5.2.4.1 Soil Mixing Zone Depth (Z_s)

When modeling exposures to COPCs in soils, the depth of contaminated soils is important in calculating the appropriate soil concentration. Tilling might mix deposited COPCs deeper into the soil, whether manually in a garden or mechanically in a large field. Increasing the volume of soil through which COPCs are mixed will tend to decrease (i.e. dilute) concentrations. The value of Z_s you choose may affect the outcome of the risk assessment, because soil concentrations that are based on soil depth are used to calculate exposure via several pathways:

- ingestion of plants contaminated by root uptake;
- direct ingestion of soil by humans, cattle, swine, or chickens; and
- surface runoff into water bodies.

For example, in calculations of exposures resulting from uptake through plant roots, the average concentration of COPCs over the depth of the plant root determines plant uptake.

In general, U.S. EPA (1992d, 1998c) estimated that if the area under consideration is likely to be tilled, soil depth is about 10 to 20 centimeters, depending on local conditions and the equipment used. If soil is not moved, COPCs were assumed to be retained in the shallower, upper soil layer. In this case, earlier Agency guidance (U.S. EPA 1990e; U.S. EPA 1998c) typically recommended a value of 1 centimeter.

U.S. EPA (1998c) recommended selecting Z_s as follows:

Soil Depth (Z_s)	Exposure	Description
1 cm	Direct ingestion of soil	Human exposure: in gardens, lawns, landscaped areas, parks, and recreational areas. Animal exposure: in pastures, lawns, and parks (untilled soils).
1 cm	Surface water runoff in nonagricultural areas	These areas are typically assumed to be untilled.
20 cm	Plant uptake for agricultural soils	The root depth is assumed to equal the tilling depth of 20 centimeters. In untilled soils, the root zone does not directly reflect tilling depth, although it is assumed that tilling depth is an adequate substitute for root zone depth.
20 cm	Surface water runoff in agricultural areas	These areas are typically assumed to be tilled.

We recommend the following values for Z_s:

Recommended Values for: Soil Mixing Zone Depth (Z_s)
2 cm - untilled 20 cm - tilled

We recommend a default Z_s of 2 cm for estimating surface soil concentrations in untilled soils, based on a study that profiled dioxin measurements within soil (Brzuzy et al. 1995). We recommend a default Z_s of 20 cm for estimating surface soil concentrations in tilled soils, as in U.S. EPA (1998c).

5.2.4.2 Soil Dry Bulk Density (*BD*)

BD is the ratio of the mass of soil to its total volume. This variable is affected by the soil structure, type, and moisture content (Hillel 1980).

U.S. EPA (1994r) recommended deriving wet soil bulk density by weighing a thin-walled, tube soil sample (e.g., a Shelby tube) of known volume and subtracting the tube weight (ASTM Method D2937). Moisture content can then be calculated (ASTM Method 2216) to convert wet soil bulk density to dry soil bulk density.

As in U.S. EPA (1994g; 1998c) and presented in Hoffman and Baes (1979), we recommend the following value for *BD*:

Recommended Value for: Soil Dry Bulk Density (*BD*)
1.50 g/cm^3

5.2.4.3 Available Water ($P + I - RO - E_v$)

The average annual volume of water available ($P + I - RO - E_v$) for generating leachate is the mass balance of all water inputs and outputs from the area under consideration. A wide range of values for these site-specific parameters could apply in the various Agency regions.

The average annual precipitation (*P*), irrigation (*I*), runoff (*RO*), and evapotranspiration (E_v) rates and other climatological data are available from either data recorded on site or from the Station Climatic Summary for a nearby airport.

Meteorological variables—such as the evapotranspiration rate (E_v) and the runoff rate (*RO*)—might also be found in resources such as Geraghty et al. (1973). You could also estimate surface runoff by using the Curve Number Equation developed by the U.S. Soil Conservation Service (NC DEHNR 1997). U.S. EPA (1985b) cited isopleths of mean annual cropland runoff corresponding to various curve numbers developed by Stewart et al. (1975). Curve numbers were assigned to an area on the basis of soil type, land use or cover, and the hydrologic conditions of the soil (NC DEHNR 1997).

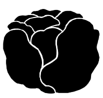
The wide range of available values, however, demonstrates the uncertainties and limitations in our ability to estimate these parameters. For example, Geraghty et al. (1973) presented isopleths for annual surface water contributions that include interflow and ground water recharge. U.S. EPA (1994g) recommended reducing these values by 50 percent, to represent surface runoff only.

5.2.4.4 Soil Volumetric Water Content (θ_{sw})

The soil volumetric water content (θ_{sw}) depends on the available water and the soil structure. A wide range of values for these variables may apply in the various Agency regions. As in earlier guidance documents, (U.S. EPA 1993i; U.S. EPA 1994g; NC DEHNR 1997), we recommend using a default value of 0.2 ml/cm^3 for θ_{sw}.

