Janet T. Mills
Governor

Jeanne M. Lambrew, Ph.D.
Acting Commissioner

Maine Department of Health and Human Services
Maine Center for Disease Control and Prevention
11 State House Station
286 Water Street
Augusta, Maine 04333-0011
Tel; (207) 287-8016; Fax (207) 287-9058
TTY: Dial 711 (Maine Relay)

Derivation of PFOS soil screening levels for a soil-to-fodder-to-cow's milk agronomic pathway

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Prepared by the
Maine Center for Disease Control and Prevention

Contacts:

Andrew Smith, SM, ScD
State Toxicologist
Maine Center for Disease Control and Prevention
Tel: (207) 287-5189
Email: andy.e.smith@maine.gov

Thomas Simones, PhD
Toxicologist
Maine Center for Disease Control and Prevention
Tel: (207) 287-3365
Email: thomas.simones@maine.gov

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Summary

In developing soil screening levels for the protection of human health, incidental soil ingestion for a young child is often considered the most health protective exposure pathway. Discovery of perfluorooctanesulfonic acid (PFOS) contamination in cow's milk at a small, local dairy farm in Maine suggests that soil screening levels based on direct soil contact may be inadequate to protect individuals from exposure through cow's milk at farms where PFOS is present in the soil. To better understand the exposure pathway leading to PFOS milk contamination at a dairy farm, the Maine CDC developed soil screening levels for a soil-to-fodder, fodder-to-cow's milk, milk-to-human exposure pathway. The agronomic pathway soil screening levels were developed using a modified EPA Preliminary Remediation Goals for Radionuclide Contaminants at Superfund Sites (PRGR) equation. The agronomic pathway equation calculates a soil screening level to meet a prescribed PFOS milk action level based on chemical transfer from soil to plants used as dairy cow feed, dairy cow feed consumption, soil consumption while grazing and transfer from intake into milk. The soil screening levels were derived using a PFOS action level for milk of 210 ng/L. This cow's milk action level is established as guidance for determining whether a farm's milk from dairy cattle should be considered adulterated, and therefore neither sold or delivered for sale in accordance with Title 22 MRS §2155-A. Maine CDC developed the PFOS milk action level using the EPA reference dose for PFOS of 20 ng/kg/day, a 90th percentile milk intake level for a 1-2-year-old child, with consideration of background exposure to PFOS from other dietary and environmental sources. For the soil screening levels, PFOS-specific soil-to-hay, soil-to-corn, and milk transfer factors were selected from published peer-reviewed studies in the scientific literature and a study conducted and published by a European state agency. For soil adherence to hay, the EPA PRGR default soil plant mass loading factor for pasture plants was adjusted to a geometric mean as a central tendency estimate to account for the highly skewed range of potential values. A separate soil plant mass loading factor identified in the scientific literature was selected for corn. Soil screening levels were developed for two fodder intake scenarios: a predominantly grass-based dairy farm scenario using EPA PRGR default intakes for hay and corn silage and an average Maine dairy farm scenario using hay and corn silage estimates based on more typical Maine dairy farm practices. Terms accounting for the fraction of fodder grown on PFOS-contaminated land and the fraction of the year cattle are fed PFOS-contaminated fodder were set at EPA PRGR default values of 1. The fraction of the year spent grazing was adjusted to 0.5 to account for snow cover in Maine. These two fraction terms can be adjusted using site-specific information if appropriate. The resulting soil screening levels for a grass-based dairy farm and a more typical, average Maine dairy farm are 6,400 and 11,000 ng/kg dry weight, respectively. These agronomic exposure pathway soil screening levels are more than 150-fold lower than the current residential soil (1,700,000 ng/kg dry weight) and 2- or more fold lower than soil leaching-to-ground water (21,000 ng/kg dry weight) exposure pathways in the current Remedial Action Guidelines for soil in Maine.

1. Background

In 2016, per- and polyfluoroalkyl substances (PFAS) contamination was discovered at a small local dairy farm in Maine. The contamination was identified during an investigation to determine a possible source of perfluorooctanesulfonic acid (PFOS) and perfluorooctanoic acid (PFOA) in a nearby public water system supply well identified during the third installment of the U.S. Environmental Protection Agency (EPA) unregulated contaminant monitoring rule (UCMR). Subsequent investigation uncovered contamination of the farm's well water, soil, hay, and cow's milk. PFOS was the primary PFAS detected in the various media at the farm. In the farm's well water, which served as both the dairy cow's and the family's drinking water source, PFOS was detected at a concentration of 42 nanograms/liter (ng/L). Prior sampling of a monitoring well located in close proximity to the farm well detected PFOS at concentrations ranging from 100 to 130 ng/L. Soil samples from the farm's fields contained 566 to 878,000 nanograms/kilogram (ng/kg dry weight) PFOS. One sample of hay believed to be grown and harvested on-site contained 9,669 ng/kg wet weight PFOS. An initial milk sample from the farm's milk tank had a measured PFOS concentration of 1,420 ng/L. Two confirmatory milk tank samples taken two months after the initial sample contained 690 and 938 ng/L PFOS. Using published literature values on milk transfer from dietary PFOS intake, the observed PFOS levels in hay appeared to be the major contributor to observed milk levels (Vestergren et al. 2013 and Kowalczyk et al. 2013).

At the request of the Maine Department of Agriculture, Conservation and Forestry (DACF) the Maine Center for Disease Control and Prevention (Maine CDC) developed an action level for PFOS in cow's milk of 210 ng/L (Maine CDC 2017). This cow's milk action level was established as guidance for determining whether a farm's milk from dairy cattle should be considered adulterated, and therefore neither sold or delivered for sale in accordance with Title 22 MRS §2155-A. The adulterated milk action level is based on the 20 nanogram/kilogram body weight/day (ng/kg/day) reference dose used to develop the EPA Office of Water's lifetime health advisory for PFOS in drinking water (USEPA 2016). The cow's milk action level was developed to be protective of high-end milk consumption for a 1- to 2-year-old child with consideration of background exposure to PFOS from dietary and environmental exposures.

Since PFOS levels in cow's milk were above the 210 ng/L action level and hay PFOS levels were sufficiently elevated to explain the observed milk levels, it seemed likely that an agronomic exposure pathway, e.g., soil-to-hay-to-cow-to-milk, would have a lower soil screening level than the current Maine Department of Environmental Protection's (DEP) Remedial Action Guideline (RAG) of 1,700,000 ng/kg dry weight. The residential PFOS soil RAG utilizes the same EPA reference dose, 20 ng/kg/day, as the milk action level but is based on an incidental soil ingestion exposure pathway for young children. The DEP soil RAGs are developed for the most common exposure scenarios typically encountered at hazardous waste sites in Maine. For individual chemicals, the lowest soil RAGs are most often the direct contact soil RAGs for a child residential exposure pathway or the soil leaching-to-groundwater pathway[1]. The DEP RAGs do not include RAGs for agronomic exposure pathways; nor does the EPA Regional Screening Level (RSL) framework from which the RAGs are developed. This document details the derivation of soil screening levels for a soil-to-hay/corn-to-cow-to-milk agronomic exposure pathway using a modified EPA Preliminary Remediation Goals for Radionuclide Contaminants at Superfund Sites (PRGR) equation.

