10.0 Farm Food Chain Module

10.1 Purpose and Scope

The Farm Food Chain Module predicts the accumulation of contaminants in the edible parts of plants through the uptake of constituents from soil and the deposition of vapor-phase and particle-bound constituents from the air. Concentrations are predicted for fruits and vegetables that are grown above ground, as well as for root vegetables. In addition, the module predicts the annual average contaminant concentrations in beef and milk products from cattle raised on farms. The concentrations in produce, beef, and milk are used as inputs to the Human Exposure Module to calculate the applied daily dose to human receptors that consume fruits and vegetables from home gardens or consume produce, beef, or milk produced on a farm. Figure 10-1 shows the relationship and information flow between the Farm Food Chain Module and the 3MRA modeling system.

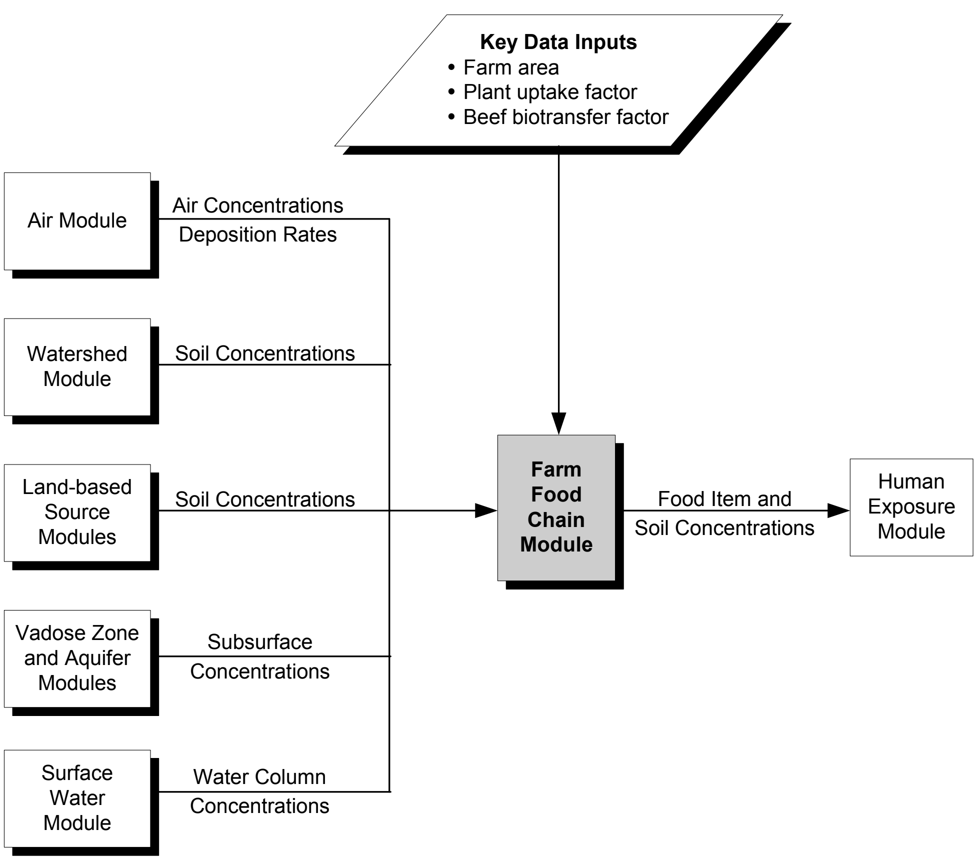

Figure 10-1. Information flow for the Farm Food Chain Module in the 3MRA modeling system.

The modeling construct for the Farm Food Chain Module is based on recent and ongoing research conducted by EPA ORD and presented in *Methodology for Assessing Health Risks Associated with Multiple Pathways of Exposure to Combustor Emissions* (U.S. EPA, 1998).

The Farm Food Chain Module performs the following four functions:

1. **Calculates contaminant concentrations in plants due to contaminants in air.** The Farm Food Chain Module calculates the contaminant concentration in plants due to the deposition of particle-bound and vapor-phase contaminants onto fruits, vegetables, and feed crops that grow above the ground.

2. **Calculates contaminant concentrations in plants due to contaminants in soil.** The Farm Food Chain Module calculates the contaminant concentration in plants due to uptake and translocation of contaminants in the soil into the edible parts of fruits, vegetables, and feed crops that grow above the ground.

