PFAS NEMP Supporting Document

Derivation of biosolids criteria (restricted and unrestricted use) and maximum allowable soil contaminant concentrations for PFOS, PFHxS and PFOA

National Chemicals Working Group of the Heads of EPAs Australia and New Zealand

September 2022

Cataloguing data

This publication (and any material sourced from it) should be attributed as: HEPA 2022, PFAS NEMP Supporting Document - Derivation of biosolids criteria (restricted and unrestricted use) and maximum allowable soil contaminant concentrations for PFOS, PFHxS and PFOA, CC BY 4.0. Heads of EPA Australia and New Zealand

ISBN XXX-X-XXXXX-XXX-X

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Acknowledgements

The Heads of EPA Australia and New Zealand (HEPA) acknowledge the contributions of Commonwealth, State and Territory agencies and thank everyone who provided input and feedback to inform the development of this plan.

Acknowledgement of Country

We acknowledge the Traditional Custodians of Australia and their continuing connection to land and sea, waters, environment and community. We pay our respects to the Traditional Custodians of the lands we live and work on, their culture, and their Elders past and present.

Contents

Tables

Figures

Introduction

Purpose

This supporting document presents the background information on the derivation of the biosolids criteria presented in Section 15.4 of the PFAS National Environmental Management Plan (NEMP) (NEMP 3.0).

Background

The PFAS NEMP 3.0 presents criteria for PFAS in biosolids (unrestricted and restricted use biosolids) and maximum allowable soil contaminant concentrations (MASCCs) that apply different margins of safety (Table 1).

Table 1 Criteria for PFOS+PFHxS and PFOA in biosolids and maximum allowable soil contaminant concentrations (MASCCs) based on a 1, 2 and 5-fold margin of safety

Criteria type	Margin of safety	PFOS+PFHxS (µg/kg)	PFOA (µg/kg)
Restricted use biosolids	5	6.2	25
	2	15	65
	1	31	130
Unrestricted use biosolids [a]	5	0.22	1.0
	2	0.55	2.5
	1	1.1	5
MASCCs	5	0.22	1.0
	2	0.55	2.5
	1	1.1	5

[a] Unrestricted use threshold may not be applicable in all jurisdictions. Where is it applicable, it should be applied to the final biosolids product for land application.

These criteria were based on the outcomes of a human health and ecological risk assessment (HHERA) for PFOS+PFHxS, and PFOA in biosolids undertaken for the NSW Environment Protection Authority (EPA) by the Contaminants and Risk Team of the NSW Department of Planning and Environment (formly NSW Department of Planning, Industry and Environment).

Scope

This supporting document summarises

- the PFAS biosolids HHERA, which is the basis for the criteria presented in NEMP 3.0
- the criteria derivation process for:
  - restricted use biosolids
  - unrestricted use biosolids
  - maximum allowable soil contaminant concentrations for agriculture (used to calculate a contaminant limited biosolids application rate, CLBAR)

- comparison to biosolids criteria currently available from other jurisdictions
- a potential framework for applying the PFAS criteria and MASCCs for land application of restricted use biosolids in agriculture.

1 Summary of the PFAS biosolids HHERA

The primary aim of the HHERA was to determine if PFAS in biosolids require regulation in NSW and to identify the key exposure pathways to be considered when deriving criteria for regulation. The HHERA used data from a NSW EPA sampling and analysis program of 20 sewage treatment plants (STPs) across the state.

The HHERA assessed risks to four scenarios of biosolids application based on how biosolids are currently used in NSW and what is permitted in the NSW Environmental Guidelines: Use and Disposal of Biosolids Products (NSW EPA, 2000) (the NSW Biosolids Guidelines):

- Scenario 1 – ‘unrestricted use’ biosolids in residential gardens
- Scenario 2 – ‘unrestricted use’ biosolids in land rehabilitation
- Scenario 3 – ‘restricted use’ biosolids in agriculture
- Scenario 4 – ‘unrestricted use’ biosolids in agriculture.

Terminology on unrestricted and restricted use are based on the NSW Biosolids Guideline classification (NSW EPA, 2000). Note each of these classifications may not be applicable in all jurisdictions.

Scenarios 1, 2 and 4 assumed ‘unrestricted use’ biosolids are applied to soil with no incorporation as there are no limits on land application rates for this category of biosolids. Therefore, the concentrations in the unrestricted use biosolids were assumed to be equal to the concentration in biosolids amended soil (BAS) (i.e. assumed biosolids are used to form a topsoil). Scenario 2 assumes the area will be used as public open space and will not be used for agriculture in the future.

Scenario 3 assumed that biosolids are land applied and incorporated into the soil as required by the NSW Biosolids Guidelines for restricted use biosolids in agriculture. The assessment was done for four land application rates: low (10 t/ha)/high (50 t/ha) application rates and single/repeat applications. The concentrations in the BAS for Scenario 3 were estimated by assuming the biosolids were incorporated into 1300 dry t soil/ha (incorporation depth = 10 cm and soil bulk density = 1.3 g/cm^3).