Recommended Value for: **Soil Volumetric Water Content (θ_{sw})**
0.2 ml/cm^3

5.3 CALCULATING COPC CONCENTRATIONS IN PRODUCE



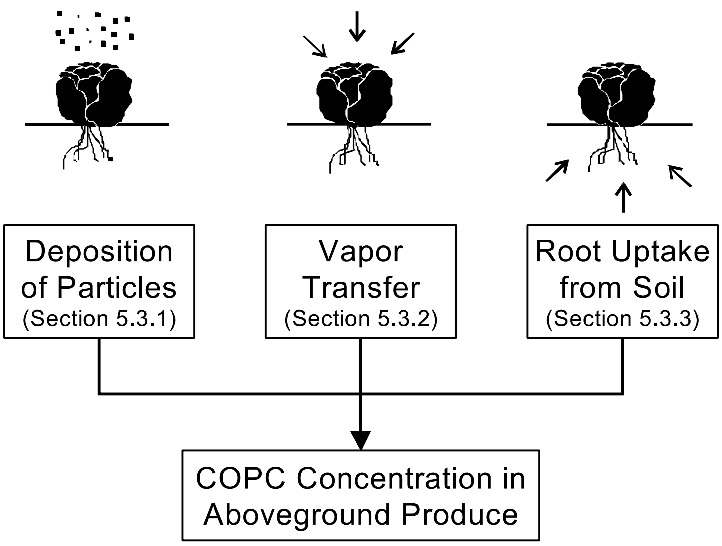
Indirect exposure resulting from ingestion of produce depends on the total concentration of COPCs in the leafy, fruit, and tuber portions of the plant. Because of general differences in contamination mechanisms, we recommend separating produce into two broad categories—aboveground produce and belowground produce. In addition, aboveground produce can be further subdivided into exposed and protected aboveground produce.

Aboveground Produce

Aboveground exposed produce is typically assumed to be contaminated by three possible mechanisms:

- **Direct deposition of particles**—wet and dry deposition of particle phase COPCs on the leaves and fruits of plants (Section 5.3.1).
- **Vapor transfer**—uptake of vapor phase COPCs by plants through their foliage (Section 5.3.2).
- **Root uptake**—root uptake of COPCs available from the soil and their transfer to the aboveground portions of the plant (Section 5.3.3).

FIGURE 5-3
COPC CONCENTRATION IN PRODUCE



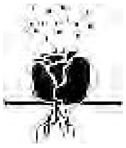
As in U.S.EPA (1998c), we recommend calculating the total COPC concentration in aboveground ***exposed*** produce as a sum of contamination occurring through all three of these mechanisms. However, edible portions of aboveground ***protected*** produce, such as peas, corn, and melons, are covered by a protective covering. They are therefore protected from contamination from deposition and vapor transfer. Root uptake of COPCs is the primary mechanism through which aboveground protected produce becomes contaminated (Section 5.3.3). Appendix B further describes the equations and parameters we recommend to calculate COPC concentrations in exposed and protected aboveground produce.

Belowground Produce

For belowground produce, we recommend assuming contamination occurs only through one mechanism—root uptake of COPCs available from soil (Section 5.3.3). The HHRAP doesn't address contamination of belowground produce via direct deposition of particles and vapor transfer because we assume that the root or tuber is protected from contact with contaminants in the vapor phase. Appendix B further describes the equations and parameters we recommend to calculate COPC concentrations in belowground produce.

Generally, we don't consider risks associated with exposure to VOCs via food-chain pathways significant. This is primarily because VOCs are typically low-molecular-weight COPCs that do not persist in the environment and do not bioaccumulate (U.S. EPA 1994r; U.S. EPA 1996g). However, as discussed in Chapter 2, we recommend evaluating all COPCs, including VOCs, for each exposure pathway.

5.3.1 Aboveground Produce Concentration Due to Direct Deposition (*Pd*)



Some earlier guidance documents (U.S. EPA 1990e; 1998c) recommended using Equation 5-13 to calculate COPC concentrations in aboveground vegetation resulting from wet and dry deposition onto plant surfaces of leafy plants and exposed produce (*Pd*):

$$Pd_i = \frac{1{,}000 \cdot [Dyd + (Fw \cdot Dywv)] \cdot Rp_i \cdot [1.0 - \exp(-kp \cdot Tp_i)]}{Yp_i \cdot kp} \qquad \text{Equation 5-13}$$

where

Pd_i	=	Concentration of pollutant due to direct deposition in the *i*th plant group (µg COPC/g plant tissue DW))
1,000	=	Units conversion factor (kg/10^3 g and 10^6 µg/g pollutant)
Dyd	=	Yearly dry deposition from particle phase (g/m^2-yr)
Fw	=	Fraction of COPC wet deposition that adheres to plant surfaces (unitless)
Dywv	=	Yearly wet deposition from vapor phase (g/m^2-yr)
Rp_i	=	Interception fraction of the edible portion of plant tissue for the *i*th plant group (unitless)
kp	=	Plant surface loss coefficient (yr^{-1})

Tp_i	=	Length of plant's exposure to deposition per harvest of the edible portion of the *i*th plant group (yr)
Yp_i	=	Yield or standing crop biomass of edible portion of the *i*th plant group (kg DW/m^2)

U.S. EPA (1994r) modified Equation 5-13 to include stack emissions adjusted to remove the fraction of air concentration in vapor phase [Q (1 - F_v)] (Equation 5-14).

We recommend using Equation 5-14 to calculate *Pd*. We further discuss the use of this equation in Appendix B, Table B-2-7.