3. **Calculates total contaminant concentrations in plants.** The Farm Food Chain Module sums plant concentrations across relevant mechanisms, including direct deposition of particle-bound contaminants, vapor-phase uptake, and translocation of contaminants from soil into the edible parts of plants.

4. **Calculates contaminant concentrations in beef and milk.** The Farm Food Chain Module calculates exposures to beef and dairy cattle through ingestion of contaminated forage, feed crops, soil, and drinking water, and the resulting beef and milk concentrations.

For each year in the simulation, the module predicts point estimates and spatially averaged contaminant concentrations within the area of interest (AOI). Point estimate concentrations are used to evaluate exposures of residential home gardeners that grow and eat fruits and/or vegetables within the AOI. The point estimates reflect the concentrations at locations of residential receptors that are used to represent the populations in various Census tracts throughout the AOI. The spatially averaged concentrations are used to evaluate exposures of farmers that raise and eat their own produce, beef, or milk products. The spatial averages reflect the concentrations at the farm boundaries delineated in the site layout that defines all of the characteristics of the AOI.

For both farmers and residential receptors, the Farm Food Chain Module predicts a time series of annual average concentrations of contaminants in fruits and vegetables.[1] With the exception of root vegetables, the categories of fruits and vegetables are designated as either “exposed” or “protected.” For the farm food chain modeling framework, the term “exposed” means that the contaminant concentrations in plants are calculated based on uptake and accumulation from aerial deposition, uptake during transpiration, and uptake from the soil. The

[1] Botanically, “fruit” refers to any part that develops from the flower (i.e., reproductive parts) and includes what are considered fruits as well as vegetables in terms of grocery items. For example, tomatoes, corn, and beans all develop from the flower and are thus all considered fruits in botanical terms. In the context of this discussion, the conventional grocery item terminology is used.

term "protected" means that the outer covering of the fruit or vegetable is not edible and serves as a barrier to contaminant transfer from air; therefore, the contaminant concentration in plants for protected fruits and vegetables is attributed only to the uptake of contaminants from the soil through the root system and subsequent translocation into the edible portions of the plant. Each of these categories is explained in further detail below.

- **Exposed vegetables.** The term "exposed vegetables" refers primarily to fruiting plants and edible vegetative parts of plants that are exposed directly to contaminant loadings from the air. For example, cucumbers, tomatoes, peppers, and green beans are included in the category of exposed vegetables, although all of these develop from flowers and are thus considered fruits in botanical terms.

- **Protected vegetables.** This category of vegetables includes plants with the edible part protected from airborne contaminants by a nonedible covering. For example, peas and lima beans are considered protected vegetables because their outer pod is not eaten, so the plant load in the edible portion is exclusively due to soil-to-plant transfer of contaminants. Aerial deposition is not included in calculating contaminant concentrations in protected vegetables.

- **Exposed fruits.** Exposed fruits include produce commonly referred to as "fruits" that have an edible outer skin. This category includes a number of tree fruits (e.g., apples, pears) and various vine fruits (e.g., strawberries, grapes). The plant concentration is a function of both the soil concentration and the concentration of contaminants in the air.

- **Protected fruits.** Protected fruits have limited relevance in many exposure scenarios because they include fruits with a fairly narrow range of growing climates. Although a variety of melons can be grown throughout much of the contiguous United States, other protected fruits, such as bananas, pineapples, and citrus fruit, are found only in the warmest regions of the country, such as Florida. As with protected vegetables, the concentration in the edible portion is exclusively due to soil-to-plant transfer of contaminants.

- **Root vegetables.** This category cuts across a number of botanical categories, including leaves, stems, and roots. The common theme for this category is that all of these vegetables grow below the soil surface. Consequently, a host of vegetables, such as potatoes (stem), onions (leaf), and carrots (root), are lumped together in this category. As with protected fruits and vegetables, the concentration in root vegetables is predicted based on the contaminant concentrations in soil.