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[1] DEP RAGs, Table 3 Maine Remedial Action Guidelines for the Soil Exposure Pathway, by Exposure Scenario (https://www.maine.gov/dep/spills/publications/guidance/rags/ME-Remedial-Action-Guidelines-10-19-18cc.pdf).

2. Soil screening level derivation methods

2.1. Soil screening level equation

The soil-to-fodder-to-cow's milk soil screening levels are derived using a modified EPA PRGR equation (Equation 1). The EPA PRGRs were developed to derive screening levels for radionuclides for various exposure scenarios, including an agricultural farming scenario for the consumption of milk from dairy cow's present on a farm with contaminated soil (USEPA 2017). The EPA PRGR soil screening level equation for this agronomic pathway models radionuclide transfer from soil to plant material used as dairy cattle feed, consumption of the contaminated feed and soil, and transfer into cow's milk to meet a radionuclide-specific cow's milk PRG based on direct consumption.

Several modifications were made to the default PRGR equation (Appendix 1) to calculate PFOS soil screening levels. First, the radionuclide-specific parameter values in the equation, i.e., cow's milk concentration, cow's milk transfer factor, and plant transfer factor, were replaced with PFOS-specific values. Second, the default PRGR equation exposure time parameters - Animal on-site fraction and Fraction of year animal on-site - were modified to make the terms specific to fodder intake and soil intake from grazing exposures. For fodder intake, the fraction terms were modified to Fraction of fodder from contaminated land and Fraction of year animal fed contaminated fodder. For soil intake from grazing, only the Animal on-site fraction exposure term is included in the default PRGR equation. This single term in the soil intake portion of the equation was replaced with two terms - Fraction of grazing on contaminated land and Fraction of year animal spends grazing.

Equation 1. Soil screening level for cow's milk.

$$SL_{soil} = \frac{C_{milk} \times \left(\frac{1}{D_{milk}}\right)}{TF_{milk} \times \left[\left(I_{fodder} \times F_{land-f} \times F_{year-f} \times \left(TF_{plant} + MLF\right)\right) + \left(I_{soil} \times F_{land-g} \times F_{year-g}\right)\right]}$$

where:

SL_{soil} = Soil screening level (ng/kg dry weight)
C_{milk} = Concentration in cow's milk (ng/L)
D_{milk} = Milk density (kg/L)
TF_{milk} = Milk transfer factor (day/kg)
I_{fodder} = Fodder intake rate (kg/day)
F_{land-f} = Fraction of fodder from contaminated land (unitless)
F_{year-f} = Fraction of year animal fed contaminated fodder (unitless)
TF_{plant} = Soil-to-plant transfer factor (ng/kg dry plant/ng/kg dry soil)
MLF = Soil plant mass loading factor (g dry soil/g dry plant)
I_{soil} = Soil intake rate (kg/day)
F_{land-g} = Fraction of grazing on contaminated land (unitless)
F_{year-g} = Fraction of year animal spends grazing (unitless)

2.2. Dairy farm exposure scenarios

The default EPA PRGR equation models a “subsistence” dairy farm scenario where all dairy cattle feed, primarily grass and hay, is grown in contaminated soil on-site[2]. Under this scenario the dairy farm relies on more forage (grass and hay) and silage from forage than grain as feed sources. In Maine, the typical dairy farm uses more silage from corn and grain as feed sources than grass or hay. To account for differences in dairy farm feeding practices, separate soil screening levels were calculated for a grass-based dairy farm scenario and an average Maine dairy farm scenario. The grass-based dairy farm scenario utilizes EPA default intakes for grass/hay and silage with a greater percentage of intake from grass/hay than silage and considers silage to come from corn grown on-site. The average Maine dairy farm scenario uses feed intakes provided from the University of Maine Cooperative Extension based on typical Maine dairy farm feeding practices.

Due to differences in PFOS uptake and soil plant mass loading between grass and corn plants individual soil screening levels were calculated separately for hay and corn silage intake. The crop-specific soil screening levels are combined using a default EPA summing equation to derive the soil screening levels for two exposure scenarios (Equation 2) (USEPA 2017).

Incidental soil ingestion by dairy cattle while grazing on pasture land is accounted for in the hay soil screening level calculations. For corn silage, the incidental soil ingestion intake term is set to zero under the assumption that dairy cattle will not be grazing on land used to grow corn silage.

Grain as a feed source is assumed to contribute negligible amounts of PFOS to overall intake as studies suggest that PFOS transfer into the plant grain, corn or wheat, is minimal (Sthal et al. 2009, Fischer et al. 2008, Blaine et al. 2013, Ghisi et al. 2019). Therefore, only exposure from hay and corn silage is considered in calculating the soil screening levels. Any additional feed sources that may be used to meet total dietary intake requirements are also considered PFOS-free. The soil screening levels do not address concurrent exposure from a PFOS-contaminated water source at a farm. PFOS exposure from water is considered a separate exposure pathway.

Equation 2. Combined total soil screening level equation.

$$SL_{soil\ total} = \left(\frac{1}{\frac{1}{SL_{soil-to-hay}} + \frac{1}{SL_{soil-to-corn\ silage}}} \right)$$

where:

$SL_{soil\ total}$ = Combined total soil screening level (ng/kg dry weight)

$SL_{soil\text{ -}to\text{-}hay}$ = Soil-to-hay specific soil screening level (ng/kg dry weight)

$SL_{soil\text{ -}to\text{-}corn\ silage}$ = Soil-to-corn silage specific soil screening level (ng/kg dry weight)

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[2] EPA PRG for Radionuclides land use descriptions and exposure scenarios - https://epa-prgs.ornl.gov/radionuclides/users_guide.html