Recommended Equation for Calculating:
Aboveground Produce Concentration Due to Direct Deposition (*Pd*)

$$Pd = \frac{1{,}000 \cdot Q \cdot (1 - F_v) \cdot [Dydp + (Fw \cdot Dywp)] \cdot Rp \cdot [1.0 - \exp(-kp \cdot Tp)]}{Yp \cdot kp} \qquad \text{Equation 5-14}$$

where

Pd	=	Plant (aboveground produce) concentration due to direct (wet and dry) deposition (mg COPC/kg DW)
1,000	=	Units conversion factor (mg/g)
Q	=	COPC emission rate (g/s)
F_v	=	Fraction of COPC air concentration in vapor phase (unitless)
$Dydp$	=	Unitized yearly average dry deposition from particle phase (s/m^2-yr)
Fw	=	0.2 for anions, 0.6 for cations & most organics (unitless)
$Dywp$	=	Unitized yearly wet deposition from particle phase (s/m^2-yr)
Rp	=	Interception fraction of the edible portion of plant (unitless)
kp	=	Plant surface loss coefficient (yr^{-1})
Tp	=	Length of plant exposure to deposition per harvest of the edible portion of the *i*th plant group (yr)
Yp	=	Yield or standing crop biomass of the edible portion of the plant (productivity) (kg DW/m^2)

Chapters 2 and 3 explain how we recommend quantifying the COPC emission rate (Q). Appendix A-2 describes how we recommend determining the COPC-specific parameter *Fv*. Chapter 3 describes how the modeled air parameters *Dydp* and *Dywp* are generated. Appendix B explains our recommendations for *Fw*. *Rp*, *kp*, *Tp*, and *Yp* are neither site- nor COPC-specific, and are described in Sections 5.3.1.1 through 5.3.1.4.

5.3.1.1 Interception Fraction of the Edible Portion of Plant (*Rp*)

U.S. EPA (1998c) stated that NRC models assumed a constant of 0.2 for *Rp* for dry and wet deposition of particles (Boone et al. 1981). However, Shor et al. (1982) suggested that diversity of plant growth necessitated vegetation-specific *Rp* values.

As summarized in Baes et al. (1984), experimental studies of pasture grasses identified a correlation between initial *Rp* values and productivity (standing crop biomass [*Yp*]) (Chamberlain 1970):

$$Rp = 1 - e^{-\gamma Yp} \qquad \text{Equation 5-14A}$$

where

Rp	=	Interception fraction of the edible portion of plant (unitless)
γ	=	Empirical constant (Chamberlain [1970] gives the range as 2.3 to 3.3 for pasture grasses; Baes et al. [1984] used the midpoint, 2.88, for pasture grasses.)
Yp	=	Standing crop biomass (productivity) (kg DW/m^2 for silage; kg WW/m^2 for exposed produce)

Baes et al. (1984) also developed methods for estimating *Rp* values for leafy vegetables, silage, and exposed produce. However, these vegetation class-specific calculations produced *Rp* values that were independent of productivity measurements. This independence led to potentially unreasonable estimates of surface plant concentrations. Therefore, Baes et al. (1984) proposed using the same empirical relationship developed by Chamberlain (1970) for other vegetation classes. Baes et al. (1984) developed class-specific estimates of the empirical constant (γ) by forcing an exponential regression equation through several points. Points included average and theoretical maximum estimates of *Rp* and *Yp*. The following class-specific empirical constants (γ) were developed:

- Exposed produce = 0.0324
- Leafy vegetables = 0.0846
- Silage = 0.769

U.S. EPA (1994r) and U.S. EPA (1995e) proposed a default aboveground produce *Rp* value of 0.05, based on a weighted average of class-specific *Rp* values. Specifically, class-specific *Rp* values were calculated using the equation developed by Chamberlain (1970) and the following empirical constants:

- Leafy vegetables were assigned the same empirical constant (0.0846) developed by Baes et al. (1984).

- Fruits, fruiting vegetables, and legumes were assigned the empirical constant (0.0324) originally developed by Baes et al. (1984) for "exposed produce."

Vegetables and fruits included in each class are as follows:

- Fruits—apple, apricot, berry, cherry, cranberry, grape, peach, pear, plum/prune, and strawberry
- Fruiting Vegetables—asparagus, cucumber, eggplant, sweet pepper, and tomato
- Legumes—snap beans
- Leafy Vegetables—broccoli, brussel sprouts, cauliflower, celery, lettuce, and spinach

The class-specific *Rp* values were then weighted by relative ingestion (by humans) of each class, to determine a weighted average *Rp* value of 0.05. However, the produce classes and relative ingestion values used by U.S. EPA (1994r) and U.S. EPA (1995e) to calculate and weight the *Rp* values are not current with the U.S. EPA *1997 Exposure Factors Handbook* (U.S. EPA 1997b). In addition, the overall *Rp* value presented in U.S. EPA (1994r; 1995e) was based on limited information; subsequent revision to U.S. EPA (1994r; 1995e) resulted in an overall *Rp* value of 0.2 (RTI 1997).

For purposes of consistency, we combined the produce classes into two groups—exposed fruit and exposed vegetables. We used the exposed produce empirical constant (γ) to calculate *Rp*. Since the exposed vegetable category includes leafy and fruiting vegetables, we calculated *Rp* for leafy and fruiting vegetables. We then calculated the exposed vegetable *Rp* by a weighted average based on productivity (*Yp*) of leafy and fruiting vegetables, respectively. The relative ingestion rates used to determine an average weighted *Rp* value we derived from the intake of homegrown produce discussion presented in the 1997 *Exposure Factors Handbook* (U.S. EPA 1997b). We recommend using the weighted average *Rp* value of 0.39 as a default *Rp* value, because it represents the most current parameters, including standing crop biomass and relative ingestion rates.

Recommended Value for: Interception Fraction of the Edible Portion of Plant (*Rp*)
0.39

Unweighted *Rp* and ingestion rates used for the weighting are as follows:

Aboveground Produce Class	*Rp*	Ingestion Rate (g DW/kg-day)
Exposed fruits	0.053	0.19
Exposed vegetables	0.982	0.11

One of the primary uncertainties associated with this variable is whether the algorithm developed by Chamberlain (1970) and the empirical constants developed by Baes et al. (1984) for use in this algorithm accurately represent aboveground produce. Specifically, Chamberlain (1970) based his algorithm on studies of pasture grass rather than aboveground produce. Baes et al. (1984) noted that their approach to developing class-specific *Rp* values is "at best *ad hoc,"* but stated that this approach was justified, because the consequences of using *Rp* estimates that are independent of productivity are "serious."