For each scenario, a range of relevant human health and ecological pathways were assessed (a list of the exposure pathways assessed for each scenario is provided in Appendix A). Consistent with current guidance in the PFAS NEMP, the HHERA assessed ecological risks from perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA), and human health risks were assessed for the sum of PFOS and perfluorohexane sulfonate (PFOS+PFHxS) and PFOA. Although other PFAS were detected in the biosolids, the potential risks from these were not assessed in the HHERA. The risk assessment only considered home consumption of produce. Market supply of produce was not assessed. However, market supply is likely to result in lower exposure due to dilution of products in the market.

A risk quotient (RQ) approach was used to quantify the risk for each exposure pathway (Equation **1**). A RQ above 1 indicates that the exposure concentration/dose is above the 'safe' or 'recommended' concentration/dose and further investigation or management may be required.

Equation 1

$$\boldsymbol{RQ = \frac{exposure\ concentration\ or\ dose}{toxicity}}$$

In Equation **1**, '*toxicity*' was either a screening criterion or the tolerable daily intake (TDI) minus background, depending on the pathway assessed. To account for the limited dataset that was used in the HHERA and the presence of other PFAS in the biosolids, in cases where the RQ was greater than 0.2, regulation was recommended. This provides a 5-fold margin of safety (MoS).

The overall outcome of the HHERA was that PFAS in biosolids require regulation and that criteria should be derived for unrestricted and restricted use biosolids. The key exposure pathways (i.e. pathways with the highest RQs) identified in the HHERA that should be used to derive criteria were:

- PFOS+PFHxS – consumption of milk from grazing dairy cows (human health)
- PFOA – ecological secondary consumers.

This supporting document summarises

- the criteria derivation process for:
  - restricted use biosolids
  - unrestricted use biosolids
  - maximum allowable soil contaminant concentrations for agriculture (used to calculate a contaminant limited biosolids application rate, CLBAR)
- comparison to biosolids criteria currently available from other jurisdictions
- a potential framework for applying the PFAS criteria and MASCCs for land application of restricted use biosolids in agriculture.

2 Criteria derivation

All criteria (restricted use biosolids, unrestricted use biosolids and MASCCs) were derived using ‘backwards’ risk calculations at three margins of safety (MoS). This approach involves starting with an acceptable or tolerable exposure and working backwards to determine an acceptable biosolids (or soil in the case of the MASCCs) concentration. This approach ensures exposure (human health or ecological) won’t exceed an acceptable level. The MoS used were 1, 2 and 5, which means that risk calculations at the three MoS result in RQ values of 1, 0.5 and 0.2, respectively. The application of an MoS can be used to account for uncertainties in the assumptions, potential exposure from multiple pathways and potential exposure to PFAS other than PFOS, PFHxS and PFOA. All criteria presented in the PFAS NEMP and Table 1 above were rounded down to two significant figures.

2.1 Derivation of the PFOS+PFHxS criteria

The criteria for PFOS+PFHxS were all calculated using the same assumptions as the risk calculations in the HHERA (i.e. forward risk calculations) for the key exposure pathway (i.e. milk consumption from grazing dairy cows). To do this, all risk calculations and assumptions were entered into excel and the ‘solver’ function was used to back calculate the biosolids (or soil) concentrations that resulted in the acceptable daily intake (TDI minus background) via this pathway. That is, the acceptable daily intake was set, and excel calculated the corresponding biosolids (or soil) concentration to achieve that intake. Screenshots from the excel tables are shown in Figure 1 and full details of the forward risk calculations for this pathway are shown in Appendix B.

Figure 1 Example of excel table used to calculate biosolids (and soil) criteria for PFOS+PFHxS

Grazing dairy cows (child)		
CB	**31.08384117**	**ug/kg**
Cs	1.151253377	ug/kg
livestock IRs	0.5	kg/day
Cp	1.611754727	ug/kg
TFs	1.4	
Livestock IRp	13	kg/day
Livestock BW	500	kg
Livestock daily intake	0.043056876	ug/kg/day
t1/2	56	days/yr
Cserum	13.38209053	ug/L
MSR	0.02	
Cmilk	0.267641811	ug/kg
IRmilk	1.1	kg/day
Specific gravity of milk (SG)	0.968	L/kg
AoF	1	
FI	1	
EF	365	days/yr
ED	6	years
BW	15	kg
AT	2190	days
Acceptable daily intake	**0.018999**	**ug/kg/day**

	A	B	C
1	TDI - background	0.019	ug/kg/day
2	% TDI acceptable	100	%
3	acceptable daily intake	0.019	ug/kg/day
4			
5	mass of biosolids	50	t/ha
6	mass of soil	1300	t/ha
7			

This approach allowed all criteria (restricted use, unrestricted use and MASCCs) to be calculated at the same time. The parameter 'Cs' in Figure 1 is the soil concentration that equates to the acceptable daily intake (TDI – background) of PFOS+PFHxS via this pathway. This was used as the unrestricted use biosolids criteria and the MASCCs. This allows for unrestricted use biosolids to be used as a topsoil without exceeding the acceptable exposure to human health via this pathway. For the MASCCs, this concentration ensures that soil concentrations of PFOS+PFHxS following land application of biosolids won't exceed a concentration resulting in an unacceptable daily intake via this pathway.

The parameter 'CB' in Figure 1 is back calculated from 'Cs' assuming a single land application rate of 50 dry t/ha and a soil incorporation mass of 1300 t/ha (Table 2). The biosolids criteria resulting from these calculations (Table 1) assume that there is no PFAS contamination in the in-situ soil at the land application site. Prior to land application, the concentrations of PFOS, PFHxS and PFOA in the in-situ soil should be characterised. If these compounds are detected in the soil, the MASCCs and CLBAR approach can be used to ensure that risks to human health and the environment will remain low following biosolids application to soil.

