Human health soil screening criteria for PFOS, PFHxS and PFOA

Calculation protocols and draft values for potential inclusion in the PFAS National Environmental Management Plan

OEH led a National Chemicals Working Group (NCWG) project, tasked with considering whether the human health soil screening values for 'Residential with garden / accessible soil' in the PFAS National Environmental Management Plan (PFAS NEMP) should be updated in the second version of the PFAS NEMP. This NCWG work led to the preparation of this report.

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Abbreviations

ASC NEPM	Assessment of Site Contamination, National Environment Protection Measure
DoEE	Australian Government Department of the Environment and Energy
DW	dry weight
EPA	Environment Protection Authority
FSANZ	Food Standards Australia and New Zealand
GV	guideline value
HEPA	Heads of EPAs Australia and New Zealand
HILs	health investigation levels
NCWG	National Chemicals Working Group
NEMP	National Environmental Management Plan
NSW OEH	NSW Office of Environment and Heritage
PFAA	perfluoroalkyl acid; includes perfluoroalkyl sulfonic acids (PFSAs) and perfluoroalkyl carboxylic acids (PFCAs)
PFAS	per- and poly-fluoroalkyl substance
PFBS	perfluorobutane sulfonate
PFHxS	perfluorohexane sulfonate
PFOA	perfluorooctanoic acid
PFOS	perfluorooctane sulfonate
PFOSA	perfluorooctane sulfonamide
PFSA	perfluoroalkane sulfonate
QLD DES	Queensland Department of Environment and Science
RfC	reference concentration
TDI	tolerable daily intake
TF	transfer factor
US EPA	United States Environmental Protection Agency
WW	wet weight

1. Introduction

At the request of Environment Ministers around Australia, the Heads of EPAs Australia and New Zealand (HEPA) and the Australian Government Department of the Environment and Energy (DoEE) collaborated to develop and publish the PFAS[1] National Environmental Management Plan (PFAS NEMP) in January 2018 (the PFAS NEMP 1.0) (HEPA 2018). The document contains a nationally consistent approach to environmental management of PFAS.

Included in the PFAS NEMP are environmental guideline values (GVs) intended to be protective of ecological and human health for a range of scenarios. These include interim screening criteria for protection of human health from exposure to PFAS contaminated soil. Criteria are available for the following land-use scenarios, broadly consistent with the land-use scenarios used nationally for other contaminants (health investigation levels (HILs) A – D) in the National Environment Protection (Assessment of Site Contamination) Measure (ASC NEPM; NEPC 2013a; NEPC 2013b):

- residential with garden / accessible soil
- residential with minimal opportunities for soil access
- public open space
- industrial/commercial.

The human health soil screening criteria published in the PFAS NEMP 1.0 were originally developed by the NSW Office of Environment and Heritage (OEH) and NSW Health for the NSW Environment Protection Authority (EPA), as draft values to use in site investigations in New South Wales (OEH 2017). Subsequently, OEH and the Queensland Department of Environment and Science (QLD DES) identified that recalculating the screening criteria for the 'Residential with garden / accessible soil' scenario is justified. This was based on availability of additional data to calculate soil to plant transfer factors (TFs) and to better account for uptake of PFHxS[2] in the PFOS[3] + PFHxS screening criteria (explained in more detail in Section 3). This need was also identified in PFAS NEMP 1.0, which recommends future work to review and further refine the transfer factors used to derive the criteria.

The aims of this report are to:

- provide an overview of the derivation process for each of the land-use scenarios, and
- propose revised criteria for the 'Residential with garden / accessible soil' scenario based on a review of soil to plant transfer factors.

This document was prepared by OEH to assist the National Chemicals Working Group (NCWG) make recommendations to HEPA on whether the human health soil screening values for 'Residential with garden / accessible soil' in the NEMP should be updated in the subsequent version of the PFAS NEMP (i.e. PFAS NEMP 2.0). Drafts of this document have been peer-reviewed by relevant staff from NSW Health, QLD DES and the Western Australia Department of Water and Environmental Regulation. Appendix A to this report contains a review of available transfer factors and a protocol for specifically accounting for PFHxS uptake in the GV derivation, prepared jointly by NSW OEH and QLD DES.

[1] Per- and poly-fluoroalkyl substance(s)

[2] Perfluorohexane sulfonate

[3] Perfluorooctane sulfonate

2. Proposed human health guideline values for inclusion in the PFAS NEMP

Table 1 summarises screening criteria proposed for inclusion in the PFAS NEMP 2.0. This includes the revised 'Residential with garden / accessible soil' screening criteria for PFOS + PFHxS and PFOA. The proposed screening criteria for the other land-use scenarios listed in Table 1 are consistent with those in the PFAS NEMP 1.0. The derivation method for all criteria is summarised in the following sections.