2.3. Soil screening level equation parameter inputs

PFOS milk concentration

The milk concentration is the current Maine CDC milk action level for PFOS in cow's milk of 210 ng/L (MECDC 2017). Maine CDC developed the milk action level for the DACF as an adulteration level to consider milk at a dairy farm as adulterated with PFOS, and therefore should neither be sold or delivered for sale in accordance with Title 22 MRS §2155-A. The 210 ng/L milk action level is based on the EPA Office of Water's 20 nanogram/kilogram body weight/day (ng/kg/day) reference dose (RfD) used to develop their lifetime health advisory for PFOS in drinking water (USEPA 2016). The EPA RfD was selected for consistency with current risk assessment practices at federal agencies, including the U.S. Food and Drug Administration (FDA) (the federal agency responsible for establishing food tolerance levels), and risk assessment-based values in Maine, including the DEP's RAGs and screening levels for the beneficial use of solid waste. Maine CDC developed the milk action level to be protective of high-end, 90th percentile, milk consumption for a 1- to 2-year-old child using consumption data from the U.S. Centers for Disease Control and Prevention's (U.S. CDC) National Health and Nutrition Examination Survey (NHANES) and the U.S. Department of Agriculture (USDA) Food Patterns Equivalents Database (FPED) (USCDC, 2017 and USDA, 2016). It is common practice in human health risk assessment to use intake rates at a 90th or 95th percentile to model a reasonable maximum exposure. For example, the FDA typically uses the 90th percentile of a daily intake to represent a high-end consumer and the EPA PFOS/PFOA drinking water health advisory is based on the 90th percentile consumer-only estimate for water ingestion on a body weight basis for lactating women (FDA 2006 and USEPA 2016).

Background exposure to PFOS from all other sources, whether dietary or environmental, was accounted for in the milk action level with application of a relative source contribution (RSC) factor. The PFOS-specific RSC factor is based on human PFOS serum level data from U.S. CDC NHANES biomonitoring studies. A simple pharmacokinetic model was used to convert serum level data to oral equivalent doses for comparisons to the PFOS RfD (USEPA 2016). The calculated PFOS RSC based on human serum data is greater than 95%. For RSC factors it is EPA guidance that values should not exceed an 80% ceiling, nor fall below a 20% floor (USEPA, 2000). As the calculated PFOS RSC was above the 80% ceiling, the RSC was limited to 80%.

Cow's milk transfer factor

The PFOS-specific transfer factor used for dairy cow intake to milk is 0.02. This value comes from a study in Sweden examining PFAS intake from feed and water at a local dairy farm and measured PFAS levels in cow's milk (Vestergren et al. 2013). Six PFAS, including PFOS, were measured in feed, water, and milk. PFAS concentrations in feed and water sourced at the farm were considered to represent general background contaminant levels as there were no known PFAS point sources, e.g., biosolids spreading, or any other known PFAS sources on the farm (Vestergren et al. 2013). The average PFOS concentrations in silage, barley, and water were 6.3 ng/kg wet weight, 3.9 ng/kg wet weight, 0.073 ng/L, respectively. PFOS levels in dietary supplements were below the limit of detection. Average feed and water intake for cows on the farm were 38.5 kg/day wet weight for silage, 8.8 kg/day wet weight for barley, 8.6 kg/day wet weight for supplements, and 50 L/day for water. Combining the average intakes with the corresponding PFOS levels at the 50th percentile of measured values, the study authors estimated median daily PFOS intakes of 260 ng/day from silage, 31 ng/day from barley, 9 ng/day from supplements (a value of one-half the method detection limit was used for a PFOS concentration in supplements), and 3.6 ng/L from water. Total estimated PFOS intake from all feed and water was 303.6 ng/day. The average PFOS concentration in the cow's milk was 6.2 ng/L (6.02 ng/kg on a per mass basis). The resulting transfer factor, calculated as the PFOS milk concentration (ng/kg) divided by daily PFOS intake (ng/day), is 0.02 day/kg, reported in the study as Log -1.67 for comparison to several other contaminant transfer factors (Vestergren et al. 2013).

In a separate study, Kowalczyk et al. 2013 fed dairy cows' silage and hay harvested from fields with known PFAS contamination from spreading of contaminated fertilizer on a farm in Germany. Six dairy cows with no known PFAS exposure were fed PFAS-contaminated feed for 28 days (Kowalczyk et al. 2013). The average daily PFOS intake from PFOS-contaminated grass silage and hay was 4,473,000 ng/day. During the feeding period PFOS in the cow's milk steadily increased from below the limit of detection to an average of 24,200 ng/L on day 28. A milk transfer factor of 0.005 day/kg can be calculated from this study using the average daily PFOS intake and average milk PFOS concentration at the end of the feeding study, a value that is 4-fold lower than the estimate derived from the Vestergren et al. study. However, in the 28-day feeding study achievement of steady-state levels was unlikely as PFOS plasma and milk levels continued to increase over a 21-day depuration phase. Based on a physiologically based pharmacokinetic (PBPK) model developed from the 28-day feeding study, steady state PFOS levels would be not be reached until 2 to 4.5 months depending on the daily milk yield (van Asselt et al. 2013). Steady-state milk transfer factors based on PBPK model estimated milk concentrations at a 3,000,000 ng/day PFOS intake are 0.08, 0.04, and 0.02 day/kg for 12.5, 25, and 50 L/day milk yields, respectively. These estimated steady-state milk transfer factors are similar or higher than the empirically derived steady-state transfer factors reported by Vestergren et al. 2013.

Milk density

To convert the milk action level from a mass per volume concentration (ng/L) to a mass per mass concentration (ng/kg) a cow's milk density of 1.03 kg/L was selected. This milk density value is the default value in the EPA PRGR equation. The 210 ng/L PFOS milk action level is 203.9 ng/kg on a mass per mass basis.

Soil-to-plant transfer factor

Individual soil-to-plant transfer factors were selected for hay and corn silage. The selected soil-to-hay transfer factor for PFOS is 0.07. This transfer factor was derived from a study assessing the accumulation of PFASs in several different plant species grown in biosolid-amended fields in Decatur, Alabama (Yoo et al. 2011). Kentucky Blue grass, Tall Fescue, and Bermuda grass were collected from several farm fields with PFOS soil concentrations ranging from 35,000 to 203,000 ng/kg dry weight. Samples consisted of only the above-ground portion of the grasses. The grass samples were examined in the laboratory for any dust, dirt or stains on the plants. No exterior material was found on the plants. PFOS concentrations measured in the grasses ranged from 1,200 to 20,400 ng/kg dry weight. Using the grass and soil PFOS concentration data, the study authors calculated an arithmetic mean grass/soil accumulation factor for PFOS of 0.07 with a range of 0.034 to 0.13 (Yoo et al., 2011). Although there is some variation in the calculated transfer factor depending on the grass and field sampled the average 0.07 (0.04 standard deviation) value is likely a reasonable estimate as is it based on empirical data from a contaminated farm field exposure setting.