Table 2 Land application assumptions used to derive criteria for restricted use biosolids in agriculture

Parameter	Value	Units	Rationale
Land application rate	50	dry t/ha	Maximum application rate based on information from NSW water utilities is about 35 dry t/ha. Therefore, 50 dry t/ha give an additional conservative buffer and allows for variation in the application process.
Incorporation depth	10	cm	The current NSW Biosolids Guidelines use 7.5 cm but a deeper incorporation depth is likely based on the equipment used.
Soil bulk density	1.3	g/cm^3	Standard consideration and roughly consistent with the current NSW Biosolids Guidelines that assume 1.333 g/cm^3. With an incorporation depth of 10 cm, this assumes the biosolids are mixed with 1300 t soil/ha.

The process outlined above was used to derive PFOS+PFHxS criteria where no MoS is applied (i.e. equates to RQ = 1 in forward risk calculations). To calculate the criteria for the 2- and 5-fold MoS, these criteria were divided by 2 and 5, respectively. This equates to RQ values of 0.5 and 0.2 in the forward risk calculations.

2.2 Derivation of the PFOA criteria

The PFOA biosolids criteria were derived to be protective of the key exposure pathway for this compound which was ecological secondary consumers. To do this, the newly derived PFOA soil screening criterion was used (5 µg/kg) (derived as part of the NEMP 3.0 Section 8.7 revision). As this soil screening criterion is relevant for in-soil concentrations, the unrestricted use biosolids criterion and MASCC are equal to this value. The restricted use biosolids criterion was back calculated from this soil screening criterion using the assumptions in Table 2. The subsequent biosolids criteria/MASCCs at different MoS were then calculated as outlined for PFOS+PFHxS. If there are any changes to this soil screening criterion following public consultation of NEMP 3.0, the biosolids criteria will also need to be changed. It should be noted that this criterion was not used in the NSW HHERA as it was not available at the time.

3 Summary of other currently available biosolids guidance and criteria

Queensland is the only jurisdiction that currently has criteria available for PFAS related to land application of biosolids. These criteria, referred to as 'trigger values', are outlined in the Biosolids End of Waste Code (the Biosolids EOW code) (Qld DES, 2019) and for the compounds discussed in this supporting document (PFOS, PFHxS and PFOA) are provided in Table 3 (the Biosolids EOW code also presented soil trigger values for PFBA, PFPeA, PFHxA, sum C9-C14 perfluoroalkyl carboxylic acids, perfluoroalkyl sulfonamides and N:2 fluorotelomer sulfonic acids.). These trigger values relate to the estimated and measured soil concentrations following land application of biosolids. Therefore, they are comparable in use to the MASCCs presented in Table 1. Although the Qld DES trigger values for PFOS, PFHxS and PFOA were derived using a slightly different approach (briefly outlined below) to the criteria presented in NEMP 3.0 and outlined in this Supporting Document, the values are approximately the same. This provides additional confirmation for the suitability of the criteria presented in NEMP 3.0. The Biosolids EOW code also requires characterisation of the biosolids, characterisation of the soil at the proposed land application site, estimation of soil concentrations following land application and demonstrated agronomic benefit. Characterisation includes both standard analysis and total oxidisable precursor assay. In addition, the Biosolids EOW code also requires characterisation of the soil following biosolids land application and incorporation. Breach of a trigger value under the code results in a site-specific risk assessment, including where necessary, monitoring of potentially affected waters and agricultural produce.

3.1 Overview of approach used to derive Queensland PFAS trigger values

The soil trigger values presented in Table 3 were derived through consultation with farmers representatives, local government, water authorities, biosolids academics, biosolids appliers and the Department of Agriculture and Fisheries in Queensland. The key environmental outcome considered in the derivation of the trigger values was production of animal or plant agricultural products unlikely to breach FSANZ (2017a) trigger values and comply with requirements for food products to be safe and suitable under the *Food Act 2009 (Qld)* .

The soil trigger values for PFOS, PFOS+PFHxS, PFHxS and PFOA were derived using the FSANZ trigger values in food products such as meat and milk (FSANZ 2017a). Firstly, PFAS intake into cows was estimated assuming 80% of intake from biosolids amended soil (soil and plants) and 20% allocated to other pathways (e.g. cattle drinking water and dust inhalation). The PFAS intakes were then used to calculate the concentrations in meat and milk using transfer factors published in the literature from trials feeding cattle contaminated food and literature reported soil to plant transfer factors for fodder plants grown in Queensland. The soil trigger values were back calculated starting with 80% of the FSANZ trigger value (i.e. to allow 20% intake from other pathways).

Table 3 Soil trigger values for PFOS, PFHxS, PFOS+PFHxS and PFOA from the Biosolids End of Waste Code (source Qld DES 2019)

Contaminant	Trigger value (µg/kg)
PFOS	1
PFOS+PFHxS [a]	2
PFHxS	3
PFOA	4

[a] assumes 50% PFOS and 50% PFHxS

4 Potential framework for screening restricted use biosolids for land application in agriculture

The restricted use biosolids criteria and the MASCCs presented in NEMP 3.0 and this document can be used in combination to determine the suitability of biosolids for land application in agriculture and maximum land application rates based on PFAS (PFOS, PFHxS and PFOA) concentrations. The potential approach outlined below is a multi-tiered approach where each tier determines the need to progress to the next step.