5.3.1.2 Plant Surface Loss Coefficient (*kp*)

U.S. EPA (1998c) identified several processes—including wind removal, water removal, and growth dilution—that reduce the amount of contaminant that has deposited on plant surfaces. The term *kp* is a measure of the amount of contaminant that is lost to these physical processes over time. U.S. EPA (1998c) cited Miller and Hoffman (1983) for the following equation:

$$kp = \left(\frac{\ln 2}{t_{1/2}}\right) \cdot 365 \qquad \text{Equation 5-15}$$

where

kp	=	Plant surface loss coefficient (yr^{-1})
$t_{1/2}$	=	Half-life (days)
365	=	Units conversion factor (days/yr)

Miller and Hoffman (1983) reported half-life values ranging from 2.8 to 34 days for a variety of contaminants on herbaceous vegetation. These half-life values converted to *kp* values of 7.44 to 90.36 (yr^{-1}). U.S. EPA (1994r; 1998c) recommended a *kp* value of 18, based on a generic 14-day half-life corresponding to physical processes only. The 14-day half-life is approximately the midpoint of the range (2.8 to 34 days) estimated by Miller and Hoffman (1983).

Lacking experimental data supporting chemical- and/or site-specific values, we recommend using a default *kp* value of 18. This *kp* value is the midpoint of Miller and Hoffman's (1983) range of values. Based on this range (7.44 to 90.36), plant concentrations could range from about 1.8 times higher to about 48 times lower than the plant concentrations, based on a *kp* value of 18. If chemical- or site-specific data is available, you could also calculate site- and chemical-specific *kp* values using the equation in Miller and Hoffman (1983).

Recommended Value for: Plant Surface Loss Coefficient (*kp*)
18 yr^{-1}

The primary uncertainty associated with *kp* relates to its position as the sole surface loss term in Equation 5-14. As defined by Miller and Hoffman (1983) and U.S. EPA (1998c), *kp* only represents potential losses from the physical processes listed above, not ***all*** potential losses (e.g. chemical degradation). However, information regarding chemical degradation of contaminants on plant surfaces is limited. Including chemical degradation processes would decrease half-life values and thereby increase *kp* values. Note that effective plant concentration decreases as *kp* increases. Therefore, using a *kp* value that does not consider chemical degradation processes is protective.

In addition, there are uncertainties associated with the half-life values reported by Miller and Hoffman (1983) with regard to how accurately these values represent the behavior of risk assessment COPCs on aboveground produce. However, the relative impact of this second uncertainty is less than the omission of chemical degradation processes.

5.3.1.3 Length of Plant Exposure to Deposition per Harvest of Edible Portion of Plant (*Tp*)

U.S. EPA (1990e; 1993f; 1994r; 1998c), and NC DEHNR (1997) recommended treating *Tp* as a constant, based on the average period between successive hay harvests. Belcher and Travis (1989) estimated this period at 60 days (0.164 years), which represents the length of time that aboveground vegetation (in this case, hay) is exposed to contaminant deposition before being harvested. Calculate *Tp* as follows:

$$Tp = \frac{60\ days}{365\ days/yr} = 0.164\ yr \qquad \text{Equation 5-16}$$

where

Tp	=	Length of plant exposure to deposition per harvest of the edible portion of plant (yr)
60	=	Average period between successive hay harvests (days)
365	=	Units conversion factor (days/yr)

As in previous guidance, we recommend using a *Tp* value of 0.164 year.

Recommended Value for: **Length of Plant Exposure to Deposition per Harvest of Edible Portion of Plant (*Tp*)**
0.164 years

The primary uncertainty associated with using this value is that it is based on the growing season for hay rather than aboveground produce. The average period between successive hay harvests (60 days) may not reflect the length of the growing season or the period between successive harvests for aboveground produce at specific sites. To the extent that information documenting the growing season or period between successive harvests for aboveground produce is available, this information could be appropriate to estimate a site-specific *Tp* value. The greater the difference between site-specific *Tp* and our recommended value, the greater the effect on plant concentration estimates.

5.3.1.4 Standing Crop Biomass (Productivity) (*Yp*)

U.S. EPA (1998c) recommended that the best estimate of *Yp* is productivity, which Baes et al. (1984) and Shor et al. (1982) define as follows:

$$Yp = \frac{Yh_i}{Ah_i} \qquad \text{Equation 5-17}$$

where

Yh_i	=	Harvest yield of the *i*th crop (kg DW)
Ah_i	=	area planted to the *i*th crop (m^2)

U.S. EPA (1994r) and NC DEHNR (1997) recommended using this equation and calculated a *Yp* value of 1.6 for aboveground produce, based on weighted average *Yh* and *Ah* values for four aboveground produce classes (fruits, fruiting vegetables, legumes, and leafy vegetables). Vegetables and fruits included in each class were as follows:

- Fruits—apple, apricot, berry, cherry, cranberry, grape, peach, pear, plum/prune, and strawberry
- Fruiting Vegetables—asparagus, cucumber, eggplant, sweet pepper, and tomato
- Legumes—snap beans
- Leafy Vegetables—broccoli, brussel sprouts, cauliflower, celery, lettuce, and spinach.

