

NATIONAL COLLABORATIVE STUDY ON THE INCIDENCE AND MOBILITY OF PFAS FOLLOWING LAND APPLICATION OF BIOSOLIDS

Ian Pepper, Mark Brusseau, Sarah Prasek, Jon Chorover and Greg Kester

ABSTRACT

This study successfully produced the largest U.S. dataset of soil PFAS concentrations resulting from land application of municipal biosolids. Overall, median PFAS soil concentrations of four EPA regulated PFAS analytes at 23 land application sites were less than 1 ppb. Mean values were also generally low, but were higher than median values due to the occurrence of very high values at 2 sites. Soil PFAS concentrations showed that land application of municipal biosolids rarely resulted in unacceptably elevated soil PFAS concentrations regardless of land application loading rate. These concentrations were less than or close to soil screening levels (SSLs) calculated using illustrative input parameters. Since the SSLs define the maximum soil concentrations that are protective of groundwater (less than EPA regulatory concentrations), this shows that the potential for significant leaching of PFAS and subsequent groundwater contamination is low at most land application sites across the country. This statement is supported by the significant attenuation of soil PFAS concentration with increased soil depth likely due to adsorption at the air water interface and with soil organic matter. The impact of industrial inputs in biosolids was not evaluated. However, a major factor preventing groundwater contamination is likely the quality and source of biosolids with respect to PFAS concentrations.

BACKGROUND

Perfluoroalkyl and polyfluoroalkyl substances (PFAS) are organic compounds that vary in chain length and contain highly stable carbon-fluorine bonds (Buck et al., 2011). These compounds are often categorized according to their length as short or long chain PFAS. Short chain PFAS generally consist of six or less fluorinated carbons, while long chain PFAS are seven or more (AWWA, 2019). Fluorinated properties contribute to their resistant characteristics and repellent nature against oil, grease, and water. These desirable characteristics have proven useful in many industrial, commercial, and household products. The manufacturing of PFAS began in the 1940s and their beneficial properties are responsible for their continued use. PFAS can be found in some non-stick cookware, textiles, firefighting foams, leather treatments, paper products, packaging for food, waxes, cosmetics, carpets and many other products. At present, there are several thousand compounds that have been identified as PFAS.

Although well known, per and polyfluoroalkyl substances (PFAS) are still emerging contaminants of critical concern that, until recently, have been largely unregulated. They have been shown to result in adverse human health effects and have been documented to be commonly present in the bloodstream of humans at levels of 2 ng per ml or 2 parts per billion (ppb) (Poonthong et al., 2020). Current studies have shown some of the negative health effects associated with PFAS include: increased cholesterol levels; changes present

in liver enzymes; high blood pressure in pregnant women; increased risk of kidney/testicular cancers; decreases in infant weight at birth; and a decreased immune response to immunizations in children (Steenland et al., 2020; CDC, 2021).

Concern over adverse health effects associated with exposure to PFAS led the EPA to adopt maximum contaminant levels (MCLs) for drinking water of 4 parts per trillion (ppt or ng/L) for perfluorooctanoic acid (PFOA) and perfluorooctane sulfonic acid (PFOS), 10 ppt for perfluorohexane sulfonic acid (PFHxS) and perfluorononanoic acid (PFNA), and a combined hazard index of 1 for 4 other PFAS.

Because of their use in many commercial and household products and ubiquity throughout society, PFAS are inevitably present in the wastewaters entering municipal wastewater treatment plants (WWTP). PFAS persist throughout the treatment process and ultimately end up in treated wastewater and municipal biosolids. The presence of PFAS in municipal sludge and biosolids has been well documented. For example, Venkatesan and Halden (2013) investigated PFAS concentrations in biosolids throughout the US; the most frequently detected PFAS were PFOS, PFOA, and perfluorodecanoic acid (PFDA). PFAS concentrations within biosolids are generally minimal but can be increased from industrial inputs (Washington et al., 2010). In this discussion, we focus on municipal biosolids that are not industrially impacted.