Table 1 Proposed human health soil screening criteria for the PFAS NEMP 2.0. The current PFAS NEMP 1.0 Residential with garden/accessible soil criteria are shown in brackets

Toxicity reference value	PFOS + PFHxS	PFOA	Comment
Residential with garden/ accessible soil	0.01 mg/kg *(0.009 mg/kg)*	0.3 mg/kg *(0.1 mg/kg)*	Assumes home-grown produce provides up to 10% of fruit and vegetable intake (does not account for consumption of eggs from home poultry), also includes children's day care centres, preschools and primary schools. These were derived using consistent assumptions applied to the HIL A criteria in the ASC NEPM.
Residential with minimal opportunities for soil access	2 mg/kg	20 mg/kg	Assumes no use of soil for consumption of home-grown produce and poultry and includes dwellings with fully and permanently paved yard space such as high rise-buildings and flats. These were derived using consistent assumptions applied to the HIL B criteria in the ASC NEPM.
Public open space	1 mg/kg	10 mg/kg	Relevant for public open space such as parks, playgrounds, playing fields (e.g. ovals), secondary schools (except where soil is used for agriculture studies) and footpaths. Excludes undeveloped public open space (such as urban bushland and reserves), which should be subject to a site-specific assessment where required. These were derived using consistent assumptions applied to the HIL C criteria in the ASC NEPM.
Industrial/ commercial	20 mg/kg	50 mg/kg	Assumes 8 hours is spent indoors and 1 hr spent outdoors at a site such as a shop, office, factory or industrial site. These were derived using consistent assumptions applied to the HIL D criteria in the ASC NEPM. Note: The industrial/commercial criterion for PFOA has been set at 50 mg/kg in anticipation of the Stockholm Convention low content limit of 50 mg/kg.

These soil guidance values should only be used to assess potential human exposure through direct soil contact. They should be applied in conjunction with other lines of investigation to account for potential leaching, off-site transport, bioaccumulation and secondary exposure.

Note: For all scenarios, calculations are based on 20% of Food Standards Australia and New Zealand (FSANZ) tolerable daily intakes (TDI), i.e. up to 80% of exposure is assumed to come from other pathways. The degree of conservatism in the soil criteria for investigation – human health-based guidance values (80% attributed to other exposure pathways) – means that exceeding these values may not constitute a risk if other pathways are controlled.

3. Rationale

Criteria published in the PFAS NEMP 1.0 are regarded as interim, and future work was recommended to ensure the criteria remain current as further information becomes available. No further information has been identified that would justify recalculation of the criteria values for the Residential with minimal opportunities for soil access, Public open space or Industrial / commercial land-use activities, at this stage. However, the approach taken to calculate the interim criteria for the Residential with garden / accessible soils land use is potentially overly conservative, due to the method used to estimate PFAS uptake into plants from soils.

Derivation of criteria for the Residential with garden / accessible soil scenario (OEH 2017) considers two pathways of exposure:

- direct exposure to contaminated soil
- indirect exposure from consumption of home-grown fruit and / or vegetables grown in contaminated soil.

Criteria for bioaccumulative contaminants such as PFAS are calculated using soil to plant transfer factors (TFs), which estimate the concentration of a contaminant in plant tissue based on the soil concentration of that contaminant.

The interim criteria for Residential with garden / accessible soil land use in the PFAS NEMP 1.0 were calculated by NSW OEH and NSW Health using a mixture of TFs based on concentrations of PFAS in plant tissue on both a wet weight and dry weight basis (OEH 2017). TFs derived using dry weight concentrations are not directly comparable to health-based guidance values, as screening criteria for contaminants in foods are based on wet weights. Given the water content of fresh plant produce is typically >80% for raw plants (Gebhardt & Thomas 2002), calculating TFs based on dry weight of plant tissues results in considerable conservatism. The calculation of interim criteria for Residential with garden / accessible soil land use in the PFAS NEMP 1.0 included a factor of two to partially account for the inclusion of dry weight TFs; however, more robust calculations of screening criteria can be made by explicitly accounting for TFs that are based on dry weight concentrations, by converting them to a wet weight basis.

Another issue not addressed by the interim Residential with garden / accessible soil criteria is that the plant uptake of PFHxS was assumed to be the same as for PFOS. This is relevant as screening assessments for PFHxS are done in combination with PFOS (PFOS + PFHxS) based on current guidance from FSANZ (2017). Laboratory and field studies suggest PFHxS can accumulate to a greater degree, at least in upper compartments of many plants (see Appendix A). Therefore, basing guidance on PFOS TFs alone would underestimate risks from exposure in circumstances where PFHxS is present in soil at significant concentrations.

Based on the above information, refined draft criteria for PFOS + PFHxS and PFOA for the Residential with garden / accessible soil scenario have been calculated by NSW OEH. The review of TFs has been prepared jointly by NSW OEH and QLD DES and is provided in Appendix A. The sections below summarise the methods used to calculate the criteria for all four land-use scenarios.

4. Methods and calculations

Soil criteria were calculated using the HILs Calculator Microsoft Excel spreadsheet provided on the National Environment Protection Council (NEPC) website (NEPC 2017). Input parameters (Table 2) were consistent with guidance provided in the ASC NEPM (NEPC 2013a).