In addition to calculating the concentrations in produce, the Farm Food Chain Module also generates a time series of annual average contaminant concentrations in beef and milk for each farm within the AOI. The beef and milk concentrations are calculated for beef and dairy cattle, respectively, and include three exposure pathways for cattle: (1) the consumption of contaminated feed crops (i.e., forage, grain, and silage), (2) incidental ingestion of contaminated soil while foraging, and (3) ingestion of contaminated drinking water from streams, ponds, or wells on the farm.

10.2 Conceptual Approach

As shown in Figure 10-2, contaminants may be released from waste management units (WMUs) into the air and subsequently deposit on soil and plants through wet and dry deposition. Plants may accumulate contaminants directly from the air through the deposition of both particle-bound and vapor-phase contaminants. In addition, this deposition may increase the contaminant concentrations in the soil over time, and plants may take up contaminants from the soil through the root system. Contaminants may be translocated as part of the transpiration stream to fruits and edible vegetative parts, or they may sorb directly to the outer skin of root vegetables. The Farm Food Chain Module performs the calculations for each of these uptake and accumulation mechanisms. The total contaminant concentration in plants will depend both on the category of plant being modeled (i.e., exposed versus protected) and the properties of the contaminant of concern. For example, the uptake and accumulation of dioxin-like chemicals from soil to edible parts of plants has been shown to be negligible because these chemicals are strongly sorbed to the organic fraction of soil. Because the behavior of each contaminant is, to a large degree, determined by its chemical properties, the Farm Food Chain Module uses both empirical data and regression algorithms to predict the uptake and accumulation of contaminants from environmental media into edible plant tissue.

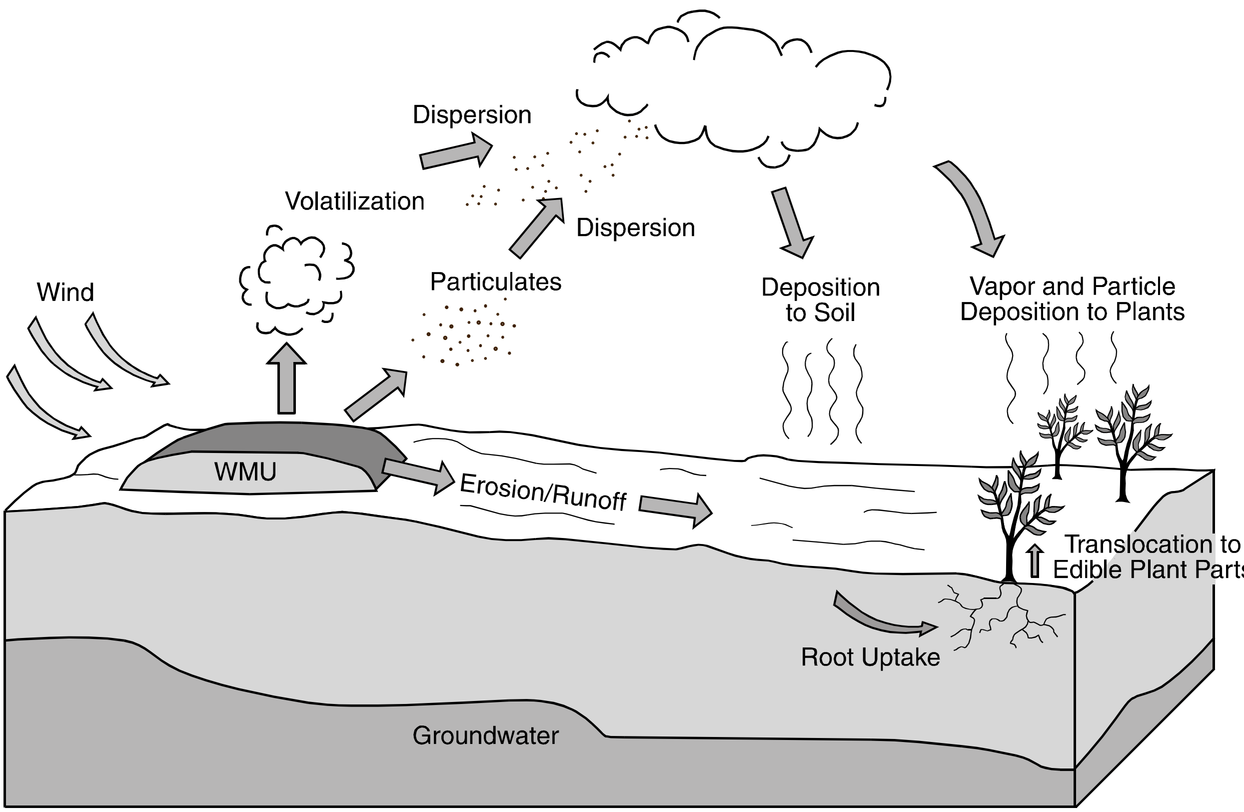

Figure 10-2. Release, exposure, and uptake mechanisms of contaminants in plants.