The use of a 0.07 soil-to-hay transfer factor for PFOS is supported by a German field study. The Ministry for Environment, Agriculture, Conservation and Consumer Protection of the State of North Rhine-Westphalia conducted a PFAS plant uptake study to assess potential food source contamination through PFAS contaminated soil (Fischer et al. 2008 and Fischer et al. 2009). PFAS transfer was evaluated in German ryegrass, corn, potatoes and summer wheat. Plants were grown in large individual box lysimeters in an outdoor field setting with soil obtained from an area impacted by the spreading of a soil conditioner contaminated with PFAS from an industrial waste source. Three soil variants a control soil, a moderately loaded soil and a highly loaded soil with increasing concentrations of PFOS were used to grow plants. The initial study was conducted in 2007 with a supplemental study conducted the following growing season in 2008 by allowing grass to regrow and replanting corn in the same plots. Grasses and corn plants were cut approximately 5 centimeters (cm) above the soil to help ensure that plant material was free of exterior dirt (Fischer et al. 2008). Average PFOS soil concentrations across the two study years in the grass plots were 17,700, 471,500, and 3,681,800 ng/kg dry weight in the control, moderately loaded, and highly loaded soils, respectively. Average PFOS grass concentrations were 1,400 ng/kg dry weight in the control soil, 36,900 ng/kg dry weight in the moderately loaded soil and 938,800 ng/kg dry weight in the highly loaded soil. The average soil-to-grass PFOS transfer factors were 0.079 in control soil, 0.078 in moderately loaded soil and 0.26 in heavily loaded soil (Fischer et al. 2009). The 0.26 transfer factor in the heavily loaded soil with an average PFOS concentration of 3,681,800 ng/kg dry weight is approximately 3-fold higher than the transfer factors observed in the control and moderately loaded soils with lower PFOS concentrations. The PFOS soil concentrations in the control and moderately loaded soil in the German field study are similar to those measured in the field study in Decatur, Alabama ranging from 35,000 to 203,000 ng/kg dry weight; and both studies find similar grass transfer factors at these PFOS soil levels.

For the soil-to-corn silage transfer factor a value of 0.02 is selected from the Germany field study. Mature corn plants were harvested with the intent that the plants would be used as corn silage for animal feed. Average PFOS soil concentrations across the two study years in the corn plots were 25,200, 472,900, and 3,155,900 ng/kg dry weight in the control, moderately loaded, and highly loaded soils, respectively. The average PFOS concentration in corn silage from control soil was 350 ng/kg dry weight, 14,200 ng/kg dry weight in moderately loaded, and 200,400 ng/kg dry weight in highly loaded soil. The soil-to-corn silage transfer factors calculated in the study across the two years were 0.014 for control soil, 0.030 for moderately loaded soil, and 0.063 for the highly loaded soil. These results suggest there may be a concentration dependent relationship between PFOS in soil and uptake into corn plants. Both grass and corn grown in the highly loaded soil resulted in the highest PFOS transfer into the plant. To date, soil PFOS levels measured in farm fields in Maine have been well below the average PFOS level in highly loaded soil of 3,155,900 ng/kg dry weight in this field study. The control and moderately loaded soil PFOS levels are more in line with levels measured in Maine soils. Thus, the average soil-to-corn silage transfer factor of 0.02 from the control and moderately loaded soils was selected over the average transfer factor of 0.04 across all three soils in this study.

In a separate pilot field trial study where biosolids had been applied to fields used to grow corn, PFOS concentrations in both soil and corn were measured to determine plant uptake (Blaine et al. 2013). PFOS soil concentrations in five fields ranged from 960 to 4,330 ng/kg dry weight. PFOS levels in the corn stover (stalks, leaves, and husks) were below the limit of quantitation (140 ng/kg dry weight) from all fields. While this study was unable to detect any PFOS in corn stover, it does provide some support for the lower transfer factor of 0.02 from the German field study. For example, at the highest soil concentration in this field study of 4,330 ng/kg dry weight use of the 0.02 corn silage transfer factor would predict a PFOS corn plant concentration of 87 ng/kg dry weight, which is below the study's limit of quantitation. Whereas use of 0.04 for the PFOS transfer factor results in a predicted concentration of 174 ng/kg dry weight just above the limit of quantitation with a soil level of 4,330 ng/kg dry weight.

Soil plant mass loading factor

The default EPA value for the mass of soil that adheres to pasture plant matter, the soil plant mass loading factor (MLF), is 0.25 grams (g) dry soil/g dry plant (USEPA 2017). This default value is based on a 1992 review and summary of several studies that measured soil mass loadings in pasture plants (Hinton 1992). The studies measuring soil plant mass loading typically employ a radioactive tracer method where a radioisotope that is abundant in the soil but poorly taken up into plants, such as plutonium (^{238}Pu), is measured in the soil and plants to calculate exterior soil mass loading. The MLF from the reviewed studies for pasture plants ranged from <0.001 to 0.5 g dry soil/g dry plant (Appendix 2, Table 1). The EPA default 0.25 pasture-specific MLF value is described as the median of the <0.001 and the 0.5 g dry soil/g dry plant loading factors (Manning et al. 2016). Since the 1992 review provides separate MLF estimates from each study, the arithmetic and geometric means were calculated for comparison to the EPA default value. The arithmetic and geometric mean MLF from the 11 provided values is 0.11 and 0.034, respectively (Appendix 2, Table 1). Rather than use the EPA default value - the average of only the lowest (<0.001) and highest (0.5) MLF values provided - the geometric mean value of 0.034 was selected as the representative MLF for hay. As the MLF data for pasture plants are skewed, the geometric mean provides a central tendency estimate that is less influenced by extreme values as compared to the arithmetic mean.

A single study was identified that examined soil mass loading onto corn plants grown in farm fields with a calculated MLF of 0.0014 g dry soil/g dry plant (Pinder and McLeod 1989). Crops, including corn, were grown on two separate agricultural fields in the southern U.S. Soil mass loadings were calculated on corn plants at the time of harvest in the two fields over the course of four individual harvest times. Soil mass loading factors were calculated based on the measured concentrations of ^{238}Pu on the corn plant and the concentration calculated in the suspendable fraction of the soil in the two fields. The average soil mass loading at harvest for corn plants was 0.0014 g dry soil/g dry plant (Pinder and McLeod 1989). The lower MLF for corn plants, relative to hay, is likely due to the taller growth form of the corn plant as compared to shorter plants where most of the plant mass is closer to the ground (Pinder and McLeod 1989).

Fodder intake rates

Separate fodder intake rates for hay and corn silage were used to model a grass-based farming scenario in which the dairy cattle diet is largely grass-based, and a more typical average dairy farm practice with a greater use of corn silage. For the grass-based farming scenario, a hay intake rate of 13.2 kg dry weight/day and a corn silage intake rate of 4.1 kg dry weight/day were utilized. These two values are based on the total fodder intake rate of 20.3 kg dry weight/day used in the default EPA PRGR exposure scenario for dairy cattle. The total intake rate is the sum of EPA intake estimates of

13.2 kg dry weight/day for forage (pasture grass and hay), 4.1 kg dry weight/day for silage (forage stored and fermented), and 3.0 kg dry weight/day for grain (USEPA 2017 and USEPA 2005). The EPA intake estimate of silage assumed to be from forage plants was applied to corn silage for the grass-based farming scenario.