Oral toxicity threshold values for PFOS and PFOA (Table 3) used were the TDI values published in FSANZ (2017). As per the advice provided in FSANZ (2017), the toxicity of PFHxS is assumed to be equivalent to PFOS. Therefore, the final screening criteria for PFOS is applied to the sum of the PFOS and PFHxS concentrations. Further, as per the advice in FSANZ (2017), PFOS, PFOA and PFHxS were not considered to be carcinogenic, and therefore criteria were calculated based on a threshold dose response curve only. This is consistent with the approach used in the PFAS NEMP 1.0. If FSANZ derives different TDIs for either PFOS, PFHxS or PFOA in the future, this guidance will need to be reconsidered.

For both PFOS + PFHxS and PFOA, the screening criteria were calculated based on an acceptable exposure of 20% of the TDI. In other words, the values are protective of human health if up to 80% of exposure comes from other pathways. This approach accounts for both background (ambient) exposure and additional exposure that might occur at contaminated locations, for example consumption of drinking water, or consumption of eggs from home raised poultry and meat. Including the potential for other exposure pathways is important for screening (Tier 1) assessments; however, it is useful to note that if other sources of PFAS are controlled (apart from ambient), a site-specific risk assessment may be useful to demonstrate if risks are acceptable at concentrations higher than these screening criteria.

Dermal uptake was assumed to be negligible (ToxConsult 2016), therefore parameters relevant to this pathway were omitted from the equations. This approach is consistent with other chemicals in the HILs calculator for which dermal uptake is not significant.

Inhalation toxicity threshold values were calculated based on the FSANZ TDI values and using the United States Environmental Protection Agency (US EPA) methodology from the Health Effects Assessment Summary Tables (HEAST; US EPA 1995). Due to the low volatility of perfluoroalkyl acids such as PFOS, PFOA and PFHxS, inhalation of gaseous PFAS was excluded. Inhalation of dust was presumed to result in a minor contribution to exposure, and was included in the calculations to be thorough, as exposure by this pathway is possible.

Table 2 Default exposure input parameters used for calculating human health soil screening criteria (NEPC 2017) based on assumptions in ASC NEPM Schedule B7 (NEPC 2013a). NR = not relevant

Parameter	Symbol	Unit	Residential		High density residential		Public open space		Industrial/ commercial
			Child	Adult	Child	Adult	Child	Adult	Adult
Soil & dust ingestion rate	IR	mg/d	100	50	25	12.5	50	25	25
Time spent outdoors	ET_o	h	4	4	1	1	2	2	1
Time spent indoors	ET_i	h	20	20	20	20	NR	NR	8
Lung retention factor	RF	–	0.375	0.375	0.375	0.375	0.375	0.375	0.375
Particulate emission factor	PEF_o	mg^3/kg	2.9×10^{10}	2.9×10^{10}	7.3×10^{10}	7.3×10^{10}	2.6×10^{7}	2.6×10^{7}	3.7×10^{10}
Indoor air dust factor	PEF_i	mg^3/kg	2.6×10^{7}	2.6×10^{7}	2.6×10^{7}	2.6×10^{7}	NR	NR	2.6×10^{7}
Fraction of indoor dust comprised of outdoor soil	TF	–	0.5	0.5	0.5	0.5	NR	NR	0.5
Body weight	BW	kg	15	70	15	70	15	70	70
Exposure frequency	EF	d/y	365	365	365	365	365	365	240
Exposure duration	ED	y	6	29	6	29	6	29	30
Averaging time	AT	d	EDx365	EDx365	EDx365	EDx365	EDx365	EDx365	EDx365
GI absorption	GAF	–	1	1	1	1	1	1	1
Oral bioavailability	BA_o	%	100	100	100	100	100	100	100
Background intake oral[1]	BI_o	%	80	80	80	80	80	80	80
Background intake inhalation[2]	BI_i	%	0	0	0	0	0	0	0

[1] To account for other oral pathways such as water, plants, foods and background (ambient) exposures from products such as clothes, carpets, etc.
[2] Background intake from inhalation is accounted for in the 80% assigned to background intake oral

Table 3 Toxicity threshold values (mg/kg bw/d) used for calculating human health soil screening criteria

PFAS	Toxicity reference value: Oral [1]	Toxicity reference value: Inhalation [2]
	mg/kg bw/d	mg/m^3
PFOS + PFHxS	0.00002	0.00007
PFOA	0.00016	0.00056

[1] Tolerable daily intake (TDI; FSANZ 2017)
[2] Reference concentration (RfC; Equation 1)

The calculation of the reference concentration (RfC) to assess exposure via inhalation of dust (in mg/m^3) was undertaken using the US EPA methodology (US EPA 1995) from the Health Effects Assessment Summary Tables (HEAST):

$$\mathrm{RfC} = \frac{\mathrm{TRV\ x\ BW}}{\mathrm{V_{inhalation}}}$$

…Equation 1

where:
RfC = reference concentration (mg/m^3)
TRV = toxicity reference value (mg/kg bw/d)
BW = body weight (70 kg)
$V_{inhalation}$ = ventilation rate (20 m^3/d)

The HILs calculations were based on the equations in NEPC 2013b (Schedule B7: Appendix B). In general, a soil HIL for an exposure pathway (x), where a threshold approach is adopted, can be back-calculated by setting the estimated intake for a chemical (i) to the acceptable intake allowable from soil for that chemical, according to Equation 2 (see Table 3 for explanation of abbreviations in Equation 2).