10.2.1 Calculate Contaminant Concentrations in Plants due to Contaminants in Air

Contaminants in the air may accumulate on the surface of plants by two mechanisms: particle-bound deposition and vapor-phase deposition. The algorithms used to simulate these processes and predict contaminant concentrations in exposed fruits, exposed vegetables, forage, and silage due to contaminants in air are described below. These processes are not considered for protected fruits, protected vegetables, or root vegetables.

The total plant load from air may be driven by either particle or vapor deposition, depending on the contaminant of concern. For example, metals released from a land application unit (LAU) can be deposited onto plant surfaces through particle-bound but not vapor-phase deposition. Therefore, the Farm Food Chain Module must include both of these mechanisms in calculating the contaminant load to plants from air. The deposition rates are calculated by the Air Module for the entire AOI; the areal average deposition rates for farms and average point estimates for residential receptor locations are provided by year.

Throughout this subsection, the subscript *i* refers to the following plant types:

- Exposed vegetables,
- Exposed fruits,
- Forage,
- Grains, and
- Silage.

Plant Concentrations from Deposition of Particle-Bound Contaminants. The plant concentration due to deposition of particle-bound contaminants in the air is calculated as a function of wet and dry deposition rates as follows:

$$C_{plant-dep^i} = \frac{1000 \times 365 \left(ParDryDep + ParWetDep \times FracAdhere^i \right) \times FracInt^i \times \left(1.0 - \exp^{\left(-kpPar^i \times LengthEx \right)} \right)}{Yield^i \times kpPar^i} \quad (10\text{-}1)$$

where

$C_{plant\_dep}^{i}$	=	concentration in plant *i* due to particulate deposition (mg/kg DW)
1000	=	units conversion factor (1,000 mg/g)
365	=	units conversion factor (365 d/yr)
ParDryDep	=	average dry deposition rate of particulates (g/m^2-d)
ParWetDep	=	average wet deposition rate of particulates (g/m^2-d)
$FracAdhere^i$	=	fraction of wet deposition that adheres to plant *i* (unitless)
$FracInt^i$	=	interception fraction for plant *i* (unitless)
$kpPar^i$	=	surface loss of particle-bound contaminant for plant *i* (1/yr)
$LengthEx^i$	=	length of plant exposure during the growing season for plant *i* (yr)
$Yield^i$	=	yield or standing crop biomass for plant *i* (kg DW/m^2).

The contaminants that reach the plant through dry deposition are assumed to remain on the plant surface until weathering occurs. In contrast, only a fraction of the contaminant from wet deposition remains on the plant's surface; the rest washes off immediately. This is reflected by the variable for the fraction of wet deposition that adheres to a plant's surface.

Not all airborne particles will contact a plant's edible surface; some will fall to the ground, others will fall on other surfaces that will undergo weathering processes, such as wind removal, water removal, and growth dilution, and most will end up in the soil or runoff. The interception fraction represents the fraction of airborne contaminants that make contact with the surface of the plant. The plant's surface can also lose contaminants due to weathering, and the aggregate losses from the plant surface are represented by the surface loss coefficient.

The duration of exposure for the plant is often determined by the growing season and is represented by the length of exposure of the plant to contaminants in the air. For instance, the exposure duration for a tomato begins when the flower begins to ripen and lasts until the tomato is harvested.

Finally, the plant biomass or yield represents the amount of standing crop assumed for a farm or residential garden, as appropriate.