For a more typical dairy farm in Maine, fodder intake estimates of 6.5 kg dry weight/day hay, 8.7 kg dry weight/day corn silage, and 8.2 kg dry weight/day grain were provided by the University of Maine, School of Food and Agriculture (personal communication, email from David Marcinkowski, June 10, 2019).

Soil intake rates

The EPA PRGR default soil intake rate is 0.4 kg/day, calculated as 2% of total dry matter intake (20.3 kg dry weight/day) for dairy cattle (USEPA 2017 and USEPA 2005). For soil intake in the grass-based farm scenario, the 2% factor was applied to the 13.2 kg dry weight/day hay intake rather than the total fodder intake value of 20.3 kg dry weight/day. This results in a soil intake value of 0.26 kg/day for this scenario under the assumption that the cow's hay or grass intake will occur during grazing periods on the farm where there will be direct contact with PFOS contaminated soil. In the average Maine farm scenario, a soil intake rate of 0.13 kg/day was calculated as 2% of hay intake at 6.5 kg dry weight/day. For corn-silage, it was assumed that no grazing will occur in fields planted in corn and no soil intake from grazing was included when deriving the crop-specific corn-silage soil screening level.

Exposure fractions

For the fodder intake exposure time terms, values of 1 were used for the Fraction of fodder from contaminated land and Fraction of year animal fed contaminated fodder. Values of 1 for these terms assume that 100% of the feed for a dairy cow is sourced from farmland with contaminated soil and the dairy cow is fed contaminated feed year-round. For the soil intake exposure time terms, a value of 1 was used for the Fraction of grazing on contaminated land and 0.5 used for the Fraction of year animal spends grazing. A value of 0.5 for yearly grazing time better reflects grazing in Maine as year-round grazing typically does not occur due to climate conditions.

Table 1. Summary of parameter inputs to calculate soil screening levels for the soil-to-fodder-to-cow's milk agronomic pathway.

Parameter (units)	Value	Source
Concentration in cow's milk (ng/L)	210	Maine CDC PFOS adulterated milk action level
Milk transfer factor (day/kg)	0.02	Vestergren et al. 2013
Milk density (kg/L)	1.03	EPA default value
Fodder intake rate (kg/day)		
Grass-based scenario		
Hay	13.2	EPA default estimates
Corn silage	4.1	
Average Maine scenario		
Hay	6.5	Maine-specific estimates
Corn silage	8.7	
Fraction of fodder from contaminated land (unitless)	1	EPA default value
Fraction of year animal fed contaminated fodder (unitless)	1	EPA default value
Soil-to-plant transfer factor (ng/kg dry plant/ng/kg dry soil)		
Hay	0.07	Yoo et al. 2011
Corn silage	0.02	Fischer et al. 2008/2009
Soil plant mass loading factor (g dry soil/g dry plant)		
Hay	0.034	Hinton, T.G. 1992
Corn silage	0.0014	Pinder and McLeod 1989
Soil intake rate (kg/day)		
Grass-based scenario	0.26	Adjusted EPA default estimates
Average Maine scenario	0.13	
Fraction of grazing on contaminated land (unitless)	1	EPA default value
Fraction of year animal spends grazing (unitless)	0.5	Maine-specific estimate

3. Soil screening levels

Individual crop soil screening levels

Table 2. PFOS crop-specific soil screening levels.

Exposure scenario	Hay soil screening level (ng/kg dry weight)	Corn-silage soil screening level (ng/kg dry weight)
Grass-based farm	6,800	120,000
Average Maine farm	13,800	54,800

Combined total soil screening levels

Table 3. Combined total PFOS soil screening levels.

Exposure scenario	Soil screening level (ng/kg dry weight)
Grass-based farm	6,400
Average Maine farm	11,000

4. Model checking

The DEP's RAGs are developed using EPA's Regional Screening Levels for Chemical Contaminants at Superfund Sites (RSL) calculator. The EPA RSL for chemical contaminants does not include agronomic exposure pathways to develop screening levels for farming scenarios. As this agronomic exposure pathway is outside the standard framework to develop the DEP RAGs, it's important to consider ground-truthing the overall model when data is available. At a dairy farm in Maine, Stoneridge Farms, measured levels of PFOS in milk, soil, hay, and water are available to conduct a model checking exercise. With a measured PFOS milk level at a farm the agronomic pathway equation and inputs can be used to calculate a corresponding soil PFOS concentration at the farm. The model-estimated soil concentration can then be compared to measured soil levels.

The Stoneridge Farms case represents more of a grass-based farming scenario where hay is the primary fodder source grown on-site. To best model dairy cattle fodder exposure at Stoneridge Farms calculations were performed using only exposure from hay intake and grazing on contaminated land. The initial PFOS milk concentration in a sample from the Stoneridge Farm's milk tank was 1,420 ng/L. A confirmatory sampling two months after the initial sampling found PFOS levels in the farm's milk tank of 938 ng/L and 690 ng/L in duplicate samples. With the initial sample of 1,420 ng/L PFOS and the average of the duplicate samples, 814 ng/L, the average PFOS milk PFOS concentration from the initial and confirmatory samplings is 1,117 ng/L. At a PFOS milk concentration of 1,117 ng/L the model estimates a PFOS soil concentration of 36,100 ng/kg dry weight. Measured PFOS soil concentrations in the Stoneridge farm fields vary across the site. The farm is transected by a north-south running road and the farm field areas can generally be broken out into westside and eastside fields. PFOS levels in fifteen soil samples collected from the westside fields ranged from 3,580 to 878,000 ng/kg dry weight. On the eastern side, four soil samples were collected with PFOS levels ranging from 566 to 5,400 ng/kg dry weight. Considering this variation, the model-estimated soil PFOS concentration of 36,100 ng/kg dry weight falls within the range of PFOS soil levels measured at the farm; and compares reasonably well to site-wide average PFOS soil levels at either the geometric mean of 25,000 ng/kg dry weight or the arithmetic mean of 123,000 ng/kg dry weight at the farm.

These milk-to-soil comparisons assume the only source of PFOS exposure is from feed. At Stoneridge Farms the initial milk concentrations described above were likely also influenced by exposure through the herds drinking water, albeit to a lesser extent than exposure from feed. The herds drinking water from the farm's well had a measured PFOS level of 42 ng/L. Based on the EPA PRGR default water intake rate of 92 L/day for a dairy cow and the 0.02 PFOS milk transfer factor at a PFOS water level of 42 ng/L the estimated milk PFOS concentration is 80 ng/L. This water source would only account for approximately 10% of the PFOS found in the farm's milk during the initial sampling events.