4.1 Data and information needed to screen biosolids for land application in agriculture

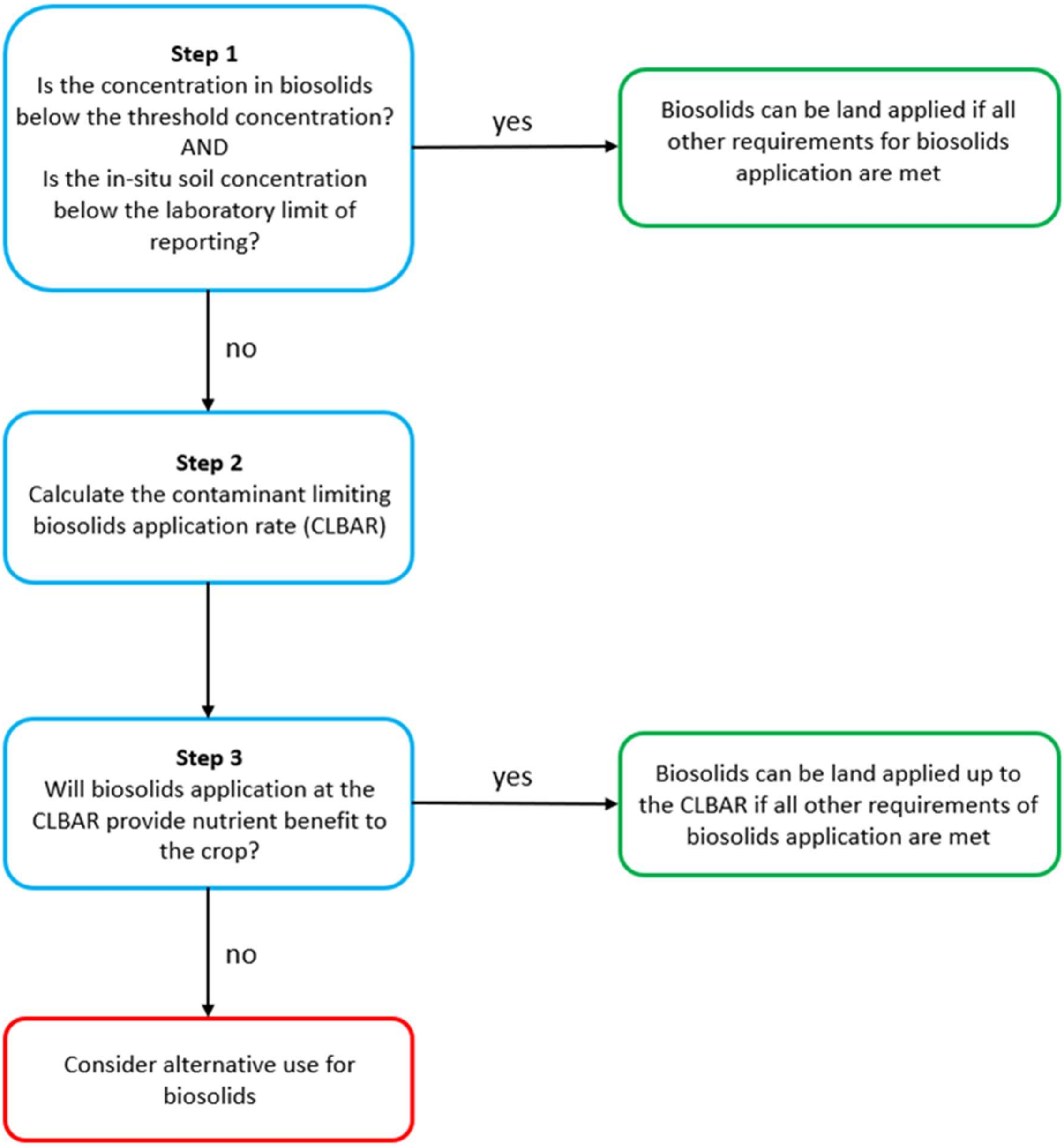
The following data and information are required to apply this potential framework:

- Concentration of PFOS+PFHxS and PFOA in biosolids to be land applied (biosolids characterisation data).
- Concentrations of PFOS+PFHxS and PFOA in the soil at the proposed land application site (soil characterisation data).
- Information about the proposed land application and soil properties, including the depth of incorporation and soil bulk density (conservative default values can be used if these are not available).

Figure 2 shows a flowchart that can be used to screen the biosolids for land application. Each of the steps of the flow chart are discussed below. Some worked examples for applying this framework are provided in Appendix C.

The analysis used to measure concentrations of PFOS+PFHxS and PFOA in biosolids and soil should have the lowest limit of reporting (LOR) achievable at the time of assessment. It is not suitable to request a less sensitive analytical method to try and meet the <LOR requirement.