Plant Concentrations from Deposition of Vapor-Phase Contaminants. As with particle-bound contaminants, vapor-phase deposition to plant surfaces occurs through wet and dry deposition processes. The mechanisms for wet and dry deposition are, to a large degree, dependent on the properties of the contaminant. Plant concentrations due to deposition of vapor-phase contaminants can be calculated two ways. For many organic chemicals, the form of the equation is essentially the same as the equation used to predict plant concentrations from particle-bound contaminants, as follows:

$$C_{plant-vap^i} = \frac{1000 \times \left(VapDryDep + VapWetDep \times FracAdhere^i \times 365\right) \times FracInt^i \left(1 - e^{\left(-kpVap \times LengthEx^i\right)}\right)}{Yield^i \times kpVap^i} \quad (10\text{-}2)$$

where

$C_{plant\_vap}^{i}$	=	concentration in plant *i* due to vapor deposition (mg/kg DW)
1000	=	units conversion factor (1,000 mg/g)
365	=	units conversion factor (365 d/yr)
VapDryDep	=	average dry deposition rate of vapor-phase contaminants (g/m^2-yr)
VapWetDep	=	average wet deposition rate of vapor-phase contaminants (g/m^2-d)
$FracAdhere^i$	=	fraction of wet deposition that adheres to plant *i* (unitless)
$FracInt^i$	=	interception fraction for plant *i* (unitless)
$kpVap^i$	=	surface loss of vapor-phase contaminant for plant *i* (1/yr)
$LengthEx^i$	=	length of plant exposure during the growing season for plant *i* (yr)
$Yield^i$	=	yield or standing crop biomass for plant *i* (kg DW/m^2).

The variables have the same function as previously described for the particulate-phase equation above.

For organic chemicals with a high affinity for lipid tissue, the mechanism of uptake and accumulation of vapor-phase organics for plants is not accurately described by the term "deposition." Evidence has shown that these compounds can be essentially stripped from the air simply by coming in contact with vegetation. An alternative model for the dry deposition of vapor-phase organic compounds is termed the "transfer" approach. This model describes the plant concentration in terms of air-to-plant transfer rather than physical deposition on plant surfaces. Further, EPA has demonstrated that wet deposition of vapor-phase lipophilic compounds can be considered negligible. Consequently, the plant concentration for lipophilic organic chemicals (functionally defined as those contaminants with an octanol-water partition coefficient greater than or equal to 100,000) is calculated as follows:

$$C_{plant\_vap^i} = \frac{Cair_{vapor} \times BTF_{air-plant^i} \times ECF_{exposed^i}}{1000 \times \rho_{air}} \tag{10-3}$$

where

$C_{plant\_vap^i}$	=	concentration in plant *i* due to vapor transfer into plant (mg/kg DW)
C_{air_vapor}	=	vapor-phase concentration in air (μg/m^3)
$BTF_{air\_plant^i}$	=	contaminant-specific air-to-plant biotransfer factor for plant *i* ([μg/g DW]/[μg/g air])
$ECF_{exposed^i}$	=	empirical correction factor to convert the air-to-plant biotransfer factor derived for leafy vegetation to a value for plant *i* (unitless)
1,000	=	units conversion factor (L/m^3)
ρ_{air}	=	density of air (constant at 1.19 g/L).

The dry deposition rate of vapor-phase, organic chemicals is not currently calculated by the Air Module. Rather, it is estimated from the vapor-phase concentration in air using the methods presented in U.S. EPA (1998), as follows:

$$VapDryDep = 0.31536 \times CvAve \times VapDdv \tag{10-4}$$

where

VapDryDep	=	average dry deposition rate of vapors (g/m^2-yr)
0.31536	=	units conversion factor ((m/yr)/(cm/s) and (g/μg))
CvAve	=	vapor-phase concentration in air (μg/m^3)
VapDdv	=	vapor phase dry deposition velocity - default value of 1 (cm/s).

The air-to-plant biotransfer factor describes the relationship between the contaminant concentration in exposed plant parts and the vapor-phase contaminant concentration in air. It may be calculated from chemical-physical properties (as it is for most organic chemicals), or it may be derived using empirical data in the open literature or EPA sources. The empirical correction factor (ECF) for each plant category *i* reflects the fact that experiments have shown that lipophilic, persistent organics such as polycyclic aromatic hydrocarbons (PAHs) and dioxins tend not to translocate from the outer surfaces of plants to inner plant parts. Without this adjustment, the biotransfer factor would be inappropriately high (i.e., it would overpredict the contaminant concentration in the inner parts of the plant). The ECF may be further adjusted to account for washing and peeling of fruits and vegetables that reduce contaminant residues in the outer skin. However, the contaminant-specific data set available to the 3MRA modeling system does not currently include washing and peeling losses in the empirical adjustment factor for aboveground plants. For many organic chemicals, the correction factor is simply set to 1, indicating that the contaminant is efficiently translocated to the inner plant parts. See Volume II of this report for further details.