5. Site-specific considerations

As a general screening level approach, the soil screening levels for both exposure scenarios assume that all feed is sourced from areas on the farm with contaminated soil and the contaminated feed source is used year-round. All grazing is also assumed to occur in areas with contaminated soil for half of the year (the yearly time spent grazing is adjusted to 0.5 to account for the climate in Maine where grazing is not likely to occur year-round due to snow cover). Where farm-specific data are available for these exposure time parameters they can be adjusted accordingly to calculate a farm-specific soil screening level. For example, if a farm utilized only a third of their land to spread biosolids contaminated with PFOS and sources its feed for dairy cattle from this portion of land as well as the remaining uncontaminated land the fraction of fodder from on-site parameter can be adjusted to 0.3. A value of 0.3 for the fraction of fodder from on-site parameter would increase the soil screening level for the average Maine dairy farm scenario from 11,000 to 32,000 ng/kg dry weight. The fraction of year the animal is fed contaminated fodder may also be adjusted from the default value of 1 with farm-specific data. If grazing occurs at a farm where the herd is contained to areas with no known PFOS soil contamination the fraction on-site grazing term can be adjusted to a value <1 depending on the time the herd spends grazing on uncontaminated versus contaminated pasture.

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Appendix 1.

Equations as listed in the EPA Preliminary Remediation Goals for Radionuclides (https://epa-prgs.ornl.gov/radionuclides/equations.html) - note default values listed and different abbreviations for some parameters in the below EPA PRG equations.

Dairy consumption back-calculated to soil equation:

$$\mathrm{PRG}_{\text{soil-far-dairy-ing}}\left(\mathrm{pCi/g}\right) = \frac{\mathrm{PRG}_{\text{far-dairy-ing}}\left(\mathrm{pCi/g}\right)}{\mathrm{TF}_{\text{dairy}}\left(\frac{\text{day}}{\text{L milk}}\right) \times \rho_{m}\left(\frac{1.03\ \text{kg}}{1\ \text{L milk}}\right)^{-1} \times \left[\begin{array}{l}\left(Q_{\text{p-dairy}}\left(\frac{20.3\ \text{kg}}{\text{day}}\right) \times f_{\text{p-dairy}}(1) \times f_{\text{s-dairy}}(1) \times \left(R_{\text{upp}} + R_{\text{es}}\right)\right) + \\ \left(Q_{\text{s-dairy}}\left(\frac{0.4\ \text{kg}}{\text{day}}\right) \times f_{\text{p-dairy}}(1)\right)\end{array}\right]}$$

where:

$$R_{\text{upp}} = \mathrm{Bv}_{\text{dry}}\left(\frac{\text{pCi / g-dry plant}}{\text{pCi / g-dry soil}}\right);\ R_{\text{es}} = \mathrm{MLF}_{\text{pasture}}\left(\frac{0.25\ \text{g-dry soil}}{\text{g-dry plant}}\right)$$

Total soil PRG equation:

$$\mathrm{PRG}_{\text{soil-far-tot}}\left(\mathrm{pCi/g}\right) = \frac{1}{\begin{array}{l}\frac{1}{\mathrm{PRG}_{\text{soil-far-sol-ing}}} + \frac{1}{\mathrm{PRG}_{\text{soil-far-sol-inh}}} + \frac{1}{\mathrm{PRG}_{\text{soil-far-sol-ext}}} + \frac{1}{\mathrm{PRG}_{\text{soil-far-produce-ing-tot}}} + \frac{1}{\mathrm{PRG}_{\text{soil-far-egg-ing}}} + \\ \frac{1}{\mathrm{PRG}_{\text{soil-far-poultry-ing}}} + \frac{1}{\mathrm{PRG}_{\text{soil-far-fish-ing}}} + \frac{1}{\mathrm{PRG}_{\text{soil-far-beef-ing}}} + \frac{1}{\mathrm{PRG}_{\text{soil-far-dairy-ing}}} + \frac{1}{\mathrm{PRG}_{\text{soil-far-swine-ing}}}\end{array}}$$

Default values as listed in the EPA Preliminary Remediation Goals for Radionuclides for the Dairy consumption back-calculated to soil equation (https://epa-prgs.ornl.gov/radionuclides/users_guide.html):

Symbol	Definition (units)	Default	Reference
TF_{dairy}	Dairy Transfer Factor (day/L)	radionuclide-specific	hierarchy selection in Section 2.4.2
ρm	Density of milk (kg/L)	1.03	Milk Composition & Synthesis Resource Library
Qp_{-dairy}	Dairy Fodder Intake Rate (kg/day)	20.3	U.S. EPA 2005 (pg. B-145)
fp_{-dairy}	Animal On-site Fraction - dairy (unitless)	1	Developed for this calculator
fs_{-dairy}	Fraction of Year Animal On-site - dairy (unitless)	1	Developed for this calculator
R_{upp}	Dry root uptake for pasture multiplier (pCi/g-dry plant per pCi/g-dry soil)	radionuclide-specific (=Bv_{dry})	hierarchy selection in Section 2.4.2
R_{es}	Soil resuspension multiplier (g dry soil per g fresh plant)	=MLF (pasture or produce)	Hinton 1992
Qs_{-dairy}	Dairy Soil Intake Rate (kg/day)	0.4	U.S. EPA 2005 (pg. B-146)
$MLF_{pasture}$	Pasture Plant Mass Loading Factor (g dry soil per g dry plant)	0.25	Hinton 1992
Bv_{dry}	Soil to Plant Transfer Factor - dry (pCi/g-dry plant per pCi/g-dry soil)	radionuclide-specific	hierarchy selection in Section 2.4.2

Appendix 2.

Table 1. Soil mass plant loading factors for plants in pastures from assorted studies (adapted from Hinton, T.G. 1992).

Locations	Technique	Mass loading factor (g soil/g dry plant)
South Carolina	Pu - tracer	0.009
Sellafield, UK	Ti - tracer	0.07
Sellafield, UK - upland/lowland site	Ti - tracer	0.18
Sellafield, UK - summer	Ti - tracer	0.03
Sellafield, UK - winter	Ti - tracer	0.3
Norway - summer [a]	Sc - tracer	<0.001 (0.0005 used as an estimate)
Byelorussia, June 1986	Sc - tracer	0.3 - 0.5 (0.4 average used as single estimate)
Sellafield, UK	^{182}Ta - tracer, Ashing	0.05 - 0.2 (0.125 average used as single estimate)
Colorado - winter	Washing	0.013
Colorado - fall	Washing	0.044
Colorado - spring	Washing	0.005
All locations/studies combined	Arithmetic mean	0.11
	Geometric mean	0.034

[a] The provided MLF from the Norway summer study is <0.001. To estimate a numerical value from this study a value of ½ of 0.001 was selected.