$$\mathrm{HIL_{x,i}\ (mg/kg)} = \frac{\text{Acceptable Intake}}{\text{Intake from Contamination}} = \frac{(\text{Acceptable Intake}_{\,i}\text{ from Soil})\ \mathrm{x}\ (\mathrm{BW})\ \mathrm{x}\ (\mathrm{AT})}{(\text{Contact Rate}_{\,i})\ \mathrm{x}\ (\mathrm{EF})\ \mathrm{x}\ (\mathrm{ED})}$$

…Equation 2

HILs can be derived by combining components for various pathways of exposure according to Equation 3 (dermal exposures were omitted as they were considered insignificant for PFAS).

$$\mathrm{HIL}\ (mg/kg) = \frac{1}{\left[\frac{1}{\mathrm{HIL_{ingestion}}}\right] + \left[\frac{1}{\mathrm{HIL_{plant\ uptake}}}\right] + \left[\frac{1}{\mathrm{HIL_{dust}}}\right]}$$

…Equation 3

Criteria for Residential with garden/accessible soil land use were calculated based on standard ASC NEPM assumptions for HIL A, including the assumption that home-grown fruit and vegetables constitute up to 10% of total dietary intake. These criteria are not protective of other food-based exposures such as consumption of eggs or home-slaughtered livestock, and as such are inappropriate for use in rural settings where a site-specific risk assessment is required.

To calculate the exposure from consuming home-grown plant produce for Residential with garden / accessible soil land use, the NEPM calculator uses soil to plant TFs. For these calculations, wet weight TFs were used in the final calculations. Where data were not available to directly calculate wet weight TFs, dry weight TFs were converted to wet weight TFs using literature values for plant moisture contents (see Appendix A).

As noted in Appendix A, TFs for PFOS may underestimate uptake of PFHxS. This is an important consideration as the criteria are applied to the sum of PFOS and PFHxS concentrations (FSANZ 2017). Although plant transfer studies for PFHxS are not as extensive as for PFOS, sufficient data are available to estimate comparative TFs for some of the plant types included in the NEPM HILs calculator (NEPC 2017). The available data were used to calculate ratios of PFHxS:PFOS TFs. The geometric mean of the maximum ratio for each plant species was used as a multiplier to convert PFOS TFs to PFOS+PFHxS TFs for each plant group. These combined TFs were calculated assuming 50% presence of each PFOS and PFHxS in the soil. The method used to derive TFs is described in detail in Appendix A. The final TFs used to calculate criteria for the Residential with garden/ accessible soil land use are summarised in Table 4.

Table 4 Transfer factors (TFs) used in the calculations for PFOS + PFHxS and PFOA criteria for Residential with garden / accessible soil

Category	Species	Data source	Final TF
PFOS + PFHxS[1]			
Green vegetables	Celery	Blaine et al. 2014	0.79
Root vegetables	Radish	Wen et al. 2016	0.51
Tuber vegetables	Potato	Lechner & Knapp 2011	0.20
Tree fruit	Tomato	Brignole et al. 2003	0.02
PFOA			
Green vegetables	Celery	Blaine et al. 2014	0.10
Root vegetables	Radish	Wen et al. 2016	0.15
Tuber vegetables	Potato	Lechner & Knapp 2011	0.03
Tree fruit	Cucumber	Lechner & Knapp 2011	0.03

[1] TFs for PFOS + PFHxS have been calculated using the geometric mean of limited data for PFHxS TFs as a multiplier to 'correct' PFOS TFs, and assuming 50:50 proportions of PFOS and PFHxS concentrations (as described in Appendix A).

5. Conclusions

Within the constraints of currently available information, the derivation of the draft criteria presented here is consistent with guidance for deriving soil screening criteria in the ASC NEPM. The proposed human health soil screening criteria for PFOS + PFHxS and PFOA are summarised in Table 1.

The revised criterion for PFOS + PFHxS for the Residential with garden / accessible soil land-use scenario (0.01 mg/kg) is very similar to the current interim criterion in the PFAS NEMP 1.0 (0.009 mg/kg; HEPA 2018). This similarity is the result of competing factors, i.e. the removal of conservatism from using dry weight TFs, compared with higher TFs estimated including uptake of PFHxS from soils. For PFOS + PFHxS, although the value proposed is not significantly different from the interim value, the methods are more robust, as they provide consideration of PFHxS exposure via home-grown produce consumption and contain more up-to-date studies. Therefore, NSW OEH as part of the National Chemicals Working Group, supports the inclusion of the above listed criteria for PFOS + PFHxS in an updated PFAS NEMP 2.0.

The revised value for PFOA for the Residential with garden / accessible soil land-use scenario (0.3 mg/kg) is slightly higher than the interim criterion in the PFAS NEMP 1.0 (0.1 mg/kg; HEPA 2018). These changes are due to (a) the removal of unnecessary conservatism by correcting TFs based on plant dry weights, and (b) the inclusion of data from five studies not included in the earlier derivation (see Appendix A). With the additional information, and more robust methods applied, NSW OEH as part of the National Chemicals Working Group, supports the inclusion of the revised PFOA criterion for the Residential with garden / accessible soil scenario presented here in an updated PFAS NEMP 2.0.