Class-specific *Yp* values were estimated using U.S. average *Yh* and *Ah* values for a variety of fruits and vegetables for 1993 (USDA 1994a; USDA 1994b). *Yh* values were converted to dry weight using average class-specific conversion factors (Baes et al. 1984). U.S. EPA (1994r and 1995e) calculated class-specific *Yp* values and then used relative ingestion rates of each group to calculate the weighted average *Yp* value of 1.6. However, the produce classes and relative ingestion values used by U.S. EPA (1994r and1995e) to calculate and weight the *Yp* values are not current with the U.S. EPA 1997 *Exposure Factors Handbook*. In addition, overall *Yp* value presented in U.S. EPA (1994r and U.S. EPA 1995e) was based on limited information; subsequent revision to U.S. EPA (1994r and 1995e) has resulted in an overall *Yp* value of 1.7 (RTI 1997).

For consistency, we combined the produce classes into two groups—exposed fruit and exposed vegetables. We derived the exposed vegetable *Yp* summing *Yh* values for leafy and fruiting vegetables and dividing by the sum of *Ah* values for leafy and fruiting vegetables. We derived the relative ingestion rates used to calculate an overall average weighted *Yp* value from the homegrown produce discussions presented in the 1997 *Exposure Factors Handbook* (U.S. EPA 1997b). We recommend using the weighted average *Yp* value of 2.24 as a default *Yp* value, because this value represents the most complete and thorough information available.

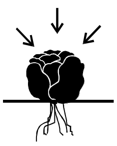
Recommended Value for: Standing Crop Biomass (Productivity) (*Yp*)
2.24

Unweighted *Yp* and ingestion rates used for the weighting are as follows:

Aboveground Produce Class	*Yp*	Ingestion Rate (g DW/kg-day)
Exposed fruits	0.25	0.19
Exposed vegetables	5.66	0.11

The primary uncertainty associated with this variable is that the harvest yield (*Yh*) and area planted (*Ah*) may not reflect site-specific conditions. To the extent to which site-specific information is available, you can estimate the magnitude of the uncertainty introduced by the default *Yp* value.

5.3.2 Aboveground Produce Concentration Due to Air-to-Plant Transfer (*Pv*)



The method we recommend for estimating COPC concentrations in exposed and aboveground produce due to air-to-plant transfer (*Pv*) was developed with consideration of items which might limit the transfer of COPC concentrations from plant surfaces to the inner portions of the plant. These limitations result from mechanisms responsible for

- inhibiting the transfer of lipophilic COPCs (e.g., the shape of the produce); and
- removing COPCs from the edible portion of the produce (e.g., washing, peeling, and cooking).

We recommend using Equation 5-18 to calculate *Pv*. We further discuss the use of this equation in Appendix B, Table B-2-8.

Recommended Equation for Calculating:
Aboveground Produce Concentration Due to Air-to-Plant Transfer (*Pv*)

$$Pv = Q \cdot F_v \cdot \frac{Cyv \cdot Bv_{ag} \cdot VG_{ag}}{\rho_a}$$ Equation 5-18

where

Pv	=	Concentration of COPC in the plant resulting from air-to-plant transfer (µg COPC/g DW)
Q	=	COPC emission rate (g/s)
F_v	=	Fraction of COPC air concentration in vapor phase (unitless)
Cyv	=	Unitized yearly average air concentration from vapor phase (µg-s/g-m^3)
Bv_{ag}	=	COPC air-to-plant biotransfer factor ([mg COPC/g DW plant]/[mg COPC/g air]) (unitless)
VG_{ag}	=	Empirical correction factor for aboveground produce (unitless)
ρ_a	=	Density of air (g/m^3)

Chapters 2 and 3 explain how we recommend quantifying the COPC emission rate (Q). Appendix A-2 describes how we recommend determining the COPC-specific parameters Fv and Bv_{ag}. Chapter 3 describes generating the modeled air parameter Cyv. As discussed below in Section 5.3.2.1, the parameter VG_{ag} depends on the lipophilicity of the COPC. Appendix B further describes how we recommend using Equation 5-18, including calculating ρ_a.

5.3.2.1 Empirical Correction Factor for Aboveground Produce (VG_{ag})

The parameter VG_{ag} was incorporated into Equation 5-18 to address the potential to overestimate the transfer of lipophilic COPCs to the inner portions of bulky produce, such as apples. Because of the protective outer skin, size, and shape of bulky produce, transfer of lipophilic COPCs (log K_{ow} greater than 4) to the center of the produce is not as likely as for non-lipophilic COPCs. As a result, the inner portions will be less affected.

To address this issue, U.S. EPA (1994m) recommended an empirical correction factor (VG_{ag}) of 0.01 for lipophilic COPCs to reduce estimated vegetable concentrations. The factor of 0.01 is based on a similar correction factor ($VG_{rootveg}$) for belowground produce. $VG_{rootveg}$ was estimated for unspecified vegetables as follows:

$$VG_{rootveg} = \frac{M_{skin}}{M_{vegetable}} \qquad \text{Equation 5-19}$$

where

$VG_{rootveg}$	=	Correction factor for belowground produce (g/g)
M_{skin}	=	Mass of a thin (skin) layer of belowground vegetable (g)
$M_{vegetable}$	=	Mass of the entire vegetable (g)

Assuming that the density of the skin and the whole vegetable are the same, this equation becomes a ratio of the volume of the skin to that of the whole vegetable. U.S. EPA (1994m) assumed that the vegetable skin is 0.03 centimeters, which is the leaf thickness of a broad-leaf tree, as was used in experiments conducted by Riederer (1990). Using this assumption, U.S. EPA (1994m) calculated $VG_{rootveg}$ values of 0.09 and 0.03 for carrots and potatoes, respectively.