Appendix 3. Equations and calculations for soil-to-fodder-to-cow's milk screening levels (SL).

Equation 1. Soil-to-cow's milk through contaminated fodder soil SL.

$$SL_{soil}\left(\frac{ng}{kg}\right)=\frac{C_{milk}\,(ng/L)\times\left(\dfrac{1}{D_{milk}\left(\frac{kg}{L}\right)}\right)}{TF_{milk}\left(\dfrac{day}{kg}\right)\times\left[\left(I_{fodder}\left(\dfrac{kg}{day}\right)\times F_{land-f}\times F_{year-f}\times\left(TF_{plant}\left(\dfrac{\frac{ng}{kg}\,dry\ plant}{\frac{ng}{kg}\,dry\ soil}\right)+MLF\left(\dfrac{g\ dry\ soil}{g\ dry\ plant}\right)\right)\right)+\left(I_{soil}\left(\dfrac{kg}{day}\right)\times F_{land-g}\times F_{year-g}\right)\right]}$$

where:

SL_{soil} = Soil screening level (ng/kg dry weight)[3]
C_{milk} = Concentration in cow's milk (ng/L)
D_{milk} = Density milk (kg/L)
TF_{milk} = Milk transfer factor (day/kg)
I_{fodder} = Fodder intake rate (kg/day)
F_{land-f} = Fraction of fodder from contaminated land (unitless)
F_{year-f} = Fraction of year animal fed contaminated fodder (unitless)
TF_{plant} = Soil-to-plant transfer factor (ng/kg dry plant/ng/kg dry soil)
MLF = Soil plant mass loading factor (g dry soil/g dry plant)
I_{soil} = Soil intake rate (kg/day)
F_{land-g} = Fraction of grazing on contaminated land (unitless)
F_{year-g} = Fraction of year animal spends grazing (unitless)

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[3] From EPA PRGs "The soil PRGs are based on dry weight because the soil intake rates are based on dry weight. Most soil data is typically reported as dry weight" (https://epa-prgs.ornl.gov/radionuclides/faq.html#FAQ14).

Table 1. Inputs for soil screening level (SL) calculations for the grass-based farm scenario and average Maine farm scenario.

	Grass-based farm scenario		Average Maine farm scenario	
Parameter (units)	Soil-to-hay SL inputs	Soil-to-corn silage SL inputs	Soil-to-hay SL inputs	Soil-to-corn silage SL inputs
C_{milk} Concentration in cow's milk (ng/L)	210	210	210	210
D_{milk} Milk density (kg/L)	1.03	1.03	1.03	1.03
TF_{milk} Milk transfer factor (day/kg)	0.02	0.02	0.02	0.02
I_{fodder} Fodder intake rate (kg/day)	13.2	4.1	6.5	8.7
$F_{land\text{-}f}$ Fraction of fodder from contaminated land (unitless)	1	1	1	1
$F_{year\text{-}f}$ Fraction of year animal fed contaminated fodder (unitless)	1	1	1	1
TF_{plant} Soil-to-plant transfer factor (ng/kg dry plant/ng/kg dry soil)	0.07	0.02	0.07	0.02
MLF Pasture plant mass loading factor (g dry soil/g dry plant)	0.034	0.0014	0.034	0.0014
I_{soil} Soil intake rate (kg/day)	0.26	0	0.13	0
$F_{land\text{-}g}$ Fraction of grazing on contaminated land (unitless)	1	1	1	1
$F_{year\text{-}g}$ Fraction of year animal spends grazing (unitless)	0.5	0.5	0.5	0.5

Equation 2. Reciprocal summing equation.

$$SL_{soil\ total}\left(\frac{ng}{kg}\right) = \left(\frac{1}{\frac{1}{SL_{soil-to-hay}\,(ng/kg)} + \frac{1}{SL_{soil-to-corn\ silage}\,(ng/kg)}}\right)$$

where:

$SL_{soil\ total}$ = Combined total soil screening level (ng/kg dry weight)
$SL_{soil\ -to-hay}$ = Soil-to-hay specific soil screening level (ng/kg dry weight)
$SL_{soil\ -to-corn\ silage}$ = Soil-to-corn silage specific soil screening level (ng/kg dry weight)

Table 2. Inputs for total soil SL calculations for the grass-based farm scenario and average Maine farm scenario.

Parameter (units)		Grass-based farm scenario	Average Maine farm scenario
$SL_{soil\ -to-hay}$	Soil-to-hay specific soil screening level (ng/kg)	6784.003	13758.435
$SL_{soil\ -to-corn\ silage}$	Soil-to-corn silage specific soil screening level (ng/kg)	116195.578	54758.836

Soil SL calculations for the grass-based farm scenario.

1a. Grass-based farm scenario soil-to-hay SL calculation:

$$SL_{soil-to-hay} = \frac{210\ (ng/\cancel{L}) \times \left(\frac{1}{1.03\left(\frac{kg}{\cancel{L}}\right)}\right)}{0.02\left(\frac{day}{kg}\right) \times \left[\left(13.2\left(\frac{kg}{day}\right) \times 1 \times 1 \times \left(0.07\left(\frac{\cancel{\frac{ng}{kg}\,dry\ plant}}{\cancel{\frac{ng}{kg}\,dry\ soil}}\right) + 0.034\left(\frac{\cancel{g\ dry\ soil}}{\cancel{g\ dry\ plant}}\right)\right)\right) + \left(0.26\left(\frac{kg}{day}\right) \times 1 \times 0.5\right)\right]}$$

$$SL_{soil-to-hay} = \frac{203.9\ (ng/kg)}{0.02\left(\frac{day}{kg}\right) \times \left[\left(13.2\left(\frac{kg}{day}\right) \times (0.104)\right) + \left(0.13\left(\frac{kg}{day}\right)\right)\right]}$$

$$SL_{soil-to-hay} = \frac{203.9\ (ng/kg)}{0.02\left(\frac{day}{kg}\right) \times \left[\left(1.3728\left(\frac{kg}{day}\right)\right) + \left(0.13\left(\frac{kg}{day}\right)\right)\right]}$$

$$SL_{soil-to-hay} = \frac{203.9\ (ng/kg)}{0.02\left(\frac{\cancel{day}}{\cancel{kg}}\right) \times \left[\left(1.5028\left(\frac{\cancel{kg}}{\cancel{day}}\right)\right)\right]}$$

$$SL_{soil-to-hay} = \frac{203.9\ (ng/kg)}{0.030056}$$

$$SL_{soil-to-hay} = 6784.003\ \ ng/kg$$

$$\boldsymbol{Rounded\ SL_{soil-to-hay}\ =\ 6,800\ \ ng/kg\ \ dry\ weight}$$

1b. Grass-based farm scenario soil-to-corn silage SL calculation:

