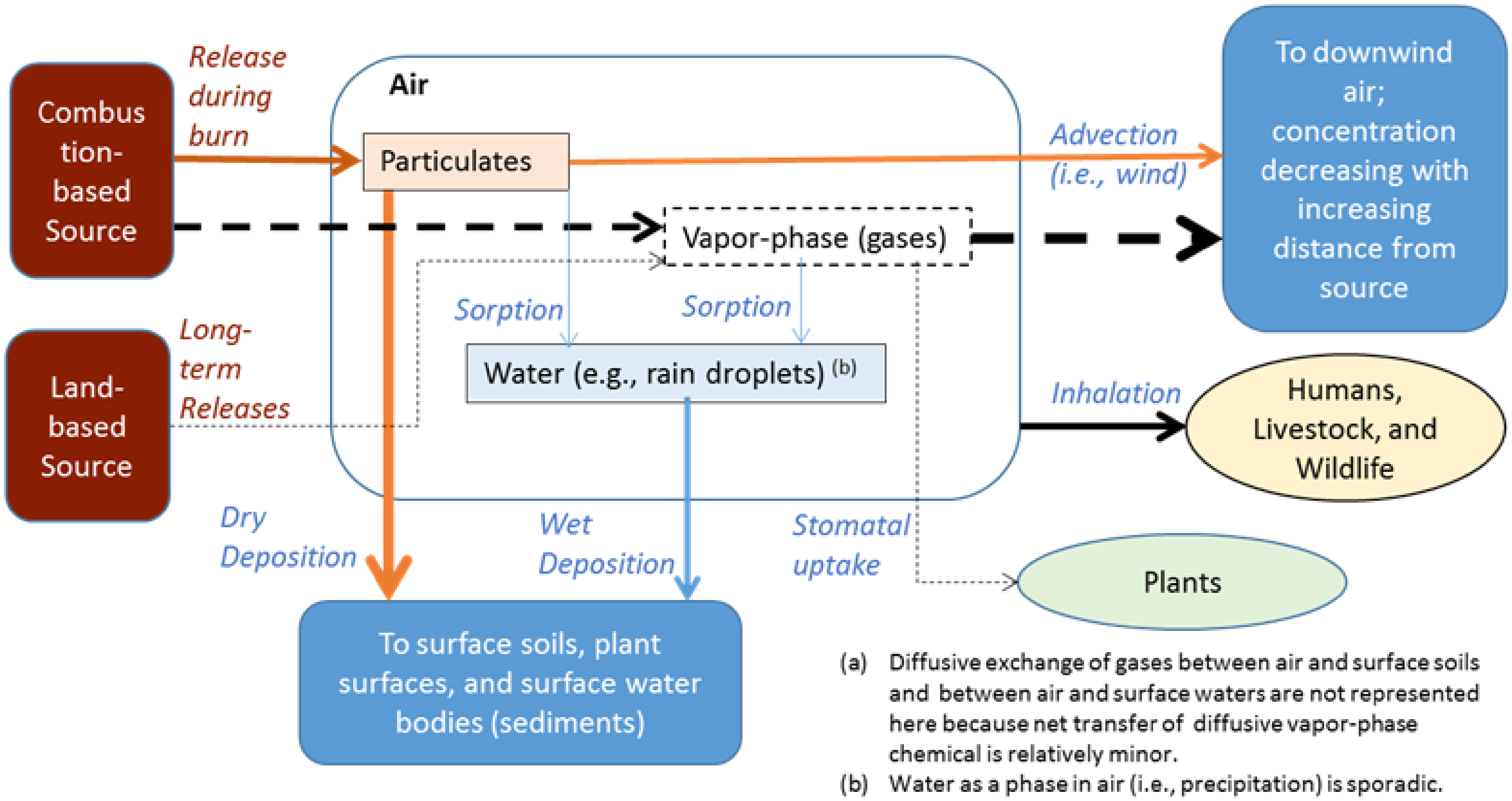
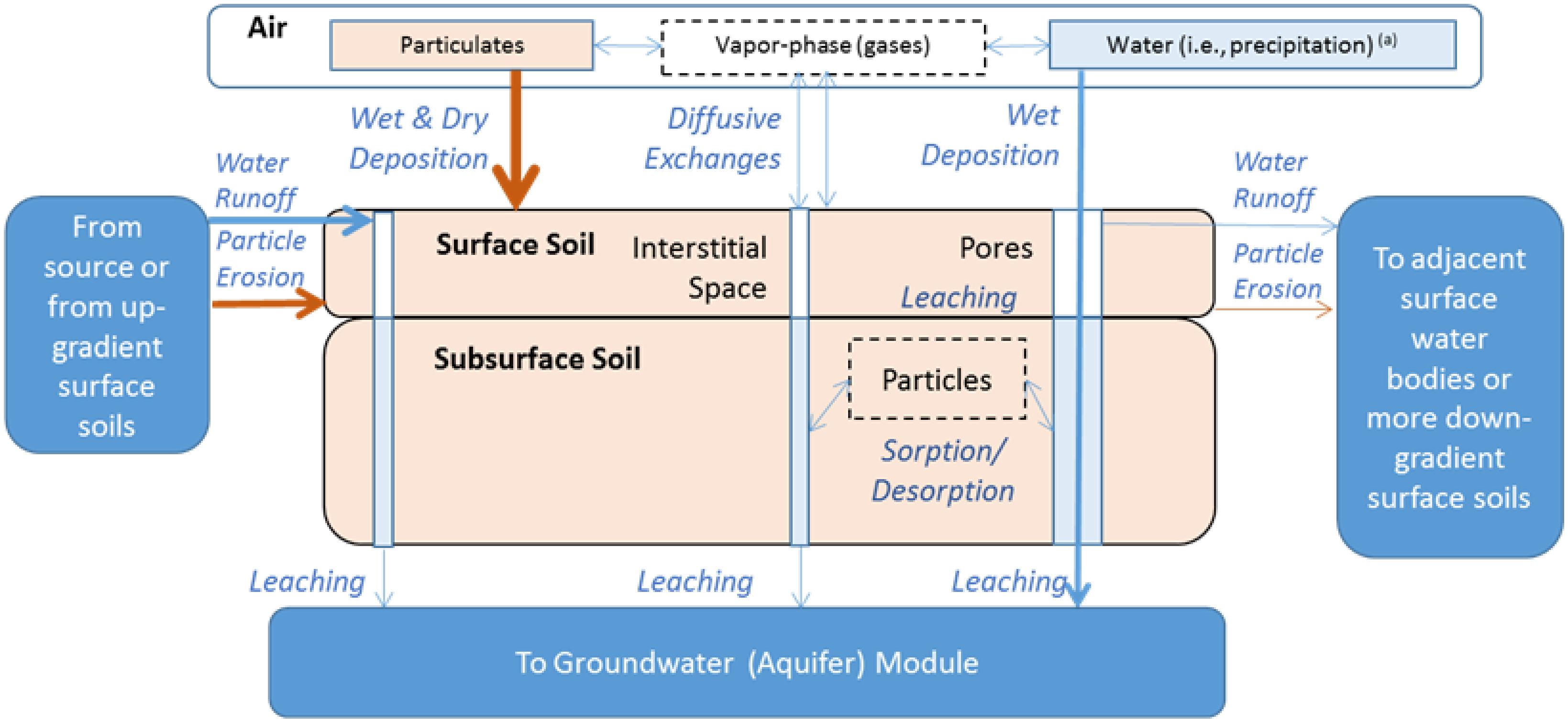
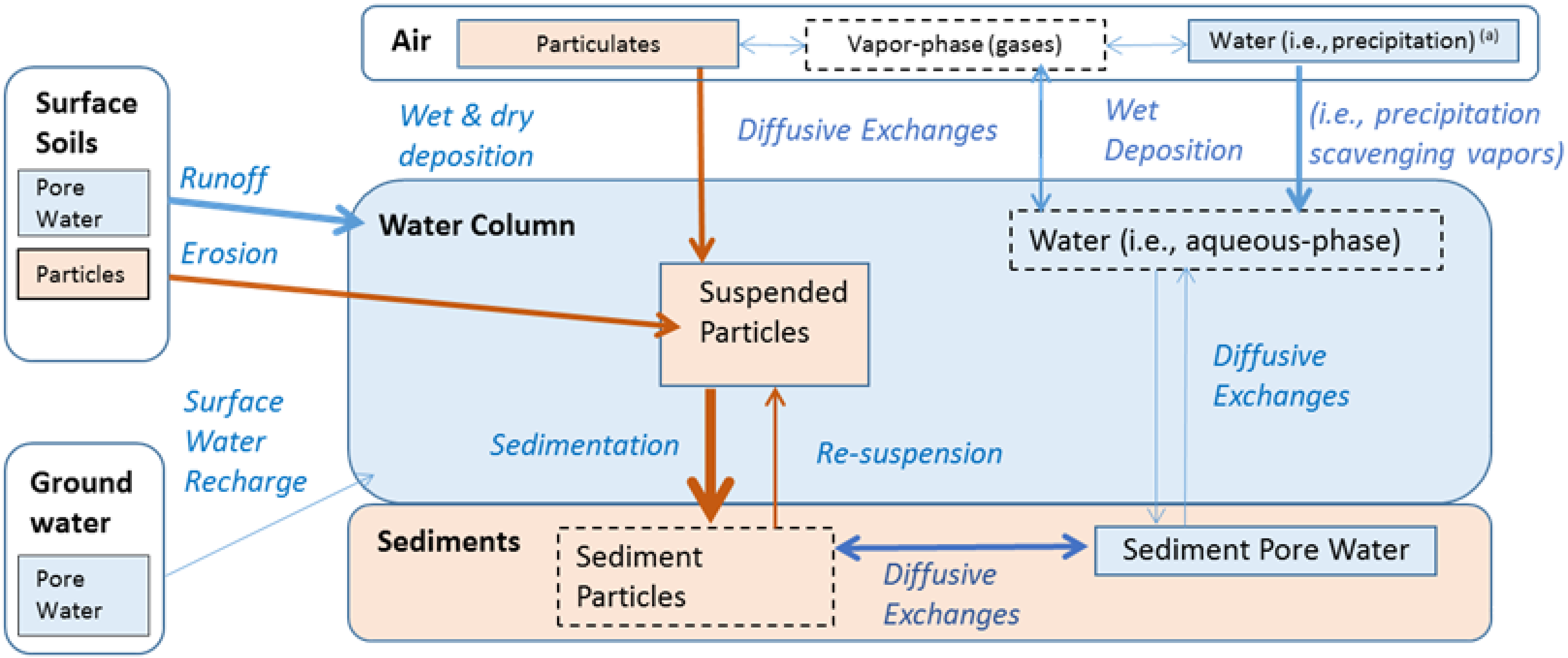