Based on the work by Wipf et al. (1982), U.S. EPA (1994m) identified other processes—such as peeling, cooking, and cleaning—that further reduce the vegetable concentration. U.S. EPA (1994m) recommended a $VG_{rootveg}$ value of 0.01 for lipophilic COPCs. These are less than the estimates of 0.09 and 0.03 for the carrots and potatoes mentioned earlier, but greater than the estimate would be if the correction factor was adjusted for cleaning, washing, and peeling, as described by Wipf et al. (1982). Following this line of reasoning, U.S. EPA (1994m) recommended a lipophilic COPC VG_{ag} value of 0.01 for all aboveground produce except leafy vegetables. As with $VG_{rootveg}$, U.S. EPA (1994m) noted that assignment of this value is based on the consideration that it "should be less than estimated just based on surface volume to whole fruit volume ratios."

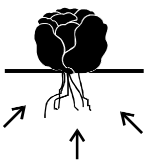
U.S. EPA (1994m) recommended a lipophilic COPC VG_{ag} of 1.0 for pasture grass because of a direct analogy to exposed azalea and grass leaves (for which data were available). Pasture grass is described as "leafy vegetation." However, the leafy vegetable group, as defined in Section 5.3.1.1, is composed of bulkier produce such as broccoli, brussel sprouts, cauliflower, celery, lettuce, and spinach. In addition, the outer leaves of most of the produce in this category are removed during preparation. Therefore, the VG_{ag} value of 1.0 for leafy vegetables is inappropriate and may overestimate COPC concentrations. A default lipophilic COPC VG_{ag} value of 0.01 for leafy vegetables is more appropriate for leafy vegetables, because the leafy vegetable category represents bulkier, more protected plants as compared to single leaves of grass blades. U.S. EPA (1994r) and NC DEHNR (1997) recommended a lipophilic COPC VG_{ag} value of 0.01, for all classes of aboveground produce.

For COPCs with a log K_{ow} greater than 4, we recommend using a lipophilic VG_{ag} value of 0.01 for all aboveground exposed produce. For COPCs with a log K_{ow} less than 4, we recommend using a VG_{ag} value of 1.0, because we assume these COPCs pass more easily through the skin of produce.

Recommended Values for: Empirical Correction Factor for Aboveground Produce (VG_{ag})
0.01 for COPCs with a log K_{ow} greater than 4
1.0 for COPCs with a log K_{ow} less than 4

Uncertainty may be introduced by assuming VG_{ag} values for leafy vegetables (such as lettuce) and for legumes (such as snap beans). Assuming a VG_{ag} value of 0.01 for legumes and leafy vegetables may underestimate concentrations because these species often have a higher ratio of surface area to mass than other bulkier fruits and fruiting vegetables, such as tomatoes.

5.3.3 Produce Concentration Due to Root Uptake (*Pr*)



Root uptake of contaminants from soil may contribute to COPC concentrations in aboveground exposed produce, aboveground protected produce, and belowground produce. As in previous guidance (U.S. EPA 1994m; U.S. EPA 1994r; and U.S. EPA 1995e), we recommend using Equations 5-20A and 5-20B to calculate *Pr*. We discuss the use of these equations further in Appendix B.

Recommended Equation for Calculating:
Produce Concentration Due to Root Uptake (*Pr*)

Exposed and protected aboveground produce:

$$Pr = Cs \cdot Br$$ Equation 5-20A

Belowground produce:

$$Pr = \frac{Cs \cdot RCF \cdot VG_{rootveg}}{Kd_s \cdot 1\ kg/L}$$ Equation 5-20B

where

Pr	=	Concentration of COPC in produce due to root uptake (mg/kg)
Cs	=	Average soil concentration over exposure duration (mg COPC/kg soil)
Br	=	Plant-soil bioconcentration factor for produce (unitless)
RCF	=	Root concentration factor (unitless)
$VG_{rootveg}$	=	Empirical correction factor for belowground produce (unitless)
Kd_s	=	Soil/water partition coefficient (L/kg)

Appendix B and Section 5.2 explain how we recommend calculating *Cs*. Appendix A-2 describes how we recommend calculating the COPC-specific parameters *Br*, *RCF*, and Kd_s. Similar to VG_{ag} and as discussed in Section 5.3.2.1, $VG_{rootveg}$ is based on the lipophilicity of the COPC.

Equation 5-20A is based on the soil-to-aboveground plant transfer approach developed by Travis and Arms (1988). This approach is appropriate for evaluating exposed and protected aboveground produce; however, it might not be appropriate for soil-to-belowground plant transfers. For belowground produce, U.S. EPA (1994m) and U.S. EPA (1995e) recommended Equation 5-20B, which includes a root concentration factor (RCF) developed by Briggs et al. (1982). RCF is the ratio of COPC concentration in the edible root to the COPC concentration in the soil water. Since Briggs et al. (1982) conducted their experiments in a growth solution, in order to use this equation you must divide the COPC soil concentration (*Cs*) by the COPC-specific soil/water partition coefficient (Kd_s) (U.S. EPA 1994m).

As in U.S. EPA (1994m), we recommend using a $VG_{rootveg}$ value of 0.01 for lipophilic COPCs (log K_{ow} greater than 4) based on root vegetables like carrots and potatoes. A value of 0.01 appears to represent the most complete and thorough information available. For COPCs with a log K_{ow} less than 4, we recommend a $VG_{rootveg}$ value of 1.0.