Plant uptake of PFAAs[4], including PFOS, PFHxS and PFOA, is also likely to be influenced by parameters such as organic carbon content, presence of specific minerals such as clays and iron oxides, pH, and major ion concentrations in soils (Li et al. 2018). Further refinement of soil to plant TFs, and hence the criteria for PFOS + PFHxS and PFOA, may be possible when the behaviour of PFAS under varying physicochemical conditions is better understood.

It should be noted that the proposed PFOS + PFHxS criterion for Residential with garden / accessible soil could underestimate plant uptake in soils where the PFHxS concentration is significantly higher than the PFOS concentration. Conversely, where the PFHxS concentration is significantly lower than the PFOS concentration, the criterion may be over-conservative. In those situations, a site-specific risk assessment may be considered to provide a refined estimate of risk.

[4] perfluoroalkyl acids

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Appendix A: Derivation of soil to plant transfer factors for PFOS, PFHxS and PFOA

This appendix prepared by NSW OEH and QLD DES informs the derivation of the revised soil criterion for the Residential with garden / accessible soil scenario, and summarises:

- compilation of transfer factors for PFOS, PFOA and PFHxS from scientific literature
- derivation of representative transfer factors for PFOS and PFOA in edible plant compartments
- a protocol for converting PFOS transfer factors to final adjusted transfer factors for use in calculation of soil screening values for PFOS + PFHxS.

Drafts of this appendix have been peer-reviewed by relevant staff from the Western Australia Department of Water and Environmental Regulation.

Data selection and derivation of transfer factors – PFOS and PFOA

A total of 16 relevant publications including data on PFOS or PFOA uptake into plants were identified from the literature. These were primarily studies cited in ToxConsult (2016), which formed the basis of interim criteria published in the PFAS NEMP 1.0. As part of this review, several additional publications were identified:

- five additional studies from a more extensive / broader search, which investigated uptake into plants from compost or biosolids-amended soils: Blaine et al. 2013, Blaine et al. 2014a, Bizkarguenaga et al. 2016, Wen et al. 2016 and Navarro et al. 2017
- three studies on TFs from water to plants: Felizeter et al. 2012, Blaine et al. 2014b and Australian Department of Defence 2017.

The focus of the data selection for the review of TFs was on studies that provided data for uptake of PFAS from soil to plants, and plant types and compartments used for food consumption. Of the 16 publications, several were excluded from further consideration:

- Navarro et al. (2017) was excluded as PFOA contamination was evident in some soil results. In addition, the limits of detection for PFOS in plants were too close (or higher than) measured results, to be able to confidently calculate TFs.
- Weinfurtner et al. (2009) was considered as part of the PFAS NEMP 1.0, though was excluded in this review. This is because the original work was not available in English, so the quality could not readily be assessed by the authors. Including the Weinfurtner et al. (2009) data would not have changed the choice of TFs included in the final calculations, as the TFs from that study were below the maximum TFs from the other studies.
- The three studies based on TFs from water to plants were not considered suitable and were excluded in this review. This is because Felizeter et al. (2012) was based on a nutrient solution in a hydroponic setting, and the Blaine et al. (2014b) and Australian Department of Defence (2017) studies were based on irrigation with PFAS contaminated water. These studies are not suitable for calculation of soil to plant TFs, but they provide further evidence of PFAS accumulation in plants. These studies investigating PFAS uptake from water may assist in risk assessment involving plant exposures via irrigation with contaminated water.

Reported soil and plant concentrations from the remaining eleven publications were used to calculate TFs for PFOS and PFOA uptake from soil into plant tissues using Equation A1.

$$TF = \frac{C_{plant}}{C_{soil}}$$

…Equation A1

where:

C_{plant} = concentration of PFOS or PFOA in wet weight of plant

C_{soil} = concentration of PFOS or PFOA in dry weight of soil

Where PFAS concentrations in plant tissue were reported in the studies as dry weight concentrations, data were converted to a wet weight concentration using Equation A2.

$$C_{plant} = C_{plant.dry} \times (\frac{100 - MC}{100})$$

…Equation A2

where:

$C_{plant.dry}$ = concentration of PFOS or PFOA in plant on a dry weight basis

MC = moisture content of raw plant

The derived TFs for PFOS and PFOA are summarised in Tables A1 and A2, respectively, for the four categories used to derive health investigation levels (HILs) in the ASC NEPM (green vegetables, root vegetables, tubers, and tree fruit). The maximum TF for each category was selected for deriving the soil criterion. The selected TFs were found to be in the range of TFs for other plant categories (Tables A3 and A4) (considering dry to wet weight conversions), providing additional confidence in the suitability of the selected TFs.

The TFs summarised in Tables A1 to A4 show there is considerable variation in TFs for the same plant species. This variation appears to result largely from a dependence on soil concentration, where higher soil concentrations result in lower TFs. This finding supports the use of the maximum TF for each plant category, rather than using the mean or median, which would underestimate plant concentrations in less contaminated soils.