Figure A.18. Air module[a].



(a) Precipitation is sporadic and can take different forms with different vapor (and particulate) scavenging efficiencies

Figure A.19. Soil module[a].



(a) Precipitation is sporadic and can take different forms with different vapor (and particulate) scavenging efficiencies

Figure A.20. Surface water module[a].

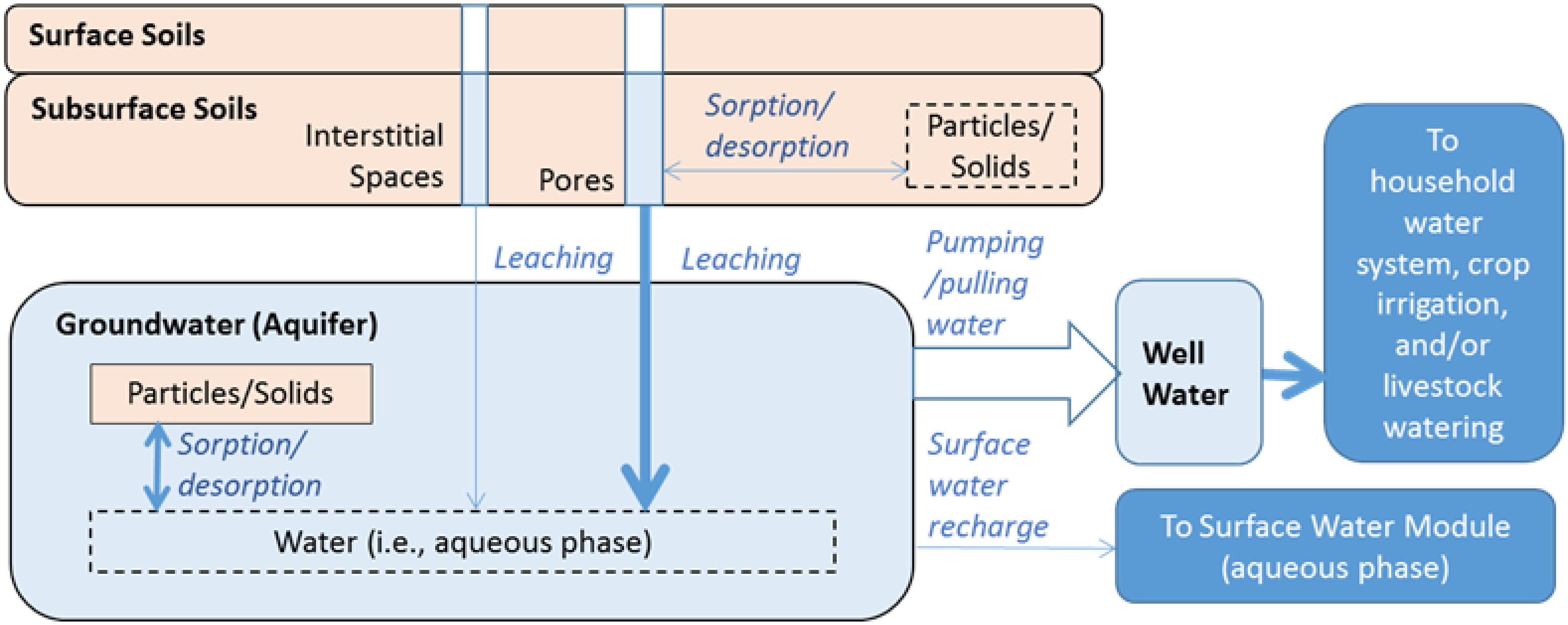


Figure A.21. Groundwater (aquifer) module.

A.3.2. Biotic Compartment Modules

Livestock Carcass Management Option	Figure
Aquatic Ecosystem	A.22
Terrestrial Plants	A.23
Livestock	A.24
Terrestrial Wildlife	A.24
Human Receptors	A.26