Recommended Values for: **Empirical Correction Factor for Belowground Produce (*$VG_{rootveg}$*)**
0.01 for COPCs with a log K_{ow} greater than 4
1.0 for COPCs with a log K_{ow} less than 4

5.4 CALCULATING COPC CONCENTRATIONS IN BEEF AND DAIRY PRODUCTS

We generally recommend that you estimate COPC concentrations in beef tissue and milk products on the basis of the amount of COPCs that cattle are assumed to consume through their diet. The HHRAP assumes the cattle's diet consists of:

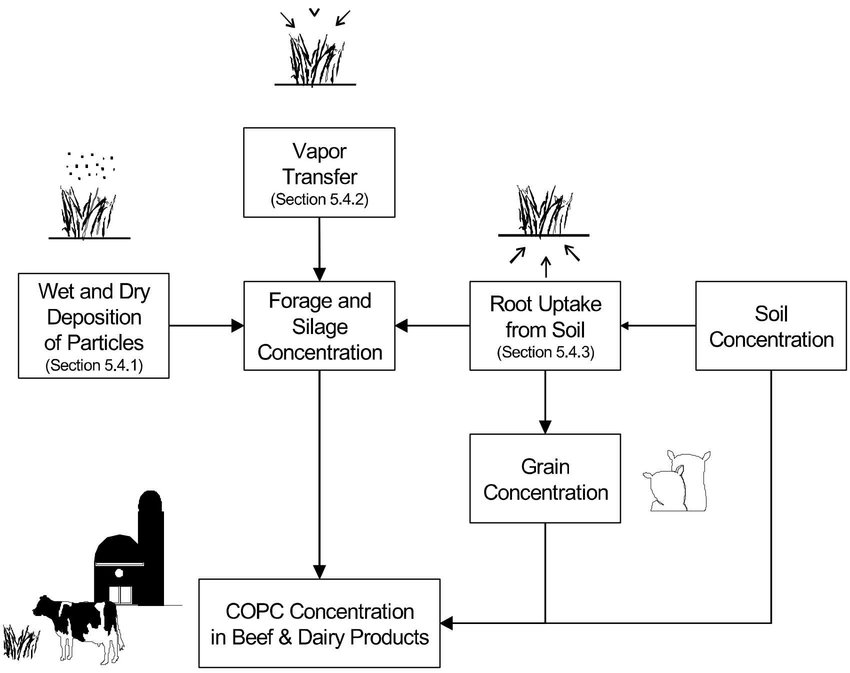
- forage (primarily pasture grass and hay),
- silage (forage that has been stored and fermented), and
- grain.

Additional contamination may occur through the cattle ingesting soil. The HHRAP calculates the total COPC concentration in the feed items (e.g., forage, silage, and grain) as a sum of contamination occurring through the following mechanisms:

- **Direct deposition of particles**—wet and dry deposition of particle phase COPCs onto forage and silage (Section 5.4.1).
- **Vapor transfer**—uptake of vapor phase COPCs by forage and silage through foliage (Section 5.4.2).
- **Root uptake**—root uptake of COPCs available from the soil and their transfer to the aboveground portions of forage, silage, and grain (Section 5.4.3).

Feed items consumed by animals can be classified as exposed or protected, depending on whether they have a protective outer covering. Because the outer covering on protected feed acts as a barrier, we assume that there is negligible contamination of protected feed through deposition of particles and vapor transfer. In the HHRAP, grain is classified as protected feed. As a result, we recommend that you assume grain contamination occurs only through root uptake. We also recommend assuming that contamination of exposed feed items, including forage and silage, occurs through all three mechanisms.

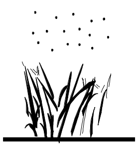
FIGURE 5-4
COPC CONCENTRATION IN BEEF AND DAIRY PRODUCTS



The HHRAP assumes that the amount of grain, silage, forage, and soil consumed varies between dairy and beef cattle. Sections 5.4.4 (beef) and 5.4.5 (dairy) describe the methods we recommend to estimate consumption rates and subsequent COPC concentrations in cattle. As in previous guidance (U.S. EPA 1990e and 1994a; NC DEHNR 1997), we recommend assuming that 100 percent of the plant materials eaten by cattle were grown on soil contaminated by emission sources. Therefore, we recommend assuming that 100 percent of the feed items are contaminated.

Appendix B, Tables B-3-1 through B-3-11, describe how we recommend calculating (1) the COPC concentrations in soil and feed items (forage, silage, and grain) consumed by beef and dairy cattle, and (2) the resulting COPC concentrations in beef and milk.

5.4.1 Forage and Silage Concentrations Due to Direct Deposition (*Pd)*



COPC concentrations in forage and silage result from wet and dry deposition onto exposed plant surfaces; similar to aboveground produce (Section 5.3.1). Therefore, we recommend also using Equation 5-14 to calculate *Pd* for forage and silage. We discuss calculating *Pd* for Forage and silage further in Appendix B. Appendix A-2 explains how we recommend calculating COPC-specific *Fv* values for forage and silage (i.e. exactly as they are calculated for aboveground produce). Sections 5.4.1.1 through 5.4.1.4 describe how we recommend calculating *Rp*, *kp*, *Tp*, and *Yp* for use in calculating forage and silage concentrations.

5.4.1.1 Interception Fraction of the Edible Portion of Plant (*Rp*)

As discussed in Section 5.3.1.1, Chamberlain (1970) found a correlation between *Rp* and productivity, *Yp* (standing crop biomass). This correlation is expressed in Equation 5-14A.

Based on U.S. EPA (1994r and 1995b) and NC DEHNR (1997), we recommend using Equation 5-14 to calculate *Rp* values for forage and silage.