Figure 2 Flowchart of potential biosolids assessment framework for land application of restricted use biosolids in agriculture



4.2 Step 1 – screening biosolids and in-situ soil concentrations

Step 1 uses the biosolids characterisation data and in-situ soil characterisation data to determine if the biosolids can be land applied without the need to calculate the CLBAR. This can happen if:

- the concentrations of PFOS+PFHxS and PFOA are below the restricted use criteria in Table 1; and,
- the concentrations of PFOS+PFHxS and PFOA in the in-situ soil at the land application site are below the laboratory limit of reporting (LOR).

This approach assumes that the biosolids will not be applied at a rate above 50 dry t/ha and that the biosolids will be mechanically incorporated into the soil. If these things are the case, then the biosolids can be land applied as long as all other requirements for biosolids application in the relevant jurisdiction are met.

4.3 Step 2 – calculation of the contaminant limited biosolids application rate (CLBAR)

This step is needed if any of the requirements under Step 1 are not met. The CLBAR takes into account the concentration of PFOS+PFHxS and PFOA in biosolids and in the in-situ soil at the proposed land application site. The other parameter needed to calculate the CLBAR is the soil mass that the biosolids will be incorporated into. The CLBAR can be calculated using Equation **2**.

Equation 2

$$CLBAR = \frac{MASCC - MISCC}{C_{bio}} \times SM$$

Where,
CLBAR = contaminant limited biosolids application rate (dry t/ha)
MASCC = maximum allowable soil contaminant concentration (Table 1) (µg/kg)
MISCC = measured in-situ soil contaminant concentration (µg/kg)
C_{bio} = biosolids contaminant concentration (µg/kg)
SM = incorporated soil mass per hectare (dry t/ha) (Equation 3)

Equation 3

$$SM = 10000\, m^2/ha \times ID \times BD$$

Where,
ID = incorporation depth (m) (if unknown, a default value of 0.1 m can be used)
BD = bulk density (t/m^3) (if unknown, a default value of 1.3 t/m^3 can be used).

The CLBAR will determine the maximum biosolids land application rate without exceeding the acceptable soil concentration based on the highest risk exposure pathways.

4.4 Step 3 – determine if reuse will be beneficial

The land application of biosolids should be done at a rate that will provide agronomic benefit. For Step 3, the nutrient requirements of the crops to be planted following biosolids application should be considered to determine if application at the CLBAR will provide agronomic benefit. If the application rate will provide benefit, the biosolids can be land applied up to the CLBAR of the most limiting contaminant, if all other requirements for biosolids application in the relevant jurisdiction are met. If the land application at the CLBAR of the most limiting contaminant will not provide benefit for the crops, an alternative use of the biosolids should be considered. Determination of agronomic benefit should be undertaken by a qualified agronomist.

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Appendix A: PFAS exposure pathways and receptors assessed in the human health and ecological risk assessment

For all pathways and receptors assessed in the HHERA, biosolids-amended soil (BAS) was the source of PFAS (PFOS+PFHxS and PFOA) contamination. The lists below provide a brief overview of the pathways and receptors assessed for each scenario

Scenario 1 – unrestricted use biosolids in residential gardens

- Ecological
  - Terrestrial organism (direct toxicity)
- Human health
  - Incidental ingestion of soil/dust from BAS
  - Consumption of home-grown fruit and vegetables grown in BAS
  - Consumption of chicken eggs from chicken foraging on BAS

Scenario 2 – unrestricted use biosolids for land rehabilitation

- Ecological
  - Terrestrial organisms (direct toxicity)
  - Terrestrial secondary consumer
  - Aquatic organism (direct toxicity) via surface runoff/groundwater impacted by leachate from BAS (potential risks from bioaccumulation were not determined as there are no reliable bioaccumulation and biomagnification factors available for aquatic organisms)
- Human health
  - Incidental ingestion of soil/dust from BAS
  - Consumption of drinking water from surface runoff/groundwater impacted by leachate from BAS

Scenario 3 – restricted use biosolids in agriculture

- Ecological
  - Terrestrial organisms (direct toxicity)
  - Terrestrial secondary consumer

    - Aquatic organism (direct toxicity) via surface runoff/groundwater impacted by leachate from BAS (potential risks from bioaccumulation were not determined as there are no reliable bioaccumulation and biomagnification factors available for aquatic organisms)
- Human health
    - Incidental ingestion of soil/dust from BAS
    - Consumption of crops grown on BAS
    - Consumption of crops irrigated with surface runoff/groundwater impacted by leachate from BAS
    - Consumption of livestock meat from livestock grazing on BAS
    - Consumption of livestock meat from livestock eating fodder grown in BAS
    - Consumption of livestock meat from livestock drinking surface runoff/groundwater impacted by leachate from BAS
    - Consumption of milk from dairy cows grazing on BAS
    - Consumption of milk from dairy cows eating fodder grown in BAS
    - Consumption of milk from dairy cows drinking surface runoff/groundwater impacted by leachate from BAS
    - Incidental ingestion of surface runoff/groundwater (e.g. during irrigation) impacted by leachate from BAS
    - Consumption of drinking water from surface runoff/groundwater impacted by leachate from BAS

Scenario 4 – unrestricted use biosolids in agriculture

Assessment of this scenario was streamlined and only considered the highest risk pathways from Scenario 3. This was done to determine if unrestricted use biosolids posed a higher risk in agriculture compared to Scenarios 1 and 2. This was used to determine the key exposure pathway.