Table A1 PFOS soil to plant transfer factors for ASC NEPM plant categories, calculated from data in the listed data sources

DW = dry weight; WW = wet weight; NR = not required as plant concentrations were available on a wet weight basis.

Plant	TF	Basis	Data source	Moisture content [1]	Max. TF adjusted to WW [2]
	(mg/kg_{plant})/ (mg/kg_{soil})	Plant DW or WW		%	(mg/kg_{plant})/ (mg/kg_{soil})
Green vegetable					
Celery	1.4	DW	Blaine et al. 2014a	86*	**0.20**
Lettuce	0.1 – 0.2	DW	Bizkarguenaga et al. 2016	96	0.01
Lettuce	0.1 – 1.7	DW	Blaine et al. 2013	96	0.07
Lettuce	0.7 – 2.2	DW	Brignole et al. 2003	96	0.09
Lettuce	0.4	DW	Wen et al. 2016	96	0.02
Onion	0.8 – 1.4	DW	Brignole et al. 2003	90	0.14
Root vegetable					
Peeled carrot	0.4 – 0.6	DW	Bizkarguenaga et al. 2016	88	0.07
Carrot peel	0.4 – 05	DW	Bizkarguenaga et al. 2016	88	0.06
Peeled carrot	0.04 – 0.05	WW	Lechner & Knapp 2011	NR	0.05
Carrot peel	0.03 – 0.04	WW	Lechner & Knapp 2011	NR	0.04
Radish	0.07 - 0.7	DW	Blaine et al. 2014a	90*	0.07
Radish	2.6	DW	Wen et al. 2016	95	**0.13**
Tuber vegetable					
Peeled potato	<LOD – 0.002	WW	Lechner & Knapp 2011	NR	0.002
Peeled potato	0.0006 – 0.0007	DW	Stahl et al. 2009	79	0.0002
Potato peel	0.01 – 0.05	WW	Lechner & Knapp 2011	NR	**0.05**
Potato peel	0.007 – 0.02	DW	Stahl et al. 2009	79	0.004
Fruit					
Cucumber	0.002	WW	Lechner & Knapp 2011	NR	0.002
Tomato	0.02 – 0.07	DW	Brignole et al. 2003	94	0.004
Pea	0.03	DW	Blaine et al. 2014a	82*	**0.005**

[1] Moisture contents from Gebhardt and Thomas 2002, except potato data from USDA 2018 and values marked with * were from Blaine et al. (2014a)
[2] TFs in **bold** were used in the criterion calculations.

Table A2 PFOA soil to plant transfer factors for ASC NEPM plant categories, calculated from data in the listed data sources

DW = dry weight; WW = wet weight; NR = not required as plant concentrations on wet weight basis were available.

Plant	TF	Basis	Data source	Moisture content [1]	Max. TF adjusted to WW [2]
	(mg/kg_{plant})/ (mg/kg_{soil})	Plant DW or WW		%	(mg/kg_{plant})/ (mg/kg_{soil})
Green vegetable					
Celery	0.1 – 0.7	DW	Blaine et al. 2014a	86*	**0.10**
Lettuce	1.6 – 2.1	DW	Bizkarguenaga et al. 2016	96	0.08
Lettuce	1.3, 2.5	DW	Blaine et al. 2013	96	**0.10**
Lettuce	1.2	DW	Wen et al. 2016	96	0.05
Root vegetable					
Peeled carrot	0.3	DW	Bizkarguenaga et al. 2016	88	0.04
Carrot peel	0.4 – 0.6	DW	Bizkarguenaga et al. 2016	88	0.07
Peeled carrot	0.05	WW	Lechner & Knapp 2011	NR	0.05
Carrot peel	0.04	WW	Lechner & Knapp 2011	NR	0.04
Radish	3.0	DW	Wen et al. 2016	95	**0.15**
Radish	0.5 – 0.9	DW	Blaine et al. 2014a	90*	0.09
Tuber vegetable					
Peeled potato	0.01	WW	Lechner & Knapp 2011	NR	0.01
Peeled potato	0.0007 – 0.001	DW	Stahl et al. 2009	79	0.0002
Potato peel	0.02 – 0.03	WW	Lechner & Knapp 2011	NR	**0.03**
Potato peel	0.002 – 0.008	DW	Stahl et al. 2009	79	0.002
Peeled potato	0.01	WW	Lechner & Knapp 2011	NR	0.01
Fruit					
Cucumber	0.03	WW	Lechner & Knapp 2011	NR	**0.03**
Pea	0.03	DW	Blaine et al. 2014a	82*	0.005

[1] Moisture contents from Gebhardt and Thomas 2002, except potato data from USDA 2018 and values marked with * were from Blaine et al. (2014a).
[2] TFs in **bold** were used in the criterion calculations.

Table A3 PFOS soil to plant transfer factors, for plant categories not included in the ASC NEPM calculations, calculated from data in the listed data sources

DW = dry weight; WW = wet weight.