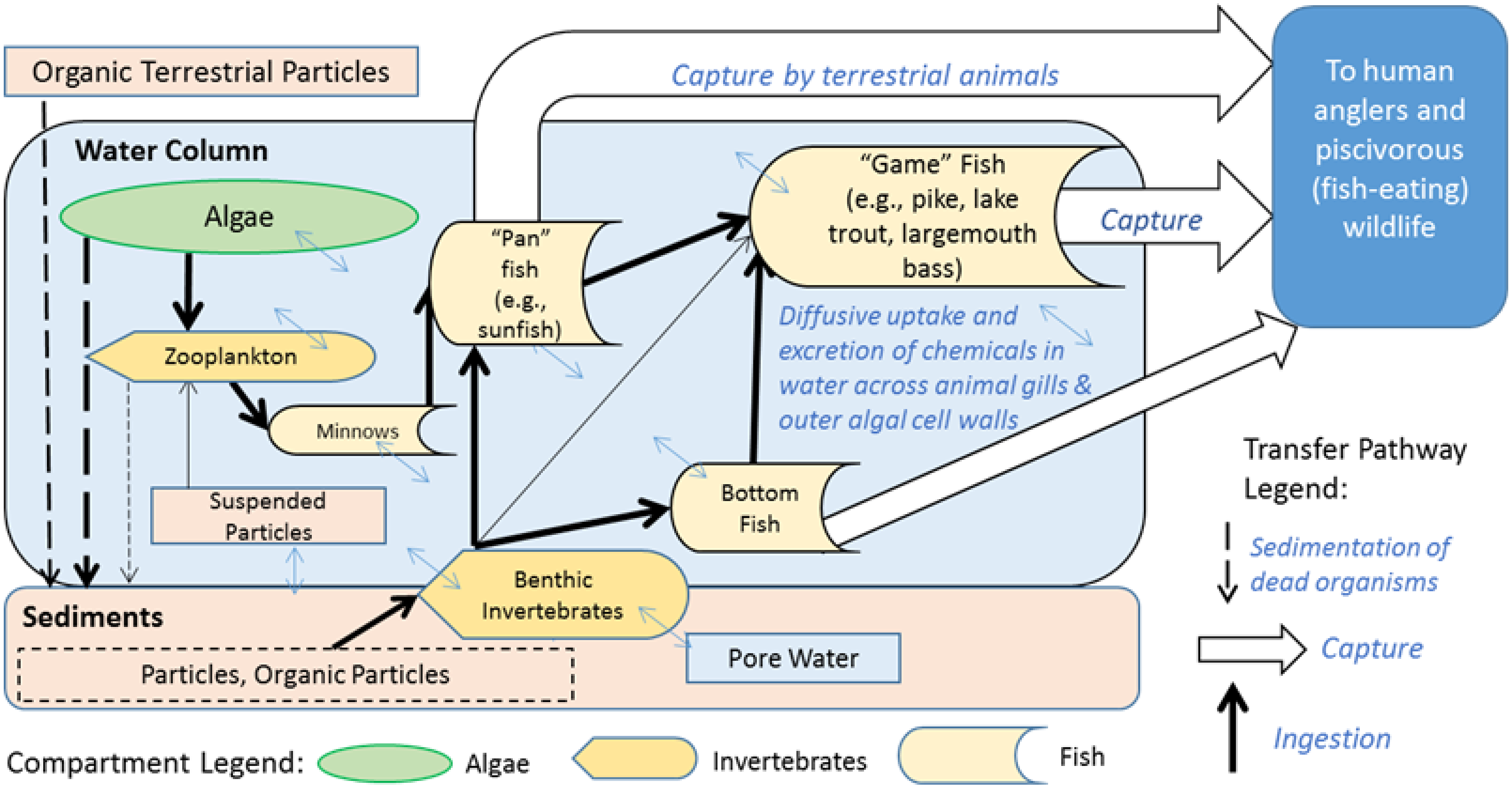


Figure A.22. Aquatic ecosystem biotic module.

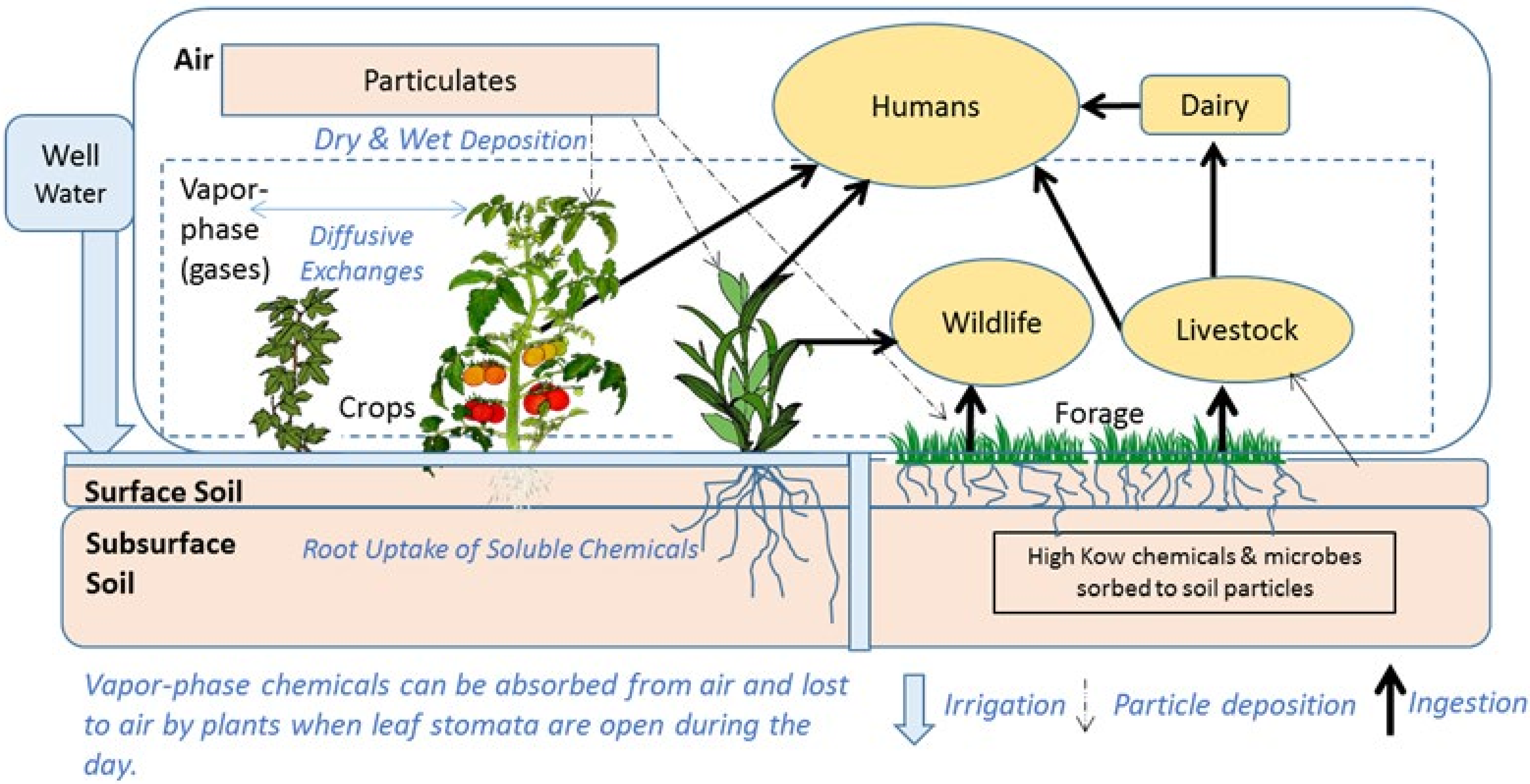


Figure A.23. Terrestrial plants module.

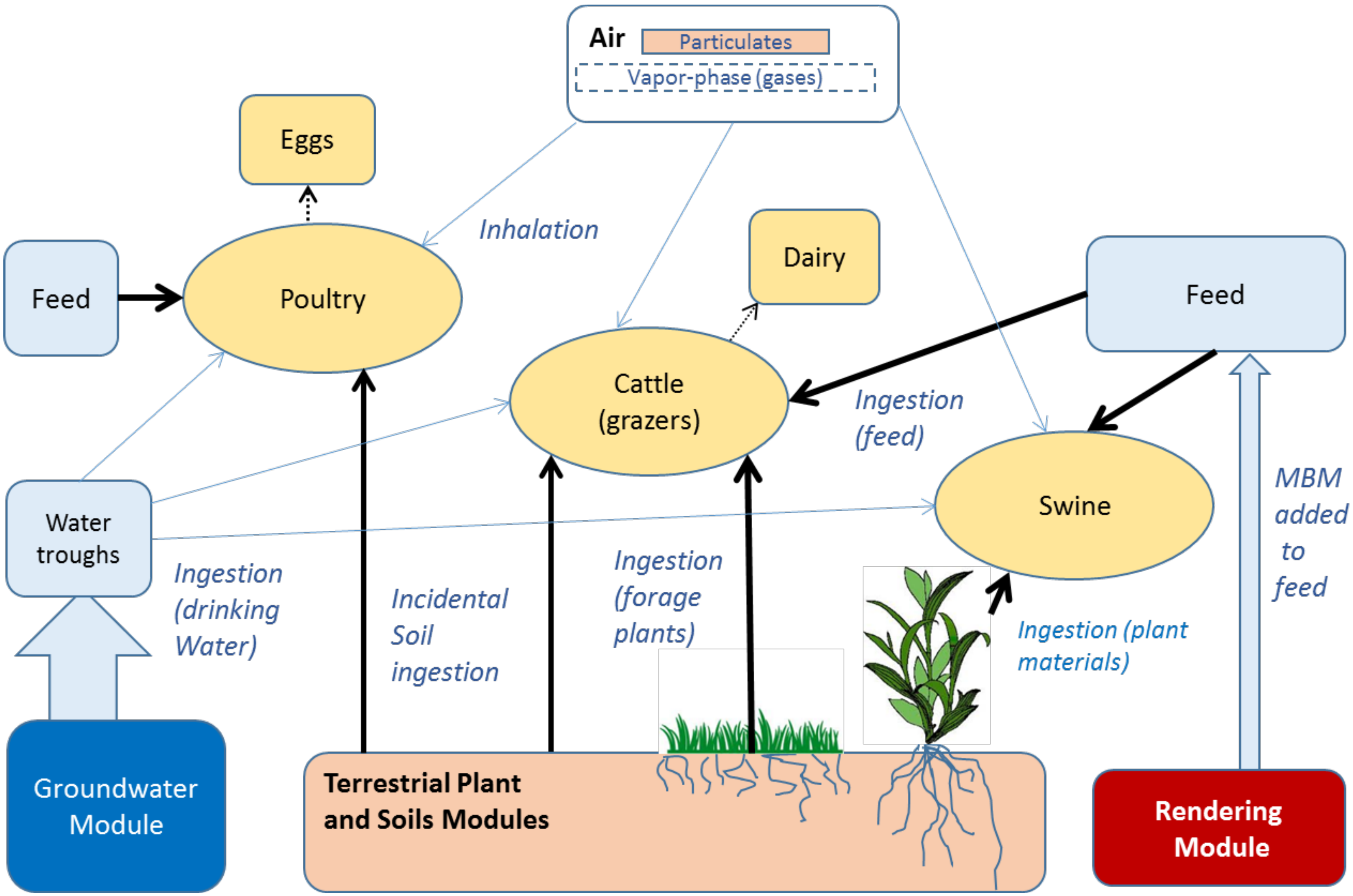


Figure A.24. Livestock module.