Appendix B: consumption of milk from dairy cows grazing on biosolids-amended soil – summary, calculations, and assumptions

Consumption of milk from grazing dairy cows was identified in the HHERA as the key exposure pathway for PFOS+PFHxS. In the HHERA, this was assessed by combining two exposure pathways together:

- BAS ingestion by grazing dairy cows then consumption of milk
- BAS uptake into plants followed by plant ingestion by grazing dairy cows then consumption of milk

This section summarises the calculations used for the forward risk assessment in the HHERA for PFOS+PFHxS for this exposure pathway. The same calculations and assumptions were used in the backwards risk assessment to derive the thresholds presented in this document. All assumptions assessed the risks from consumption of home grown/produced products. They are not relevant for market supply of agricultural products which is likely to result in lower exposure due to dilution of products in the market.

This document does not outline all of the assumptions that were used in the HHERA. Only assumptions relevant to the key exposure pathway and criteria derivation are provided.

B.1 Exposure calculations

The daily intakes for dairy cows (µg/kg-bw/day) of PFOS+PFHxS were calculated using Equation B1 (see **Error! Reference source not found.**) for description of parameters and assumptions).

Equation B1

$$Dairy\ cow\ daily\ intake = \frac{(C_S \times IR_S \times FI) + (C_P \times IR_P \times FI)}{BW}$$

Table B1 Summary of assumptions used to calculate grazing dairy cow intakes of PFOS+PFHxS from soil and plants (Equation B1)

Parameter	Value	Units	Description
C_S	variable	µg/kg	Concentration in soil – dependant on the concentration in biosolids and the biosolids application rate
IR_S	0.5	kg/day	Dairy cow soil ingestion rate – based on soil intake rate of 0.00484 kg/day/kg for a 500 kg cow (API, 2004)
C_P	variable	µg/kg	Concentration in plant/grass (dry weight) (see additional text below)
IR_P	13	kg/day	Dairy cow plant ingestion rate (dry matter) (based on API, 2004)

FI	1	unitless	Fraction ingested from the source – assumes 100% of soil and plant consumed by grazing dairy cows comes from areas where biosolids have been used (API, 2004)
BW	500	kg	Dairy cow body weight (based on API, 2004)

The parameter C_P was calculated by multiplying the soil concentration (C_S) with a soil to plant transfer factor. The transfer factors used were 1.4 for PFOS and 4.3 for PFOA. These were selected by calculating the 95th percentile of transfer factors available in the literature (see Appendix D for the list of transfer factors considered). The transfer factor for PFOS was also used for PFHxS. Although PFHxS is likely to be taken up more readily into plant, the contribution from PFHxS to PFOS+PFHxS in the HHERA was <5%. Therefore, this was considered to have a negligible impact on the estimated plant concentrations.

The dairy cow intake (**Error! Reference source not found.**) was then used to calculate the serum concentration in the cow (C_{serum}) (µg/L) using Equation B2.

Equation B2

$$C_{serum} = \frac{dairy\ cow\ daily\ intake\ \times t\,1/2}{0.693\ \times Vd}$$

In Equation B2, t1/2 is the serum elimination half-life, which is compound specific. The values used were for beef steer, which are 56 days for PFOS and 1.3 days for PFOA (van Asselt et al. 2013 ; Vestergren et al. 2013). The value of 0.693 is a factor based on pharmacokinetic models and Vd is the volume distribution where 0.26 L/kg is assumed to be the extracellular fluid volume (Maksiri et al. 2015 ; Chaiyabutr at al. 2008).

Following this, the concentrations in milk (C_{milk}) were calculated using Equation B3.

Equation B3

$$C_{milk} = MSR\ \times\ C_{serum}$$

In Equation **3**, MSR is the milk to serum ratio, which was assumed to be 0.02 for PFOS+PFHxS and 0.2 for PFOA (ToxConsult 2016).

The milk concentrations were used to calculate daily intakes for children (µg/kg-bw/day) (Equation B4, see Table B2 for parameters and assumptions). The assumptions to estimate intakes for children are presented as the risk posed to this age group is higher and drive the conclusions of the risk assessment.

Equation B4

$$Child\ daily\ intake = \frac{C_{milk} \times IR_{milk} \times SG \times AoF \times FI \times EF \times ED}{BW \times AT}$$

Table B2 Summary of assumptions used to calculate daily intakes for a child consuming milk from dairy cows grazing on biosolids-amended soil (Equation B4)

Parameter	Value	Units	Description
C_{milk}	variable	µg/L	Concentration in milk – will depend on the concentration in biosolids-amended soil
IR_{milk}	1.1	kg/day	Milk ingestion rate – high consumers of milk (90th percentile) (FSANZ 2017a)
SG	0.968	L/kg	Specific gravity of cow milk (ratio of density of milk to density of water at 20°C is 1.0033. Therefore 0.968 is the inverse) (Sherbon 1988)
AoF	1	unitless	Oral absorption factor – assumes 100% bioavailability
FI	1	unitless	Fraction ingested from the source – assumes 100% of milk is consumed from dairy cows grazing on the area biosolids have been land applied
EF	365	days/year	Exposure frequency
ED	6	years	Exposure duration (NEPC 2013)
BW	15	kg	Body weight (NEPC 2013)
AT	2190	days	Averaging time = EF × ED
SG	0.968	L/kg	Specific gravity of cow milk (ratio of density of milk to density of water at 20°C is 1.0033. Therefore 0.968 is the inverse) (Sherbon 1988)
AoF	1	unitless	Oral absorption factor – assumes 100% bioavailability
FI	1	unitless	Fraction ingested from the source – assumes 100% of milk is consumed from dairy cows grazing on the area biosolids have been land applied
EF	365	days/year	Exposure frequency
ED	6	years	Exposure duration (NEPC 2013)
BW	15	kg	Body weight (NEPC 2013)
AT	2190	days	Averaging time = EF × ED

The daily intake was then compared to the background adjusted tolerable daily intake (TDI) using Equation B5 to calculate a human health risk quotient.