Plant	TF	Calculation basis	Data source
	$(mg/kg_{plant})/(mg/kg_{soil})$	Plant DW or WW	
Vegetative parts DW			
Alfalfa	0.4	DW	Wen et al. 2016
Alfalfa	0.06 – 1.6	DW	Brignole et al. 2003
Carrot	1.4 – 2.1	DW	Bizkarguenaga et al. 2016
Cucumber	0.05 – 0.5	DW	Moshfeghi 2015
Flax	0.9 – 1.3	DW	Brignole et al. 2003
Maize	0.1 – 0.2	DW	Stahl et al. 2009
Maize	0.2	DW	Wen et al. 2016
Mung bean	0.7	DW	Wen et al. 2016
Oats (straw)	0.2 – 0.8	DW	Stahl et al. 2009
Onion	0.7	DW	Brignole et al. 2003
Radish	0.5	DW	Wen et al. 2016
Ryegrass	0.2	DW	Wen et al. 2016
Soybean	0.3	DW	Wen et al. 2016
Soybean	0.4 – 4.1	DW	Brignole et al. 2003
Tomato	0.8 – 2.2	DW	Brignole et al. 2003
Wheat	0.2 – 1.5	DW	Stahl et al. 2009
Wheat (straw)	0.2 – 0.3	DW	Wen et al. 2014
Wheat	0.1 – 0.5	DW	Zhao et al. 2014
Vegetative parts WW			
Carrot	0.3 – 0.4	WW	Lechner & Knapp 2011
Cucumber	0.1 – 0.2	WW	Lechner & Knapp 2011
Potato	0.3 – 0.4	WW	Lechner & Knapp 2011
Wheat grass	0.2	WW	Bräunig et al. 2018
Roots			
Alfalfa	3.1	DW	Wen et al. 2016
Lettuce	3.9	DW	Wen et al. 2016
Maize	2.7	DW	Wen et al. 2016
Mung bean	4.2	DW	Wen et al. 2016
Ryegrass	1.4	DW	Wen et al. 2016
Soybean	4.7	DW	Wen et al. 2016
Wheat	1.2 – 1.6	DW	Wen et al. 2014
Wheat	0.9 – 2.1	DW	Zhao et al. 2014
Grains			
Flax	0.04 – 0.09	DW	Brignole et al. 2003
Oats	0.002 – 0.02	DW	Stahl et al. 2009
Maize	<LOD – 0.008	DW	Stahl et al. 2009
Wheat	<LOD – 0.0007	DW	Stahl et al. 2009
Wheat	0.06 – 0.08	DW	Wen et al. 2014
Legumes			
Soybean	0.02 – 0.4	DW	Brignole et al. 2003

Table A4 PFOA soil to plant transfer factors, for plant categories not included in the ASC NEPM calculations, calculated from data in the listed data sources

DW = dry weight. WW = wet weight.

Plant	TF	Calculation basis	Data source
	$(mg/kg_{plant})/(mg/kg_{soil})$	Plant DW or WW	
Vegetative parts DW			
Alfalfa	3.2	DW	Wen et al. 2016
Carrot	1.1 – 3.1	DW	Bizkarguenaga et al. 2016
Cucumber	0.2 – 0.4	DW	Moshfeghi 2015
Maize	0.1 – 0.3	DW	Stahl et al. 2009
Maize	0.2	DW	Wen et al. 2016
Mung bean	8.4	DW	Wen et al. 2016
Oats	0.2 - 4.3	DW	Stahl et al. 2009
Radish	5.3	DW	Wen et al. 2016
Ryegrass	1.3	DW	Wen et al. 2016
Soybean	0.3	DW	Wen et al. 2016
Wheat	1.9 – 6.8	DW	Stahl et al. 2009
Wheat	0.7 – 1.5	DW	Wen et al. 2014
Wheat	0.09 -0.3	DW	Zhao et al. 2014
Vegetative parts WW			
Carrot	0.5	WW	Lechner & Knapp 2011
Cucumber	0.8 – 1.0	WW	Lechner & Knapp 2011
Potato	0.4	WW	Lechner & Knapp 2011
Wheat grass	0.6	WW	Bräunig et al. 2018
Roots			
Alfalfa	10.3	DW	Wen et al. 2016
Lettuce	6.1	DW	Wen et al. 2016
Maize	1.7	DW	Wen et al. 2016
Mung bean	7.8	DW	Wen et al. 2016
Ryegrass	2.4	DW	Wen et al. 2016
Soybean	3.2	DW	Wen et al. 2016
Wheat	1.7 – 4.9	DW	Wen et al. 2014
Wheat	1.1 – 2.3	DW	Zhao et al. 2014
Grains			
Oats	0.03 – 0.1	DW	Stahl et al. 2009
Maize	0.003 – 0.009	DW	Stahl et al. 2009
Wheat	0.009 – 0.1	DW	Stahl et al. 2009
Wheat	0.1 – 0.2	DW	Wen et al. 2014

Consideration of PFHxS

FSANZ (2017) conservatively advises that the toxicity of PFHxS should be considered equivalent to PFOS. Therefore, the interim soil criteria for PFOS should apply to the sum of PFOS and PFHxS soil concentrations.