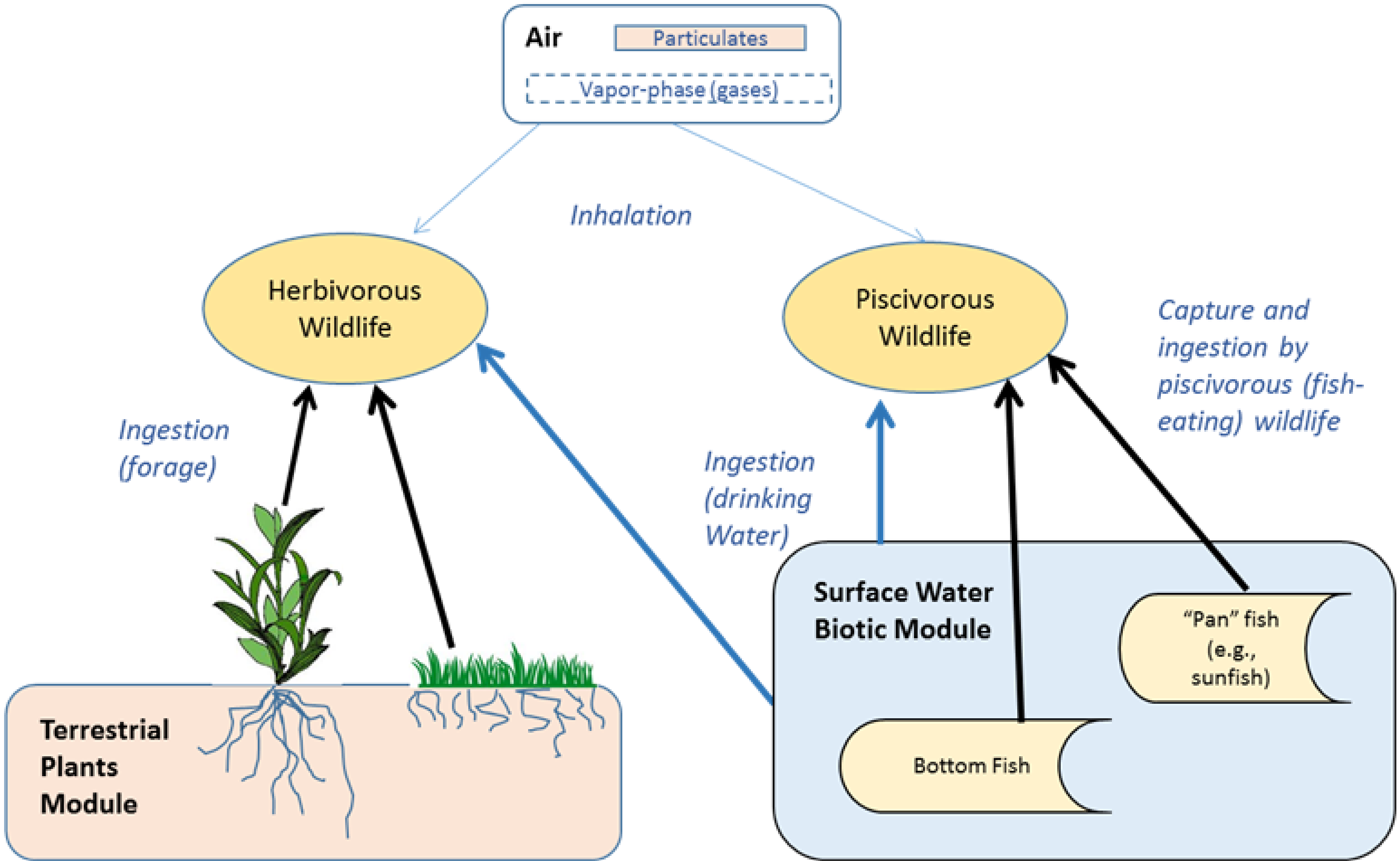


Figure A.25. Terrestrial wildlife module.

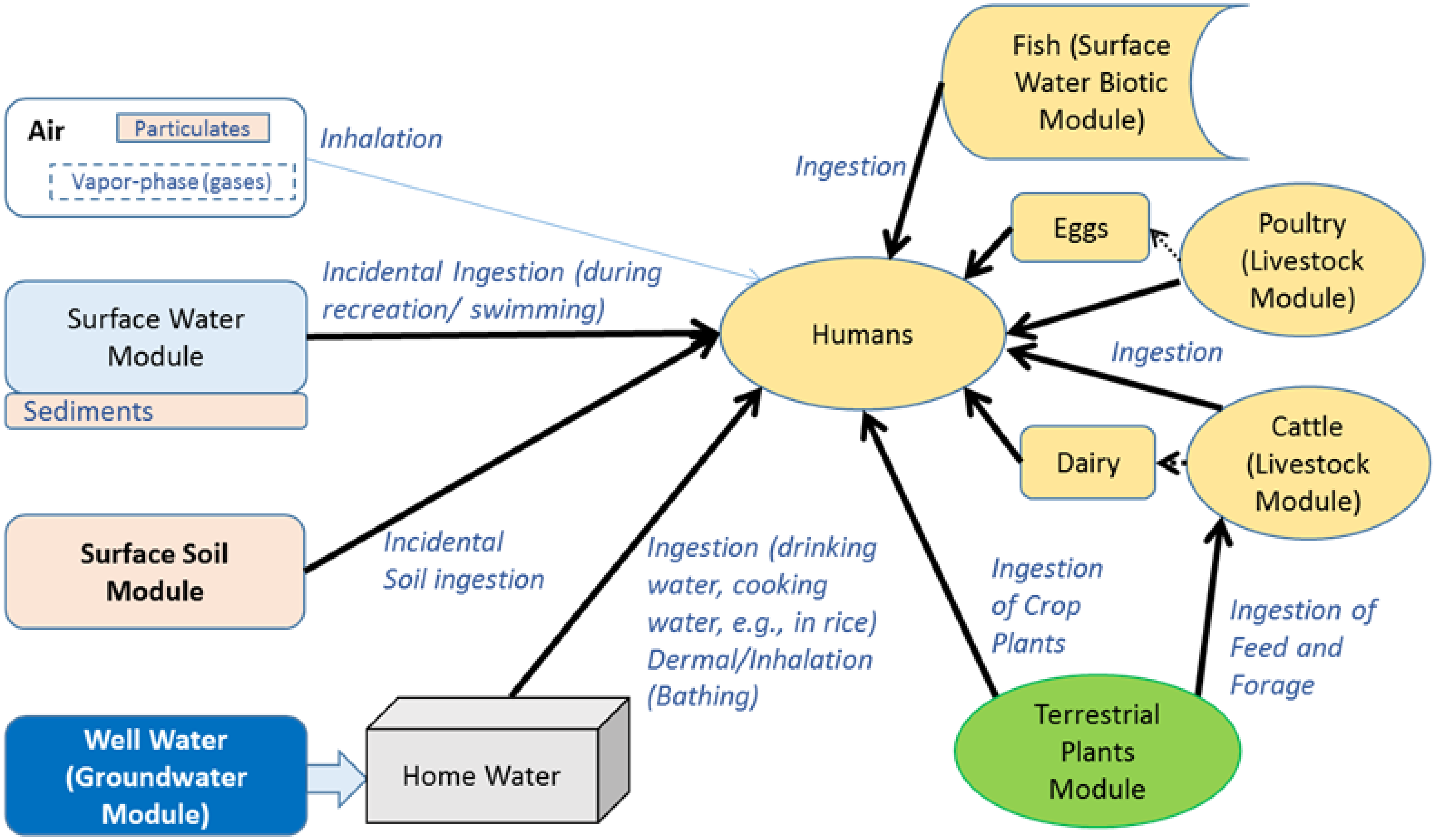


Figure A.26. Human receptor module.