Equation B5

$$RQ = \frac{child\ daily\ intake}{TDI - background}$$

In Equation B5, the TDIs for PFOS+PFHxS and PFOA were 0.02 and 0.16 µg/kg-bw/day, respectively (FSANZ 2017b) , and the background was assumed to be 0.001 µg/kg-bw/day (ToxConsult 2016).

Appendix C: examples for applying the framework for screening biosolids for land application in agriculture

C.1 Example 1

As an example, the following data and information are available for land application of biosolids:

- Biosolids concentrations:
  - PFOS+PFHxS concentration = 65 µg/kg
  - PFOA concentration = 20 µg/kg
- In-situ soil concentrations:
  - PFOS+PFHxS < LOR
  - PFOA < LOR
- Incorporation depth – 0.15 m

Soil bulk density is unknown so default of 1.3 g/cm^3 will be used.

Step 1

The concentration of PFOS+PFHxS of 65 µg/kg is above the biosolids threshold concentration of 15 µg/kg (e.g. if the criteria for MoS = 2 are used). Based on this, Steps 2 and 3 need to be completed. No further consideration is required based on the PFOA concentrations.

Step 2

Calculate the incorporated soil mass per ha (SM):

$$SM = 10000 \times 0.15 \times 1.3$$

$$= 1950 \text{ t/ha}$$

Calculate the CLBAR.

$$CLBAR = [(0.55-0)/65] \times 1950$$

$$= 16.5 \text{ t/ha}$$

Note, this example assumes zero concentration when the measured concentration is below the LOR. The most appropriate way to handle <LOR concentrations in these calculations should be determined by each jurisdiction.

Step 3

An assessment of the beneficial reuse of the biosolids is completed and it is determined that based on the nutrient concentration in the biosolids, an application rate of 16.5 t/ha will provide a benefit to the crop.

Outcome

An application of 16.5 t/ha does not exceed other limiting requirements for the biosolids (e.g. the nitrogen limited biosolids application rate, NLBAR) and concentrations of all other contaminants comply with biosolids land application requirements. Considering this, the biosolids are land applied at 16.5 dry t/ha.

C.2 Example 2

As an example, the following data and information are provided for land application of biosolids:

- Biosolids concentrations:
  - PFOS+PFHxS concentration = 12 µg/kg
  - PFOA concentration = 15 µg/kg
- In-situ soil concentrations:
  - PFOS+PFHxS = 0.45 µg/kg
  - PFOA <LOR
- Incorporation depth – 0.1 m

Soil bulk density is unknown so default of 1.3 g/cm^3 will be used.

Step 1

Although the concentrations of both PFOS+PFHxS and PFOA are below the corresponding thresholds (15 and 65 µg/kg, respectively if for example a MoS of 2 is used), the concentration of PFOS+PFHxS was above the LOR in the in-situ soil at the land application site. Based on this, Steps 2 and 3 need to be completed. No further consideration is required based on the PFOA concentrations.

Step 2

Calculate the incorporated soil mass per ha (SM):

$$SM = 10000 \times 0.1 \times 1.3$$

$$= 1300 \text{ t/ha}$$

Calculate the CLBAR

$$CLBAR = [(0.55-0.45)/12] \times 1300$$

$$= 11 \text{ t/ha}$$

Step 3

An assessment of the beneficial reuse of the biosolids is completed and it is determined that based on the nutrient concentration in the biosolids, an application rate of 11 t/ha will not provide a benefit to the crop.

Outcome

An alternative use for the biosolids is considered.

Appendix D:PFOS soil to plant transfer factors from the literature for plants relevant to the grazing pathway

Table D1 PFOS soil to plant transfer factors from the literature for plants relevant to the grazing pathway