The extent to which PFHxS are transferred from soil to plant tissues is less studied than for PFOS and PFOA. Four studies were identified with data for a suite of PFAAs[5] for uptake from soil into edible plant parts (Blaine et al. 2013, Blaine et al. 2014a, Bräunig et al. 2018, Wen et al. 2014). An additional three studies were identified with data for non-edible parts of plants (Gobelius et al. 2017, Moshfeghi 2015, Zhao et al. 2014). These studies consistently showed that uptake from soil of shorter chain PFAAs (e.g. PFHxS) is greater than longer chain PFAAs (e.g. PFOS). Consequently, PFHxS TFs in those studies were higher than those for PFOS (see Table A5 below). Studies investigating uptake of PFAAs from water to plants have found similar trends (e.g. Blaine et al. 2014b, Australian Department of Defence 2017).

In addition, studies have shown that plants have the potential to uptake PFAA-precursors (e.g. PFOSA[6]) and transform these to PFAAs *in vivo* (e.g. PFOS and PFHxS) (Bräunig et al 2018; Zhao et al 2018). Based on this, PFAA uptake in plants may be confounded by the presence of precursors.

Derivation of composite PFOS + PFHxS transfer factors

There are insufficient data available to derive reliable PFHxS TFs for all plant categories in the HILs calculator (NEPC 2017). Available relevant data from six studies were compiled to calculate the ratio between the TFs for PFHxS and PFOS (see Table A5).

The ratios between PFHxS and PFOS TFs ranged from 1.2 to 25. The highest ratio (wheat grass) was reported by Bräunig et al. (2018), who noted this may have been confounded by the presence of precursors. The geometric mean of the maximum TFs for each plant species was then used as an overall ratio to allow PFOS TFs to be converted to PFOS+PFHxS TFs. The geometric mean was 6.9.

Table A5 Ratio of PFHxS to PFOS TFs based on available PFHxS and PFOS soil to plant transfer factors for ASC NEPM plant categories

Plant	PFHxS TF	PFOS TF	Ratio TFs	Study
	$(mg/kg_{plant})/(mg/kg_{soil})$	$(mg/kg_{plant})/(mg/kg_{soil})$		
Green vegetable				
Lettuce	1.1 – 7.6	0.1 – 1.7	3.4 – 15	Blaine et al. 2013
Celery	0.07, 2.3	0.05, 1.4	1.4 – 1.7	Blaine et al. 2014a
Root vegetable				
Radish	0.85, 2.1	0.07, 0.7	2.9, 13	Blaine et al. 2014a
Tuber vegetable				
No studies found				

[5] perfluoroalkyl acids

[6] perfluorooctane sulphonamide

Plant	PFHxS TF	PFOS TF	Ratio TFs	Study
Fruit				
Pea	0.17	0.03	6.7 *	Blaine et al. 2014a
Other				
Cucumber stems/leaves	0.20, 0.47	2.3, 4.2	8.8, 12	Moshfeghi 2015
Wheat grass	4.8	0.19	25 #	Bräunig et al. 2018
Wheat (grain)	0.1 – 0.2	0.06 – 0.08	2.0 – 2.5	Wen et al. 2014
Wheat (root/shoot)	0.4 – 0.7	0.1 – 0.5	1.2 – 3.2	Zhao et al. 2014
Geometric mean of maximums			6.9	

* Result for one experiment only as all other soil treatments for PFHxS were < LOR.
# The TF for wheat grass grown at a firefighting training ground (TF = 78) was excluded, as the soil concentrations (13,400 µg/kg PFOS and 450 µg/kg PFHxS) were deemed not relevant to residential situations.

A combined PFOS + PFHxS TF for each plant category was then calculated using Equation A3, which assumes equal proportions of PFOS and PFHxS in the soil. In cases where either PFOS or PFHxS dominate concentrations, site-specific assessment could be used to provide a refined estimate of risk. This can be done by changing the proportions in Equation A3.

$$\mathrm{TF}_{PFOS+PFHxS} = (\mathrm{TF}_{\mathrm{PFOS}} \times \mathrm{Proportion}_{\mathrm{PFOS}}) + (\mathrm{TF}_{\mathrm{PFOS}} \times \mathrm{Multiplier}_{\mathrm{PFHxS}} \times (1 - \mathrm{Proportion}_{\mathrm{PFOS}}))$$

…Equation A3

where:

$\mathrm{TF}_{\mathrm{PFOS+PFHxS}}$ = combined TF for PFOS + PFHxS

$\mathrm{TF}_{\mathrm{PFOS}}$ = soil to plant transfer factor for PFOS (Table A1)

$\mathrm{Multiplier}_{\mathrm{PFHxS}}$ = multiplier of 6.9 based on the geometric mean of ratios between PFHxS and PFOS TFs

$\mathrm{Proportion}_{\mathrm{PFOS}}$ = 0.5 assuming equal proportions of PFOS and PFHxS

Table A6 PFOS+PFHxS transfer factors for HILs calculator assuming 50% PFOS and 50% PFHxS in soil (by mass) as per Equation A3 and a $\mathrm{Multiplier}_{\mathrm{PFHxS}}$ of 6.9

Plant category	PFOS TF (from Table A1)	PFOS+PFHxS TF
Green vegetable	0.20	0.79
Root vegetable	0.13	0.51
Tuber	0.05	0.20
Tree fruit	0.005	0.02

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