Appendix B: Additional Radionuclide Exposure Information

B.1 Important Radioisotopes and Their Half-lives

Every chemical element has one or more radioactive isotopes that differ by the number of neutrons in the atom's nucleus. Chemical elements have a different number of protons, ranging from 1 for hydrogen to 93–103 and higher for the transuranium elements (i.e., elements with atomic numbers—that is the number of protons—higher than uranium). Hydrogen (H) has three isotopes with masses of 1, 2, and 3 grams/mole (g/mol). Only ^{3}H (tritium), with 1 proton and 2 neutrons, however, is radioactive; the other two isotopes are stable and do not emit ionizing radiation. Isotopes are identified by their atomic mass (e.g., ^{210}Po has 84 protons and 126 neutrons, for a total atomic mass of 210 g/mol).

Only approximately 50 of the more than 1,000 known radioactive isotopes of various elements occur naturally in the environment. Those include radioactive isotopes of uranium and thorium and ^{40}K. Isotope decay products (daughters) of uranium and thorium include isotopes of polonium, radium, and radon. Most currently known radioactive elements have been produced artificially in nuclear reactors. For example, all of the transuranium elements (e.g., plutonium, americium, curium, berkelium, californium) were first created and isolated in nuclear laboratories starting in the 1940s.

Groups of radioisotopes associated with uranium mining, fueling nuclear power plants, produced in reactor cores and nuclear bomb detonations, are presented in Tables B.1.1 through B.1.3, respectively.

Table B.1.1. Uranium-238 Decay Series (Uranium Mines)

Element		Isotope	Emits	Half-life	Comment
U	Uranium		α	4.5 billion years	Parent isotope – most abundant
Th	Thorium	234	β, γ	24.5 days	No change in atomic number or weight; short half-lives
Pa	Protactinium	234	β, γ	1.14 minutes	
U	Uranium	234	α	233,000 years	Each alpha (α) particle emission (loss of 2 protons and 2 neutrons) reduces the atomic number by 2 and the atomic weight (isotope number) by 4
Th	Thorium	230	α	83,000 years	
Ra	Radium	226	α	1,590 years	
Rn	Radon	222	α	3.83 days	
Po	Polonium	218	α	3.05 minutes	
Pb	Lead	214	β, γ	26.8 minutes	No change in atomic number or weight; short half-lives
Bi	Bismuth	214	β, γ	19.7 minutes	
Po	Polonium	214	α	15 milliseconds	Very short half-life
Pb	Lead	210	β, γ	22 years	No change in atomic number or weight
Bi	Bismuth	210	β, γ	5 days	
Po	Polonium	210	α	140 days	Final alpha decay leads to stable Pb
Pb	Lead	206	stable	stable	No further decay; not radioactive

Symbols: α = alpha particle; β = beta particle; γ = gamma radiation.

Uranium is a naturally occurring radioactive element with no stable isotopes. In the United States, between 1953 and 1980, uranium was mined primarily in Arizona, Colorado, New Mexico, South Dakota, Texas, Utah, Wyoming, and Washington. Table B.1.1 shows the series of elements and isotopes produced by natural ^{238}U decay, ending with ^{206}Pb, which is stable. Note that the longer the half-life, the more "stable" the isotope. ^{238}U is the most stable and most abundant isotope (99.2739–99.2752% of total uranium) with a half-life close to the age of Earth. The radioisotopes found in uranium mines are predominantly those that result from the natural decay of ^{238}U, as shown in Table B.1.1.

Table B.1.2 lists several isotopes of uranium, plutonium, and thorium, some of which are natural and some of which are created in nuclear facilities. Although some other radioisotopes can be used in nuclear power plant (NPP) fuels, uranium and plutonium are the primary elements used. ^{235}U, which is fissile (i.e., can support nuclear chain reactions in NPP reactors), is only 0.7% of natural uranium.

Table B.1.2. Some Isotopes of Uranium, Plutonium, and Thorium

Element		Iso-tope	Emits	Half-life	Comment
U	Uranium	232	α	69 years	Has been produced in breeder reactors.
		234	α	248,000 years	Product of ^{238}U decay.
		235	α	713 million years	0.7% of naturally occurring uranium; highly fissile, mined and enriched to produce NPP fuel
		238	α	4.5 billion years	Primary natural form of uranium; not fissile; breeder reactors transmutate ^{238}U to fissile ^{239}Pu
Pu	Plutonium	238	α	87.7 years	Not fissile; decays to ^{234}U; can release fast neutrons
		239	α	24,110 years	Primary fissile isotope used in NPPs and in bombs
		240	α	6,563 years	Spontaneous fission to ^{236}U
		241	β	14.4 years	Fissile; decays to ^{241}Am
		244	α	80 million years	Found in trace quantities on earth
Th	Thorium	232	α	14 billion years	Occurs naturally, longest half-life of significantly radioactive isotopes; decay series ends in stable lead; can be transmuted to ^{235}U in breeder reactors
		230	α	83,000 years	Produced in the decay chain of ^{238}U

Symbols: α = alpha particle; β = beta particle; γ = gamma radiation. NPP = nuclear power plant

Considering the uranium (U) isotopes listed in Table B.1.2 above, before use in NPP fuel rods, the proportion of uranium that is ^{235}U must be enriched from 0.7% to between 3.5% and 5.0% (USNRC 2014). ^{232}U is not naturally occurring but has been produced in fission reactors. ^{234}U is the decay product of ^{238}U after an alpha particle has been released. As noted in Table B.1.2 above, ^{238}U is the most abundant isotope of uranium, but it is not fissile.

Plutonium (Pu) is a transuranic element with atomic number 94. Scientists at the University of California at Berkeley first produced and isolated ^{238}Pu in 1940. Breeder reactors can transmutate ^{238}U into fissile ^{239}Pu. In a breeder reactor, neutrons with kinetic energy above 1 MeV enter the nuclei of ^{238}U atoms creating ^{239}Pu. Fission of ^{239}Pu produces up to one third of the power generated by a breeder reactor. Recovered from fuel recycling processes, ^{239}Pu is the primary fissile isotope in use in NPPs and in nuclear weapons (Table B.1.2). ^{240}Pu is the main impurity in recovered ^{239}Pu. Because ^{240}Pu exhibits a high rate of spontaneous fission, the "grade" of ^{239}Pu is listed by its ^{240}Pu content: weapons grade has less than 7%, fuel-grade has 7–19%, and NPP-grade can contain 19% or more ^{240}Pu. For weapons carried on submarines, less than 4% ^{240}Pu is allowed.

^{232}Th accounts for virtually all of the naturally occurring thorium. Its half-life is more than three times the age of Earth. A few thorium-based nuclear reactors have been built; more are expected. In a breeder reactor, ^{232}Th can be transmuted into ^{235}U for use in conventional NPPs.

Table B.1.3 lists some additional radioisotopes that might be released to the environment from one or more types of possible radiological incidents. For NPPs, fission product inventories are proportional to the long-term thermal power of the NPP. In 1988, the U.S. Nuclear Regulatory Commission (USNRC) estimated the inventory of fission products in NPPs (in active or spent fuel rods) at the time, in units of Ci/MWe (Curies per megawatt-electrical). Those estimates are in the "Inventory" column of Table B.1.3 (USNRC 1988, Table 2.2). The first group, iodine isotopes from 131 to 135, has short half-lives compared with the elements and isotopes that follow. ^{131}I is the iodine isotope of most concern because of its relatively longer half-life of 8 days. Radioisotopes with half-lives less than several minutes are not included in Table B.1.3.

Additional relatively well-known radioisotopes are listed with "NA" for the inventory column (i.e., not included in the USNRC 1988 list) in Table B.1.1. Some are synthesized in nuclear reactors for medical and other applications. Others occur naturally and are useful in radio-dating materials on earth.

B.2. Measuring Radiation Emissions and Exposures

Measures of radiation are complex because some radiation is pure energy (e.g., gamma and X-rays) while other types of radiation (alpha and beta) include both particles and energy. Some measures apply to emissions from a material and can be measured at a meter or so from the source. Other metrics indicate absorbed doses, and still other metrics reflect the relative damage produced in humans, which depends on the type of radiation as well as its energy levels.

B.2.1 Metrics

Table 1 in the main report identifies four metrics used to measure radioactivity and exposure. Further information on these is provided in Table B.1.3.