$$SL_{soil-to-corn\ silage} = \frac{210\ (ng/\cancel{L}) \times \left(\frac{1}{1.03\left(\frac{kg}{\cancel{L}}\right)}\right)}{0.02\left(\frac{day}{kg}\right) \times \left[\left(4.1\left(\frac{kg}{day}\right) \times 1 \times 1 \times \left(0.02\left(\frac{\cancel{\frac{ng}{kg}\ dry\ plant}}{\cancel{\frac{ng}{kg}\ dry\ soil}}\right) + 0.0014\left(\frac{\cancel{g\ dry\ soil}}{\cancel{g\ dry\ plant}}\right)\right) + \left(\cancel{0\left(\frac{kg}{day}\right) \times 1 \times 0.5}\right)\right)\right]}$$

$$SL_{soil-to-corn\ silage} = \frac{203.9\ (ng/kg)}{0.02\left(\frac{day}{kg}\right) \times \left[\left(4.1\left(\frac{kg}{day}\right) \times (0.0214)\right)\right]}$$

$$SL_{soil-to-corn\ silage} = \frac{203.9\ (ng/kg)}{0.02\left(\cancel{\frac{day}{kg}}\right) \times \left[0.08774\left(\cancel{\frac{kg}{day}}\right)\right]}$$

$$SL_{soil-to-corn\ silage} = \frac{203.9\ (ng/kg)}{0.0017548}$$

$$SL_{soil-to-corn\ silage} = 116195.578\ \ ng/kg$$

$$\boldsymbol{Rounded\ SL_{soil-to-corn\ silage}\ =\ 120{,}000\ \ ng/kg\ dry\ weight}$$

1c. Grass-based farm scenario combined soil-to-hay and soil-to-corn silage total SL calculation:

$$SL_{soil\ total} = \frac{1}{\left(\frac{1}{6784.003\ (ng/kg)} + \frac{1}{116195.578\ (ng/kg)}\right)}$$

$$SL_{soil\ total} = \frac{1}{\left(0.000147406\ (ng/kg) + 0.0000086062\ (ng/kg)\right)}$$

$$SL_{soil\ total} = \frac{1}{0.000156012\ (ng/kg)}$$

$$SL_{soil\ total} = 6409.763\ \ ng/kg$$

$$\boldsymbol{Rounded\ SL_{soil\ total} = 6,400\ \ ng/kg\ dry\ weight}$$

Soil SL calculations for the average Maine farm scenario.

2a. Average Maine farm scenario soil-to-hay SL calculation:

$$SL_{soil-to-hay}=\frac{210\ (ng/\cancel{L})\times\left(\frac{1}{1.03\left(\frac{kg}{\cancel{L}}\right)}\right)}{0.02\left(\frac{day}{kg}\right)\times\left[\left(6.5\left(\frac{kg}{day}\right)\times 1\times 1\times\left(0.07\left(\cancel{\frac{\frac{ng}{kg}dry\ plant}{\frac{ng}{kg}dry\ soil}}\right)+0.034\left(\cancel{\frac{g\ dry\ soil}{g\ dry\ plant}}\right)\right)\right)+\left(0.13\left(\frac{kg}{day}\right)\times 1\times 0.5\right)\right]}$$

$$SL_{soil-to-hay}=\frac{203.9\ (ng/kg)}{0.02\left(\frac{day}{kg}\right)\times\left[\left(6.5\left(\frac{kg}{day}\right)\times(0.104)\right)+\left(0.065\left(\frac{kg}{day}\right)\right)\right]}$$

$$SL_{soil-to-hay}=\frac{203.9\ (ng/kg)}{0.02\left(\frac{day}{kg}\right)\times\left[\left(0.676\left(\frac{kg}{day}\right)\right)+\left(0.065\left(\frac{kg}{day}\right)\right)\right]}$$

$$SL_{soil-to-hay}=\frac{203.9\ (ng/kg)}{0.02\left(\cancel{\frac{day}{kg}}\right)\times\left[\left(0.741\left(\cancel{\frac{kg}{day}}\right)\right)\right]}$$

$$SL_{soil-to-hay}=\frac{203.9\ (ng/kg)}{0.01482}$$

$$SL_{soil-to-hay}=13758.435\ \ ng/kg$$

$$\boldsymbol{Rounded\ SL_{soil-to-hay}\ =\ 13,800\ \ ng/kg\ dry\ weight}$$

2b. Average Maine farm scenario soil-to-corn silage SL calculation:

$$SL_{soil-to-corn\ silage} = \frac{210\ (ng/\cancel{L}) \times \left(\frac{1}{1.03\left(\frac{kg}{\cancel{L}}\right)}\right)}{0.02\left(\frac{day}{kg}\right) \times \left[\left(8.7\left(\frac{kg}{day}\right) \times 1 \times 1 \times \left(0.02\left(\frac{\cancel{\frac{ng}{kg}\,dry\ plant}}{\cancel{\frac{ng}{kg}\,dry\ soil}}\right) + 0.0014\left(\frac{\cancel{g\ dry\ soil}}{\cancel{g\ dry\ plant}}\right)\right) + \left(\cancel{0\left(\frac{kg}{day}\right) \times 1 \times 0.5}\right)\right)\right]}$$

$$SL_{soil-to-corn\ silage} = \frac{203.9\ (ng/kg)}{0.02\left(\frac{day}{kg}\right) \times \left[\left(8.7\left(\frac{kg}{day}\right) \times (0.0214)\right)\right]}$$

$$SL_{soil-to-corn\ silage} = \frac{203.9\ (ng/kg)}{0.02\left(\cancel{\frac{day}{kg}}\right) \times \left[0.18618\left(\cancel{\frac{kg}{day}}\right)\right]}$$

$$SL_{soil-to-corn\ silage} = \frac{203.9\ (ng/kg)}{0.0037236}$$

$$SL_{soil-to-corn\ silage} = 54758.836\ \ ng/kg$$

$$\boldsymbol{Rounded\ SL_{soil-to-corn\ silage}\ =\ 54,800\ \ ng/kg\ dry\ weight}$$

2c. Average Maine farm scenario combined soil-to-hay and soil-to-corn silage total SL calculation:

$$SL_{soil\ total} = \frac{1}{\left(\frac{1}{13758.435\ (ng/kg)} + \frac{1}{54758.836\ (ng/kg)}\right)}$$

$$SL_{soil\ total} = \frac{1}{\left(0.000072683\ (ng/kg) + 0.000018262\ (ng/kg)\right)}$$

$$SL_{soil\ total} = \frac{1}{0.000090945\ (ng/kg)}$$

$$SL_{soil\ total} = 10995.657\ \ ng/kg$$

$$\boldsymbol{Rounded\ SL_{soil\ total}\ = 11,000\ \ ng/kg\ dry\ weight}$$