10.2.2 Calculate Contaminant Concentrations in Plants due to Contaminants in Soil

Contaminant releases to soil from WMUs may occur through aerial deposition, as well as through erosion and runoff mechanisms. Over time, the contaminant concentration in soil may increase, with a resultant increase in the contaminant concentrations in the edible parts of plants. Depending on the properties of a given contaminant and the physiology of exposed vegetation, plants may take up aqueous-phase contaminants in the soil through the roots and subsequently translocate them to edible plant parts. The plant concentration is a function of the contaminant concentration in the root zone soil and the soil-to-plant bioconcentration factor, as follows:

$$C_{plant\_soil^i} = C_{soil\_RZ} \times BCF_{soil-plant^i} \qquad (10\text{-}5)$$

where

$C_{plant\_soil^i}$	=	plant concentration uptake from soil and translocation (mg/kg DW)
C_{soil_RZ}	=	depth-averaged soil concentration in the root zone (µg/g soil)
$BCF_{soil-plant^i}$	=	contaminant-specific soil-to-plant bioconcentration factor ([µg/g DW]/[µg/g soil]).

The root zone soil concentration is area averaged for farms. The soil-to-plant bioconcentration factor quantifies the potential for a contaminant in soil to be taken up by the roots and translocated to edible plant parts. As with the air-to-plant biotransfer factor, the soil-to-plant bioconcentration factor may be calculated from chemical-physical properties for most organic chemicals, or derived from empirical data for metals (see Volume II for more details). Equation 10-5 is appropriate for metals for all categories of plants (e.g., exposed fruits, protected vegetables, forage) and for organic chemicals for all categories of plants except root vegetables. However, for certain types of chemicals, such as dioxins, studies have shown that this pathway for uptake and accumulation of contaminants in plants is negligible; that is, the soil concentration does not correlate with the contaminant concentration in plant tissue. For dioxin-like chemicals, the concentration in exposed fruits and vegetables is exclusively a function of air-to-plant transfer and particle deposition.

For root vegetables, the mechanism by which plants take up organic chemicals from the soil and accumulate them in edible tissue is not adequately described by Equation 10-5. Experiments suggest that contaminant concentrations found in the outer parts of the vegetable, or skin, are due more to sorption than to passive uptake via transpiration water (U.S. EPA, 1998). Although water-soluble contaminants may be distributed more or less uniformly throughout the entire plant, lipophilic contaminants may be bound almost exclusively to the outer portion of the root vegetable. The relationship between soil pore water and plant concentrations is expressed as a root concentration factor, which is used to predict the contaminant concentration in root vegetables as follows:

$$C_{Root\_Veg} = \frac{C_{soil\_RZ} \times RootCF \times ECF_{RootVeg}}{K_{d_{soil}}} \quad (10\text{-}6)$$

where

C_{Root_Veg}	=	contaminant concentration in root vegetables (mg/kg WW)
C_{soil_RZ}	=	depth-averaged soil concentration in the root zone (µg/g soil)
RootCF	=	root concentration factor ([µg/g WW plant]/[µg/mL soil water])
$ECF_{RootVeg}$	=	empirical correction factor for root vegetables (unitless)
K_{d_soil}	=	soil-water partition coefficient (mL/g).

The soil-to-plant bioconcentration factor (in Equation 10-5) is replaced with the root concentration factor, which quantifies the potential for organic chemicals in soil pore water to accumulate in root vegetables. An empirical correction factor is included to adjust for differences between the experimental data and the application in the 3MRA modeling system. For example, much of the experimental data on the root concentration factor is based on whole barley roots, and a contaminant-specific correction factor is needed to adjust for the volume differences between barley roots and bulky root vegetables. The empirical correction factor may be further adjusted for peeling, cooking, or cleaning, which can all reduce the contaminant concentration. However, the chemical-specific data set available to the 3MRA modeling system does not currently include these losses in the empirical adjustment factor for root vegetables.