Reference	Plant	Growing media	Transfer factor	Experimental details
Braeunig et al. (2019)[a]	Wheatgrass (shoots)	AFFF-impacted soils	0.53 1.2	• Two soils collected from AFFF-impacted airport sites and one uncontaminated soil • Soil properties: pH = 6.3-8.5, OC = 0.5-2.9%, sand = 54-92%, silt = 4-25%, clay = 5-33% • Plants harvested after 10 weeks
Brignole et al. (2003)	Alfalfa (vegetation)	Spiked artificial soil	1.6 0.27 0.18 0.064	• Soil spiked with PFOS at 5 concentrations ranging to 1000 mg/kg • Soil properties: sand = 49%, silt = 30%, clay = 21%, organic matter = 2.1%, pH = 7.79 • Grown until fruit production
Brignole et al. (2003)	Flax (vegetation)	Spiked artificial soil	1.3 1.2 0.88	• Soil spiked with PFOS at 5 concentrations ranging to 1000 mg/kg • Soil properties: sand = 49%, silt = 30%, clay = 21%, organic matter = 2.1%, pH = 7.79 • Grown until fruit production
Krippner et al. (2015)	Maize (straw)	Spiked soil	0.32 0.62	• Mixture of 10 PFAS spiked at 2 concentrations: 0.25 and 1 mg/kg • Soil properties: pH = 7.2, clay = 18%, silt = 34%, sand = 48% • Plants cultivated to maturity (128 days)
Lan et al. (2018)	Wheat (shoot)	Spiked soil	0.81 0.16	• Individually tested 6 PFAS spiked at 2 concentration: 0.2 and 2 mg/kg • Soil properties: pH = 6.6, organic matter = 6.64%, sand = 25.6%, silt = 35%, clay = 39.4% • Shoots harvested after 4 weeks
Lasee et al. (2019)	Alfalfa (shoot)	Spiked sand	1.4	• Laboratory grade sand spiked with methanol stock solution containing 6 PFAAs

Reference	Plant	Growing media	Transfer factor	Experimental details
				• Plants grown for 2 months
Stahl et al. (2009)	Maize (straw)	Spiked soil-sand	0.13 0.10 0.21 0.20 0.16	• PFOS and PFOA spiked at 5 concentrations ranging from 0.25 to 50 mg/kg • Soil properties: pH = 7.0 • Plants harvested after approximately 5 months
Stahl et al. (2009)	Oats (straw)	Spiked soil-sand	0.22 0.15 0.27 0.76 0.83	• PFOS and PFOA spiked at 5 concentrations ranging from 0.25 to 50 mg/kg • Soil properties: pH = 7.0 • Plants harvested after approximately 3 months
Stahl et al. (2009)	Wheat (straw)	Spiked soil-sand	0.20 0.27 1.0 0.86 1.5	• PFOS and PFOA spiked at 5 concentrations ranging from 0.25 to 50 mg/kg • Soil properties: pH = 7.0 • Plants harvested after approximately 3.5 months
Stahl et al. (2009)	Wheatgrass (shoot)[b]	Spiked soil-sand	0.21 0.23 1.3 0.74 0.44	• PFOS and PFOA spiked at 5 concentrations ranging from 0.25 to 50 mg/kg • Soil properties: pH = 7.0 • Four grass cuttings over 6 weeks
Wen et al. (2014)	Wheat (straw)	Biosolids-amended soil	0.33 0.24 0.26 0.27	• Field collected biosolids-amended soil at 4 rates ranging from 4.5 to 36 dry t/ha (applied once a year since 2006) • Soil properties (control): pH = 8.11, organic matter = 0.78% • Plants harvested after 7 months
Wen et al. (2016)	Alfalfa (shoot)	Biosolids-amended soil	0.41	• Field collected biosolids-amended soil received 20 dry t/ha for 9 years • Soil properties (control): pH = 7.36, OC = 1.01%, Clay = 7.79%, silt = 59.1%, sand = 33.1%, CEC = 25 cmol/kg • Plants harvested after 45 days

Reference	Plant	Growing media	Transfer factor	Experimental details
Wen et al. (2016)	Maize (shoot)	Biosolids-amended soil	0.17	• Field collected biosolids-amended soil received 20 dry t/ha for 9 years • Soil properties (control): pH = 7.36, OC = 1.01%, Clay = 7.79%, silt = 59.1%, sand = 33.1%, CEC = 25 cmol/kg • Plants harvested after 45 days
Wen et al. (2016)	Ryegrass (shoot)	Biosolids-amended soil	0.18	• Field collected biosolids-amended soil received 20 dry t/ha for 9 years • Soil properties (control): pH = 7.36, OC = 1.01%, Clay = 7.79%, silt = 59.1%, sand = 33.1%, CEC = 25 cmol/kg • Plants harvested after 45 days
Zhao et al. (2014)	Wheat (shoot)	Spiked soil	0.51 0.26 0.15 0.38 0.17 0.12	• Soil spiked with mixture of 11 PFAS at 3 concentrations: 200, 500 and 1000 µg/kg (treatments with and without earthworms) • Soil properties: pH = 7.67, organic matter = 4.11%, CEC = 38.47 cmol/kg, clay = 24%, silt = 64%, sand = 12% • Plants harvested after 30 days
Zhao et al. (2017)	Rapeseed (shoot)	Spiked soil	0.65 0.55	• Soil spiked with PFOS and PFOA (300 µg/kg) with and without Cd • Soil properties: pH = 7.51, OC = 1.81% • Plants harvested after 70 days
Zhao et al. (2017)	Wheat (shoot)	Spiked soil	0.28 0.13	• Soil spiked with PFOS and PFOA (300 µg/kg) with and without Cd • Soil properties: pH = 7.51, OC = 1.81% • Plants harvested after 70 days

[a] Braeunig et al 2019 reported plant concentrations on a wet weight basis. Transfer factors in the table were calculated by first converting the plant concentrations to a dry weight assuming 15% dry matter

[b] the wheatgrass study by Stahl et al 2009 investigated plant uptake of PFAS across four cuttings over separate approximate 6-week intervals from planting. The transfer factors presented in the table from this study are the averages per concentration treatment across each of the four cuttings