Table B.1.3. Other Radioisotopes Associated with Nuclear Power and Found in the Environment

Element		Isotope	Emits	Half-life	Inventory (Ci/MWe)	Comment
Fission products in U-235 nuclear reactors						
I	Iodine	131	β, γ	8.0 days	85,000	NPP fission product
		132	β, γ	2.3 hours	120,000	Other iodine radioisotopes released, but of less concern because of shorter half-lives
		133	β, γ	20.8 hours	170,000	
		134	β, γ	42.6 minutes	190,000	
		135	β, γ	6.6 hours	150,000	
Sr	Strontium	89	β	50.5 days	94,000	NPP fission product; used in treatment of bone cancer
		90	β	29 years	3,700	NPP and weapon fission product; has medical uses
Ce	Cesium	134	β, γ	2.1 years	7,500	NPP fission product; but not produced by nuclear weapons
		136	β, γ	13 days	3,000	
		137	β, γ	30 years	4,700	Common NPP fission product of ^{235}U
Kr	Krypton	85	β, γ	10.7 years	560	NPP fission product; gas — disperses
		87	β, γ	1.3 hours	47,000	NPP fission product; gas — disperses
		88	β, γ	2.8 hours	68,000	NPP fission product; gas — disperses
Xe	Xenon	133	β, γ	5.2 days	170,000	NPP fission product; gas — disperses
		135	β, γ	9.1 hours	34,000	NPP fission product; gas — disperses
		138	β, γ	14 min	170,000	NPP fission product; gas — disperses
Other radioisotopes						
Se	Selenium	79	β	327,000 years	NA	In spent nuclear fuel and wastes from fuel reprocessing
Cl	Chlorine	36	β	≈ 300,000 years	NA	Non-reactive; suitable for geologic dating; produced by irradiation of seawater during nuclear weapons testing between 1952 and 1958
K	Potassium	40	α, β, γ	1.25 billion years	NA	Used in potassium-argon dating; ranks third as a source of radiogenic heat in the Earth's mantle, after ^{232}Th and ^{238}U
Co	Cobalt	60	β, γ	5.27 years	NA	Artificially produced in nuclear reactors, relatively long-lived source of high-intensity gamma rays used in sterilization of medical equipment and for medical radiotherapy
H	Tritium	3	β	12.3 years	NA	Produced by irradiating lithium metal in a nuclear reactor, many uses including booster in a hydrogen-bomb

Source for Inventory column in Ci/MWe: USNRC 1988, Table 2.2.
Additional acronyms: α = alpha particle emissions; β = beta particle emissions; γ = gamma radiation; Ci/MWe = Curies per MWe; NA = not applicable (not listed by USNRC 1988); NPP = nuclear power plant; MWe = megawatt-electrical – size of nuclear core; ^{235}U = fissile uranium.

- **Disintegrations per second.** Radioactivity of some materials can be measured as disintegrations per second. Alpha and beta emissions (and some lower energy gamma rays) can be measured by a Geiger counter by detecting the ionization produced by a radioactive particle. A typical Geiger counter measures the ionization effect produced in the gas contained in a Geiger-Müller tube. The electrons are immediately attracted to a thin wire of tungsten with a high positive voltage producing an electric pulse. The International Commission on Radiation Units and Measurements (ICRU) established the Becquerel (Bq) equal to one disintegration per second. In the United States, measures of radiation started as Curies (Ci), with one Ci set equal to the particle emissions from one gram of radium in one second.
- **Dose-equivalent.** Some types of radiation cause more damage than others. Therefore, a different unit is needed to equalize all ionizing radiations relative to their potential to cause biological harm. The Sievert (Sv) is defined as the amount of radiation that is roughly equivalent to the effectiveness of one Gray (or 100 RADs) of gamma radiation (see paragraph below). Because the Sv is quite large for most applications, millisieverts (mSv) commonly are used. One mSv equals 10 ergs of energy of gamma radiation transferred to one gram of living tissue.[5]
- **Exposure (gamma and X-rays).** Gamma (and X-ray) radiation are quantified by units of ionizing exposure. Using IUs, gamma emissions are reported in Coulombs (C) created per kg of matter (C/kg).[6] That is the quantity of radiation required to create one C of charge of each polarity (both negative and positive) in one kg of matter. In the United States, the Roentgen (R), on the other hand, was set to the quantity of radiation required to create one electrostatic unit (esu) of charge of each polarity in one cubic centimeter of air. Table A.2.1 provides the conversion factors between C/kg and R units of exposure. Low energy gamma radiation can be measured by a standard Geiger counter; higher energy gamma radiation can be measured in more sophisticated ionization chamber.
- **Absorbed dose.** The amount of gamma radiation absorbed is reported in units of gray (Gy) or (less preferred) units of Roentgen Absorbed Dose (RAD). One Gy is defined as one joule (J) of radiation energy per kg matter. The Gy is independent of biological context. To estimate the equivalent dose absorbed in a human body, units of Sv are used (see above). One Gy = 100 RADs. One Gy absorbed dose of alpha particles is equivalent to 20 Sv. One Gy absorbed dose of gamma radiation equals 1 Sv.

B.2.2 Comparing Metrics

Radiation weighting factors (RWF) can be used to convert the physical dose in Gy to a biologically equivalent dose in Sv. The International Commission on Radiological Protection (ICRP) has issued recommendations for human protection, starting in 1991. The RWF is intended to account for the difference in damage to humans caused by different types of radiation for equal amounts of radiation energy deposited. Photons and electrons of all energies have an

[5] One erg equals 100 nanoJoules (nJ), the amount of work done by a force of one dyne exerted for a distance of one centimeter. One erg also equals 6.24E+11 electron volts (eV).

[6] One Coulomb (C) is equivalent to one ampere-second. An electric current of 1 ampere represents 1 C of unit electric charge carriers flowing past a specific point in 1 sec. The unit electric charge is the amount of charge contained in a single electron. Thus, 6.24E+18 electrons have 1 C of charge, as would the same number of protons (but with the opposite polarity).

RWF of 1.0 (ICRP 1991, 2007 as cited in ENS 2013). The 1991 ICRP recommendation for protons with energy of more than 2 MeV was a RWF of 5 and for protons with lower energies, it was 2. However, the ICRP 2007 recommendation for protons is an RWF of 2 (ENS 2013).

For neutrons, the RWF is a function of neutron energy (e.g., see Figure 4-1 in LaPlante et al. 2011). The continuous distribution can be broken down into categories. For neutrons with energies:

- <10 keV RWF = 5
- 10 keV to 100 keV RWF = 10
- >100 keV up to 2 MeV RWF = 20
- >2 MeV up to 20 MeV RWF = 10
- >20 MeV RWF = 5

Tissue weighting factors (TWF) are used to account for differences in radiation response of different organs for equal amounts of radiation energy deposited in an organ (LaPlant et al. 2011). We do not list those here, however, because we will not use tissue-specific radiation limits; whole body radiation limits are used for purposes of this assessment. Table B.2.1 compares biologically equivalent doses of radiation for familiar sources.

Table B.2.1. Radiation Exposures by Sources or Effect Levels

Source	mrem	IU	Reference
Airport screening	0.010	0.1 µSv	Dennison 2016
Airline crew flying NY to Tokyo Polar Route	5	50 µSv	WNA 2016
Chest X-ray	10	100 µSv	Dennison 2016
Natural background (annual)	300	30 mSv	Dennison 2016
Natural background (annual)	620	6.2 mSv	USNRC 2014
CT full body scan	1,000	10 mSv	USNRC 2014
Occupational annual limit	5,000	50 mSv	Dennison 2016
Dose from 4 months on International Space Station	10,000	100 mSv	WNA 2016
Clinical signs of illness (e.g., temporary radiation sickness; likely to cause a fatal cancer years later in 5/100 persons exposed)	100,000	1 Sv	WNA 2016
50% survival (whole body exposure)	400,000	4 Sv	Dennison 2016
100% fatal within a few weeks	1,000,000	10 Sv	WNA 2016
Radiotherapy (at the site of the tumor)	8,000,000	80 Sv	Dennison 2016

Acronyms: IU = international units; µSv = microsievert; mSv = millisievert; mrem = millirems or milli (radiation exposure-man); NRC = Nuclear Regulatory Commission; WNA = World Nuclear Association.

USEPA has published Dose Conversion Factors (DCF) and Derived Response Levels (DRLs) for a 4-day exposure to gamma radiation from deposited radionuclides for each radioisotope that might occur (Table 5-5 in USEPA 1992, cited in USEPA 2013).