10.2.3 Calculate Total Contaminant Concentrations in Plants

The Farm Food Chain Module calculates the total contaminant concentration in plants for exposed fruits, exposed vegetables, forage, and silage by summing the concentrations for all potential exposure pathways for plants. This summation step is not needed for protected fruits and vegetables or root vegetables, because they take up contaminants only from the soil. For all aboveground produce, the total contaminant concentrations in plants are converted from dry weight (DW) to wet weight (WW) by adjusting for the moisture content. These WW concentrations (also referred to as whole weight or fresh weight) are required by the Human Exposure Module. This conversion is not needed for root vegetables, because the concentration is calculated in WW directly.

10.2.4 Calculate Contaminant Concentrations in Beef and Milk

The Farm Food Chain Module uses the predicted soil, plant (i.e., forage, grains, and silage), and drinking water concentrations to predict the contaminant concentrations in beef and milk for animals raised on beef and dairy farms within the AOI. The exposure scenario is based on the assumption that beef and dairy cattle consume some fraction of forage, feed grain, and silage that is grown on the farm. Furthermore, cattle are presumed to ingest surface water from stream reaches or ponds that are delineated on the farm; where no such waterbody exists, ground water is assumed to be the drinking water source for cattle. The incidental ingestion of soil refers only to the surficial soil (i.e., the top 1 cm of soil) that may be ingested during normal grazing by cattle on untilled soil. All of the exposure concentrations reflect the spatial averaging across each individual farm modeled within the AOI and a consistent temporal scale; that is, the time series of input concentrations for plants, soil, and water are matched for each year in the simulation.

The contaminant concentrations in beef or milk are calculated as a function of the biotransfer of contaminants from plants, soil, and water into beef and milk as follows:

$$C_{beef/milk} = BTF_{feed} \times \left[\sum_i \left(C_i \times CR_i \times f_i \right) + \left(C_{soil} \times CR_{soil} \times FracBio_{soil} \right) \right] + BTF_{water} \times \left(C_{water}{}^d \times IR_{water} \right) \quad (10\text{-}7)$$

where

$C_{beef/milk}$	=	contaminant concentration in beef or milk (mg/kg WW)
BTF_{feed}	=	contaminant biotransfer factor from feed into beef or milk (d/kg tissue WW)
C_i	=	contaminant concentration in plant type *i* (forage, grain, or silage) grown on farm (mg/kg DW)
CR_i	=	consumption rate of plant type *i* for beef or dairy cattle (kg plant DW/d)
f_i	=	fraction of plant type *i* grown on farm (unitless)
C_{soil}	=	contaminant concentration in surficial soil at farm (mg/g soil)
CR_{soil}	=	quantity of contaminated soil eaten by beef or dairy cattle (kg soil/d)
$FracBio_{soil}$	=	fraction of contaminant in soil bioavailable relative to vegetation (unitless)
BTF_{water}	=	contaminant biotransfer factor from water into beef or milk (d/kg tissue WW)
$C_{water}{}^d$	=	dissolved contaminant concentration in drinking water (mg/L)
IR_{water}	=	drinking water ingestion rate for beef or dairy cattle (L/d).

Biotransfer from the soil (the second term in brackets in Equation 10-7) is adjusted by the fraction of bioavailable contaminant in the soil to account for differences in absorption efficiency when contaminant is ingested through plant matter versus through contaminated soil. For some contaminants, vegetation is a more efficient vehicle for biotransfer because the breakdown and digestion of plant matter releases a higher fraction of contaminant available for absorption in the gut. Data on the biotransfer of dissolved contaminants in water into beef and milk were not identified. Nevertheless, because of the potential importance of this pathway, the biotransfer factor for water is set equal to the biotransfer factor for feed for beef and milk, respectively.

The values for biotransfer factors, consumption rates, and fraction contaminated food items differ for beef and dairy cattle. For example, dairy cattle tend to have a much higher water ingestion rate to support lactation; therefore, the ingestion rate of water for dairy cattle is higher than the value for beef cattle.