Substituting the Baes et al. (1984) empirical constant (**fl**) value of 2.88 for pasture grass, and the standing crop biomass value of 0.24 kg DW/m^2 (these variables are discussed in Section 5.3.1.1) into Equation 5-14, the forage-specific *Rp* is 0.5. Substituting the Baes et al. (1984) empirical constant (**fl**) value of 0.769 for silage, and the standing crop biomass value of 0.8 kg DW/m^2 into Equation 5-14, the silage-specific *Rp* value is 0.46.

Recommended Value for: Interception Fraction of the Edible Portion of Plant (*Rp*)
Forage = 0.5 Silage = 0.46

Several uncertainties are associated with the *Rp* variable:

- The empirical relationship developed by Chamberlain (1970) is based on a study of pasture grass, and therefore may not accurately represent site-specific silage types.
- The empirical constant for silage developed by Baes et al. (1984) used in Chamberlain's empirical relationship may also fail to accurately represent site-specific silage types.
- The range of empirical constants recommended by Baes et al. (1984) for pasture grass does not result in a significant range of estimated *Rp* values for forage (the calculated *Rp* range is 0.42 to 0.54). Therefore, using the empirical constant midpoint (2.88 for pasture grass) does not significantly affect the *Rp* value and the resulting estimate of plant COPC concentration.

5.4.1.2 Plant Surface Loss Coefficient (*kp*)

We recommend using Equation 5-15 (Section 5.3.1.2) to calculate the plant surface loss coefficient *kp* for aboveground produce. The *kp* factor is derived in the same manner for cattle forage and silage. The uncertainties of *kp* for cattle forage and silage are similar to the uncertainties for aboveground produce.

5.4.1.3 Length of Plant Exposure to Deposition per Harvest of the Edible Portion of Plant (*Tp*)

As discussed in Section 5.3.1.3, the HHRAP treats *Tp* as a constant, based on the average period between successive hay harvests. This period, which Belcher and Travis (1989) estimated at 60 days, represents the length of time that aboveground vegetation (in this case, hay) would be exposed to particle deposition before being harvested. We used Equation 5-16 (Section 5.3.1.3), to calculate a *Tp* of 0.16 year for cattle silage.

For cattle forage, we modified Equation 5-16 to consider the average of :

1. the average period between successive hay harvests, and
2. the average period between successive grazing.

Based on Belcher and Travis (1989), the we assumed the average period between hay harvests is 60 days, and the average period between successive grazing is 30 days. We therefore calculated *Tp* as follows:

$$Tp = \frac{0.5 \cdot (60\ days + 30\ days)}{365\ days/yr} = 0.12\ yr \qquad \text{Equation 5-21}$$

Recommended Value for: **Plant Exposure Length to Deposition per Harvest of the Edible Portion of Plant (*Tp*)**
Forage = 0.12 yr Silage = 0.16 yr

The primary uncertainties associated with *Tp* are similar to those for aboveground produce, as discussed in Section 5.3.1.3.

5.4.1.4 Standing Crop Biomass (Productivity) (*Yp*)

As discussed in Section 5.3.1.4, U.S. EPA (1998c) stated that the best estimate of *Yp* is productivity, as defined in Equation 5-17. Consequently, under this approach, you would consider dry harvest yield (*Yh*) and area harvested (*Ah*).

We calculated forage *Yp* as a weighted average of the calculated pasture grass and hay *Yp* values. We assumed weightings of 0.75 for forage and 0.25 for hay. The weightings are based on the fraction of a year that cattle are assumed to be pastured and eating grass (9 months per year) or not pastured and fed hay (3 months per year). We assumed an unweighted pasture grass *Yp* of 0.15 kg DW/m^2 (U.S. EPA 1994r; U.S. EPA 1994m). We then calculated an unweighted hay *Yp* of 0.5 kg DW/m^2 using Equation 5-17 and the following *Yh* and *Ah* values:

Yh	=	1.22×10^{11} kg DW, calculated from the 1993 U.S. average wet weight *Yh* of 1.35×10^{11} kg (USDA 1994b) and a conversion factor of 0.9 (Fries 1994).
Ah	=	2.45×10^{11} m^2, the 1993 U.S. average for hay (USDA 1994b).

The unweighted pasture grass and hay *Yp* values were multiplied by their weighting factors (0.75 and 0.25, respectively), and summed to calculate the recommended weighted forage *Yp* of 0.24 kg DW/m^2.

We recommend assuming a production-weighted U.S. average *Yp* of 0.8 kg DW/m^2 for silage (Shor, et al. 1982).

Recommended Values for: Standing Crop Biomass (Productivity) (*Yp*)
Forage = 0.24 kg DW/m^2 Silage = 0.8 kg DW/m^2

The primary uncertainty associated with this variable is that the harvest yield (*Yh*) and area planted (*Ah*) may not reflect site-specific conditions. To the extent that site-specific information is available, it's feasible to estimate the magnitude of the uncertainty introduced by the default *Yp* value. In addition, the weightings assumed in this discussion for the amount of time that cattle are pastured (and foraging) or stabled (and being fed silage) could be adjusted to reflect site-specific conditions, as appropriate.

5.4.2 Forage and Silage Concentrations Due to Air-to-Plant Transfer (*Pv*)

We recommend using Equation 5-18 (Section 5.3.2) to calculate the COPC concentration in aboveground produce resulting from air-to-plant transfer (*Pv*). *Pv* is calculated for cattle forage and silage similarly to the way that it's calculated for aboveground produce. We provide a detailed discussion of *Pv* in Section 5.3.2. We present differences in VG_{ag} values for forage and silage, as compared to the values for aboveground produce described in Section 5.3.2.1, in Section 5.4.2.1. We discuss calculating *Pv* further