B.3 Emergency Responses to Protect Human Health and Food Supply

In the event of a radiological emergency, livestock carcass management will be planned and implemented in the context of a broader response action. This section describes relevant phases and guidelines in those circumstances.

B.3.1 Response Phases

Under federal supervision, immediate responses to radiological incidents should be designed to best protect humans from harm. Four phases to ensuring a protective response include: (1) emergency response planning; (2) early response immediately following a release of radiation (first hours to days), (3) the intermediate response to protect persons from radiation over the following weeks and months, and (4) later phases where long-term solutions for cleanup and "disposal" are evaluated and implemented (USEPA 2013). This section briefly discusses phases 1 to 3 below.

Emergency Planning

Emergency planning is conducted at local, state, and federal levels with many agencies involved. For large NPPs, for example, state maps delineate both a 10-mile radius for actions to prevent or limit inhalation exposures and a 50-mile radius for actions to prevent or limit ingestion of radioactive materials that deposit from fallout as a radioactive plume passes (NJ OEM 2012). Large NPPs must maintain detailed rapid-response inhalation emergency plans considering the possibility of an explosion, fire, and or core meltdown, with options for protecting workers and surrounding populations within the first hours (e.g., notification and sheltering in place) and days (e.g., evacuation when safe). The plans also prescribe the computer simulation tools and the types of radiation monitoring that would be used to make decisions over the longer term. For NPPs or weapons installations near livestock production areas, the plans should include options for protection of livestock to the extent feasible under the circumstances.

Rapid Early Responses

As illustrated in Figure A.3-1, the dangerous inhalation fallout plume initially expands in size over a few hours as it travels from the source downwind. As radioactive decay proceeds, however, the dangerous fallout plume shrinks. Thus, for persons beyond the boundary of physical damages from an initial blast/fire/thermal wave, sheltering in place often is the best initial response. At some locations, people might be evacuated before the plume reaches them. Similarly, if there is time to move livestock to shelters ahead of the arrival of a plume of dangerous radioactivity, farmers might be so advised. Sheltering in structures not only reduces inhalation exposure, but it can stop deposition of radioactive isotopes onto humans and animals.

The actual distances and directions that radioactive gases and particles could travel depend primarily on the prevailing weather conditions (e.g., wind direction and speed, precipitation). Heavier particles will deposit closer to the source than lighter particles. Strong winds can spread the gases and lighter particles over a larger area, which would dilute the concentration of radioactive materials depositing to ground-level. Rain can scavenge gases and particles from the atmosphere, in what is called wet deposition, and can increase the concentration of radioactive materials on the ground, with significant local variation in concentrations.

After the initial dangerous fallout plumes have passed an area, evacuation might be recommended, with various areas designated for temporary housing. For livestock, relocation to "clean" areas, if available, could commence, with washing off the materials deposited to their fur or feathers and walking them through water decontamination stations. For livestock that cannot be relocated, provision of clean food and water, with a focus on water, is important.

Feed that has not been stored in the open can be used; foods such as clean hay bales should be covered by tarps if time permits. After a plume passes, even exposed silo bunkers can be used after the top exposed layer is removed (NJ OEM 2012). Substantial guidance on early response actions is available from numerous sources (e.g., USDHHS 2016; USEPA 2013; NJ OEM 2012 and other state guidance; USNRC 2016).

All agencies warn that livestock exposed to the radioactive plume and in a fallout area should not be slaughtered as an initial response. The possible exposures to humans from handling livestock with external contamination from fallout are too high. Only later, once radiation levels have declined, should decisions be made based on monitoring data and local conditions. Moreover, immediate slaughter requires disposing of the carcasses as biological radioactive waste—several sources quote $8,000 dollars as the cost of disposing of a single cow at a licensed radioactive waste disposal site (McMillan et al. 2011, Brandl et al. 2012).

Intermediate-Phase Responses to Airborne Releases

While early response actions are implemented, site-specific projections of the area covered by the radioactive plume and cumulative fallout are computed based on local meteorological conditions and what is known about the incident. The ingestion emergency planning zone generally starts with a 50-mile (80.5 km) radius, but more specific designations are developed as data on the incident is updated (USEPA 2013).

During the intermediate-phase, radiation monitoring helps to define when and where radiation from groundshine (deposited fallout) is sufficiently low to allow re-entry by civilian populations. For short-lived radionuclides like ^{131}I or ^{134}Cs, an area might be considered safe after 10 or fewer half-lives have passed and measurements confirm radiation levels are less than 2 times background concentrations. Exposed soils might be tilled underground; some crops could be composted. Milk products contaminated with ^{131}I could be frozen, powdered, or canned and stored until the ^{131}I radioactivity has declined to levels considered safe. Feed with potassium iodide added could help to clear inhaled or ingested ^{131}I from the thyroid gland, where it concentrates in animal bodies. For longer-lived radionuclides, like ^{89}Sr or ^{136}Cs with half-lives of 50 and 13 days, cleanup options must be evaluated on a site-by-site basis; again, radioactive decay will likely be sufficient after several months or years to allow reuse of an area. Strontium, however, bioconcentrates in bones (behaves like calcium); thus, if livestock were not provided clean feed throughout the response period, their future uses could be compromised. Cesium does not concentrate in any particular part of the body.

In areas contaminated with even longer-lived radioisotopes, decisions are more difficult, and cleanups can be very costly. For areas important to human welfare and residences, costs of cleaning and disposal of radioactive debris are compared with the need for those areas. Livestock internally contaminated with these isotopes might require slaughter, and options for disposing of radioactive carcasses would require evaluation.

B.3.2. Protective Guidelines

In the event of a radiological emergency, response actions, including carcass management activities at the site, may follow USEPA's proposed Planning Guidance and Protective Action Guides (PAGs) for Radiological Incidents. PAGs are exposure levels that should trigger protective actions in the early and intermediate phases of response following a nuclear incident. Local, state, and federal agencies can use PAGs to guide decision-making. Agencies also can recommend protective actions at lower radiation levels or modify responses to ensure the highest protection for the largest population.

First published in 1992 (USEPA 1992), the PAG Manual was revised and published for Interim Use and Public Comment in 2013 (USEPA 2013). The interim PAGs are listed in Table B.3.1 below. In the event of a nuclear incident, "early responses" focus on protection from exposures via all exposure pathways. For "intermediate responses", the dose of interest is the sum of the effective dose from external exposures and the effective dose from materials inhaled (e.g., prior to evacuation) (USEPA 2013, Section 3.4.2 on dose projections).

Table B.3.1. USEPA Protective Action Guides (PAGs) for Radiological Incidents

Phase	Action	Action Level (exposure)
Early responses (within hours or days)	Sheltering-in-place or evacuation of the public[1]	1 to 5 rem (10 mSv to 50 mSv) whole body projected dose over 4 days; beginning at 1 rem, whichever action or combination of actions results in the lowest exposure for the majority of the population
	Administration of prophylactic drugs (KI)[2]	5 rem (50 mSv) projected child thyroid dosed from radioactive iodine (based on data from Chernobyl exposure data)
	Limit emergency worker exposure	5 rem (50 mSv) per event and year (all occupational exposures) 10 rem (100 mSv) (protecting valuable property for human welfare, NPP) 25 rem (250 mSv) (lifesaving or protection of large populations)
	Supplementary administration of KI	5 rem (50 mSv) projected dose to child thyroid from exposure to iodine-131
Intermediate Responses	Relocation of public for 1 or more years	2 rem (20 mSv) projected dose over first year Subsequent years, 0.5 rem (5 mSv)/year projected dose
	Food interdiction	0.5 rem (5 mSv)/year projected dose, or 5 rem (50 mSv)/yr to any individual organ or tissue, whichever is limiting
	Limit emergency worker exposure	5 rem (50 mSv)/yr (or greater under exceptional circumstances)
Later Responses	Workers in restricted areas	> 2 mrem (20 mSv) /hr or > 100 mrem (1 mSv)/yr should operate under controlled conditions established for occupational exposures

Source: USEPA 2013, adapted from Tables 1-1, 2-2, and Section 2.7.
Abbreviations: KI = potassium iodide – not radioactive; hr = hour; mrem = millirem; mSv = millisievert; NPP = nuclear power plant; rem = radiation exposure-man; yr = year.
[1] Projected dose = sum of the effective dose from external radiation exposure (i.e., "groundshine" and "cloudshine") and the committed effective dose from inhaled radioactive material. Other protective actions would be advisable independent of a PAG (e.g., face mask to reduce inhalation of particles, decontamination by removing clothing).