10.3 Module Discussion

10.3.1 Strengths and Advantages

The Farm Food Chain Module was developed to (1) predict contaminant concentrations in produce and feed crops from multiple routes of plant uptake, and (2) estimate concentrations in beef and milk for cattle raised on farms within the AOI. Relative to other approaches that were considered for the 3MRA modeling system (e.g., fugacity-based models such as PlantX), the strengths and advantages of the Farm Food Chain Module include the following:

- **Widely used and reviewed approach.** The Farm Food Chain Module was based on the science, algorithms, and data developed by EPA's ORD to assess indirect exposures to contaminated produce, beef, and milk. This approach has been widely used by the EPA regions as well as other EPA program offices, and represents a considerable investment by EPA in indirect exposure assessment. Consequently, the approach has been reviewed in a variety of different applications and corresponds well with the categories of produce (e.g., protected vs. unprotected vegetables) that are needed to assess human health exposures.

- **Simulates major plant uptake processes for contaminants in air and soil.** The contaminant concentration in plants is a function of all relevant pathways given the type of plant and the chemical properties of the contaminant. The concentration is summed across uptake for soil as well as uptake from the air, as appropriate, for each contaminant/plant combination. Because some of the WMUs release contaminants into the air, it is crucial that the model accounts for the contaminant mass taken up directly from the air and deposited on the soil from the air and taken up via the roots.

- **Calculates point estimates for home gardeners and areal average estimates for farmers.** The Farm Food Chain Module can calculate the contaminant concentrations both in plants at points specifically designated in the site layout file (i.e., home gardeners) as well as spatially averaged across farm areas within the AOI. The averaging functions in the module include calculating contaminant concentrations in soil that includes both the regional and local watersheds, and air concentrations of particulates and vapor in the same spatial area and time frame. Therefore, the contribution to the total plant concentration from air and soil reflects the spatial character of the plant exposure through time such that the plant loads from soil and from air can be meaningfully added together.

- **Data requirements and module performance consistent with the overall design of the 3MRA modeling system.** The data requirements for the Farm Food Chain Module are relatively limited with respect to plant physiology. As a result, a wide variety of chemical contaminants may be evaluated without requiring inputs for individual plant species included under the categories presented in Section 10.1 (e.g., exposed vs. protected vegetables), or for specific compartments within the plants. Similarly, the module is computationally efficient so that national-scale analyses involving time-varying concentration profiles in air, surface water, ground water (for ingestion by cattle), and soil are feasible in a reasonable run time. Because the system simulations may span many years, and because the system was designed to support full Monte Carlo implementation, it was critical that the module be able to produce results within a time frame that would be useful to the user.

10.3.2 Uncertainty and Limitations

The technical approach underlying the Farm Food Chain Module includes a number of assumptions, uncertainties, and limitations. Limitations include the following:

- **System constraints limit each simulation to a single WMU and contaminant**. The 3MRA modeling system was designed to simulate a single contaminant for a single WMU. Consequently, multiple plant loadings of a contaminant from different WMUs (either within or outside of the AOI) are not considered. This assumption may result in an underprediction of the contaminant concentrations in produce, beef, and milk.

- **Farm Food Chain Module is driven by empirical data.** The Farm Food Chain Module uses empirically derived regression algorithms, as well as empirical data on uptake and accumulation, to predict contaminant concentrations in plants, beef, and milk. Although other models that were evaluated have several advantages over empirical models (for example, the compartmental model developed by Trapp and MacFarlane, 1995), many of these models were considered too data intensive or too computationally demanding for use in a modeling tool intended to support national-level analyses. The reliance on empirical data and models limits the model's ability to predict contaminant concentrations outside of the narrow range for which data are available.

- **Resuspension and redeposition of particle-bound contaminants are not considered.** Plant concentrations are a function of the deposition of the contaminants that have been emitted from the WMU. The plant concentration due to particle deposition does not include resuspension and redeposition of contaminants bound to soil particles. Resuspension and redeposition can occur due to tillage, wind erosion, vehicular resuspension, and rainsplash and can increase the contaminant concentration in exposed fruits, exposed vegetables, forage, and silage.

- **Contaminant concentrations in beef and milk consider only the ingestion pathway.** The beef and milk calculations consider only ingestion pathways for plant matter, surficial soil, and drinking water; exposures from the inhalation or dermal contact are not included in the calculations. For some contaminants, this limitation may result in an underestimate of the contaminant concentrations in beef and milk.

10.4 References

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