In addition, the U.S. Department of Energy's (USDOE) Federal Radiological Monitoring and Assessment Center (FRMAC) Assessment Manuals (USDOE 2010a, b) provide detailed guidance for calculating dose projections downwind of an accident. The FRMAC Assessment Manuals incorporate the International Commission on Radiological Protection (ICRP) Publication 60 series dosimetry models (ICRP 1991). In addition, the Federal Radiological Preparedness Coordination Committee (FRPCC) encourages use of computational tools (e.g., USDOE's Turbo FRMAC and USNRC's Radiological Assessment System for Consequence Analysis or RASCAL as cited in USEPA 2013) to develop incident- and location-specific projections.

Official decision makers must weigh the risks and benefits of response actions for specific incidents. One-hundred percent protection of humans is possible if evacuation occurs before an airborne plume reaches an area. However, evacuation might not be appropriate if associated risks and secondary effects are more severe than the risk of the projected exposure to radiation (USEPA 2013). Sheltering in place can be both protective and cost-effective if projected doses over the first four days are less than 1 rem (10 mSv).

In the intermediate phase, persons can be relocated to areas beyond the area contaminated by fallout (which would continue to emit radiation, called "groundshine"). Depending on the half-lives of the radioactive materials deposited to the ground, reentry might be allowed in weeks or months, or authorities might declare an area a permanent exclusion zone (e.g., around Chernobyl).

Over the longer term, three general "outcomes" are possible. For radioisotopes with short half-lives (e.g., ^{131}I), radioactive emissions can decline to acceptable levels (e.g., no more than 2 x natural radiation at a location) over weeks or months, with no cleanup actions required. For radioactive materials with longer half-lives distributed over a relatively small area at more than twice background levels, surface decontamination might be possible (e.g., surface soil scraping), with the radioactive materials moved to a controlled hazardous materials waste site. Or, if decontamination is not cost effective, the area deemed contaminated at unacceptable levels can be declared an exclusion zone for periods of years or "permanently."

B.4. Livestock Exposure and Salvage

Exposure to ionizing radiation occurs in several different ways for livestock, and the important exposure pathways change over time. Sections B.4.1 and B.4.2 discuss short-term pathways and longer-term pathways, respectively. However, for livestock to become unfit for their intended uses, and to require slaughter, internal contamination is more important than external contamination, which could be washed off. Section B.4.3 describes some options for salvaging livestock, reducing the number of animals that need to be culled under some conditions.

B.4.1 Livestock Exposure Pathways – Short Term

As described in previous sections, following a radiological incident, both humans and livestock can be exposed. Three exposure pathways are possible in the short-term (e.g., over the first few days):

1. **External exposure to penetrating radiation**—Direct exposure to penetrating gamma radiation and beta particles from cloudshine or groundshine (assume that fast neutrons occur at dangerous levels only in cores of reactors; alpha particles cannot penetrate skin). This type of radiation might affect the health of livestock; however, it would not result in livestock being radioactive themselves.
2. **Inhalation**—Direct inhalation of alpha and beta particles and radioisotopes from an atmospheric plume of contamination and inhalation of deposited radioactive particles that are re-suspended from ground as dust. Alpha particles would deposit along the respiratory tract and could damage epithelial cells. The deposited radioisotopes could continue to decay, emitting alpha, beta, and gamma radiation. Some radioisotopes might be absorbed into the bloodstream; however, the primary inhalation exposure would last for a few days.
3. **Surface contamination**—Deposition of radioactive materials to the surfaces of people and animals and deposition to the ground of materials that emit penetrating gamma rays and beta particles, irradiating humans and livestock where they stand (groundshine). Surface

contamination can be washed off via water sprays and walking livestock through a water through on their way to a clean area (e.g., see NJ OEM 2012); however, a plan for the contaminated wash-water is needed.

4. **Ingestion**—If not supplied with clean feed and water immediately, livestock, particularly free-range livestock, are likely to start ingesting contaminated feed and possibly water. Livestock might have to "fend for themselves" for several days before it is safe for farmers or emergency responders to provision or move them.

B.4.2 Livestock Exposure Pathways – Longer Term

Over the longer term, radioactive materials deposited to surfaces (e.g., buildings, crops, livestock, soils, surface waters, and any other materials open to the air) can, depending on the half-life of the radioisotopes, continue to emit radiation over weeks, years, decades, or millennia. This groundshine can be measured using Geiger counters of appropriate design.

Ingestion of radioactive materials by livestock is the primary concern over the longer term:

- Free-range livestock could ingest large quantities of radioisotopes if allowed to continue to forage on pasture or fields over which a radioactive plume passed. Grazing livestock such as beef and dairy cattle, sheep, and goats, would ingest materials deposited to the forage plant surfaces and also incidentally ingest contaminated surface soils. Chickens foraging on seeds and insects on the ground could similarly ingest fallout. If not provisioned or moved from such an area, the animals might become radioactive themselves.
- If fed grains or hay that was exposed to fallout or if watered with contaminated groundwater or open-top on-site ponds, large numbers of livestock also could ingest radioisotopes over longer periods of time

Providing clean feed and water can allow livestock to return to productive uses if they are contaminated with relatively short-lived isotopes. Salvaging livestock by such measures can limit or prevent culling animals and needing to manage radioactive carcasses.

B.4.3 Salvaging Livestock

Most livestock outside the zone of physical/thermal damage and intensive initial radiation from a radiological incident might tolerate the short-term inhalation and ingestion exposures without becoming ill. Options for saving and decontaminating livestock, which depend on the type of radioactive materials and their half-lives, depend on cost-effectiveness of managing a herd over the period of time required for radioactivity to decline to acceptable levels. Slaughter and carcass management is necessary if the livestock are very sick (unlikely) or if contaminated with radioactive materials that cannot be cleared from their system (Brandl et al. 2012; Dennison 2016).

Some measures could decontaminate livestock that have ingested radioisotopes over the short-term (e.g., 2 to 4 days) if circumstances permit (Dennison 2016):

1. Provision of clean food and water, if possible, can help eliminate many isotopes from the body, and the isotopes with shorter half-lives (e.g., ^{131}I) will decrease in radioactivity over time.

2. Binding agents like bentonite clay or Prussian blue might prevent absorption of radioactive particles that are ingested immediately following an incident before livestock can be removed from pasture, for example.

3. Testing livestock for whole body radioactivity is needed to determine when they could be slaughtered for meat products. If radioisotopes in livestock and have a short half-life, (e.g., ^{131}I), continuation on clean food and water until sufficient half-lives have passed might be all that is required. Testing for radioactivity is required to confirm when slaughter for meat products could be done.

4. Eggs and milk need to be tested. Milk contaminated with ^{131}I can be frozen or powdered or canned and stored for the few months required for radiation to fall to acceptable levels. Eggs contaminated with ^{131}I could be powdered.

For animals that have ingested radioisotopes with longer half-lives, animals and products might not be salvageable. Determining which animals need to be euthanized is a delayed priority. Measures taken to decontaminate livestock and to reduce their body burdens of radioactive materials also will reduce the number of carcasses overall and the number that need to be managed as radioactive waste compared with standard waste. For example, following the Chernobyl reactor accident, contaminated livestock were slaughtered immediately due to fear and anticipated economic losses, which complicated the carcass management process and increased the quantity of radioactive waste materials requiring special disposal (IAEA 2006). They did not consider the substantial cost associated with radiological waste disposal. Animals with internal doses below the LD_{10} (lethal dose for 10 percent of the animals) are not expected to display observable symptoms that would provide grounds for immediate disposal (Brandl et al. 2012).

Recognizing that salvaging livestock requires guidance on what level of contamination would be acceptable, Brandl et al. (2012) developed an approach to calculating absorbed doses in units of Gys to livestock using the body shape of a deer to demonstrate the approach. Based on their literature review and information from the Chernobyl accident, they concluded that estimated absorbed doses of 1 Gy or less indicates that large animal livestock could be salvaged and doses of 2 Gy and 3 Gy or less would indicate small animals and poultry, respectively, could be salvaged (Brandl et al. 2012).

How to determine how many livestock might be salvageable following a nuclear incident, however, is beyond the scope of this assessment. We provided this background to remind readers that livestock exposed to fallout from a radiological incident do not necessarily need to be culled, and information specific to an event is needed to make decisions.

References for Appendix B

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