The presence of PFAS in municipal biosolids has led to concern over the potential impacts of land application of biosolids to human health and the environment. Concerns about PFAS in Maine began in 2016, following land application of industrially contaminated biosolids and paper mill sludge. The use of hay grown on impacted fields as fodder for cows resulted in milk with unacceptably high levels of PFAS. A national furor against PFAS followed, and on April 15, 2022 the Maine State House and Senate passed a bill that banned the use of all biosolids for land application. In June 2024, Connecticut implemented a ban on land application or distribution with a simple sentence inserted into legislation (“No person shall use, sell, or offer for sale in this state as a soil amendment, any biosolids or wastewater sludge that contain PFAS”) (State of Connecticut Substitute Senate Bill No. 292). This raised concern of whether additional states or a national ban could follow. In contrast, similar concerns in Michigan have led to proactive source control measures to mitigate the industrial contamination of biosolids and prevent the land application of industrially contaminated biosolids (EGLE, 2021).

A critical factor limiting our ability to determine health risks from land application of biosolids is the lack of data. More sampling and monitoring data for PFAS in non-industrially impacted biosolids and receiving soils are needed to better characterize the magnitude of PFAS originating from land application. In addition, more detailed investigations of PFAS distributions and leaching in soil are needed beyond the few that have been conducted to date. Several projects have recently started under the auspices of the EPA, USDA, and the Water Research Foundation. These studies are anticipated to add to our understanding of the impacts of land application on soil contamination, leaching potential, and uptake into plants. However, these studies are focused on a single or a select few sites.

To expand this localized approach, a nationwide collaborative project has been initiated by the University of Arizona. This project comprises a national collaborative effort involving field studies conducted across broad geographic regions of the U.S. with differing soils, climates, and depth to groundwater (Pepper, 2022). This project is currently in progress. In this report, we provide an update on the national collaborative project that documents the current status of the project with respect to incidence and distribution of PFAS derived from land applied municipal biosolids.

APPROACH

In January 2020, the Pima County Board of Supervisors in Tucson, Arizona passed a moratorium on land application of biosolids in Pima County because of concern over the presence of PFAS analytes in biosolids. The resulting landfill disposal of Class B biosolids produced by Pima County Wastewater Department rather than land applying increased the annual cost from \$1.3M to \$3.3M. In response to this situation, the University of Arizona WEST Center began a collaborative research project with Pima County Wastewater, to evaluate whether land application of non-industrially impacted biosolids was a significant route of human exposure to PFAS, via contamination of groundwater subsequently used as a potable water supply.

Research consisted of a replicated field study implemented in Pima County in March 2020. Specifically, surface and depth soil samples were collected from agricultural plots that had received known loadings of biosolids since 1984. Soil samples were collected at three depths and analyzed for PFAS. In addition, current biosolids samples and groundwater samples used for irrigation were also assayed, as well as appropriate control plots which had not been subject to land application.

Data from the study showed that the concentrations of PFAS in long-term land application plots were low, and that the mobility of PFAS was minimal, with approximately 70% attenuation of PFAS occurring within the surface 6 feet of soil. It was also found that the irrigation water used for crops often contained significant levels of PFAS, therefore representing a contributing source of soil PFAS. Upon review of the data, the Pima County Board of Supervisors rescinded the moratorium on land application in November 2020. Pima County subsequently returned to recycling their biosolids to agricultural land as a beneficial soil amendment.

The acknowledgement that a local problem had been solved by a local study, resulting in a science-based regulation, suggested that a national problem could be addressed by a extensive national study. This gave rise to the concept of the “National Collaborative PFAS Project”, the goal of which is to evaluate whether land application of municipal biosolids is a significant public health route of exposure to per- and polyfluoroalkyl substances or PFAS. Of greatest concern are two potential indirect routes of exposure, which will be evaluated in two phases of research:

Phase I: Evaluate the potential for migration of PFAS through soil and vadose zones into groundwater following the land application of municipal biosolids.

Phase II: Evaluate the potential for crop uptake of PFAS in a variety of crops following land application of municipal biosolids.

In this report, we provide data for Phase I, which is now close to completion. The specific objectives of Phase I are:

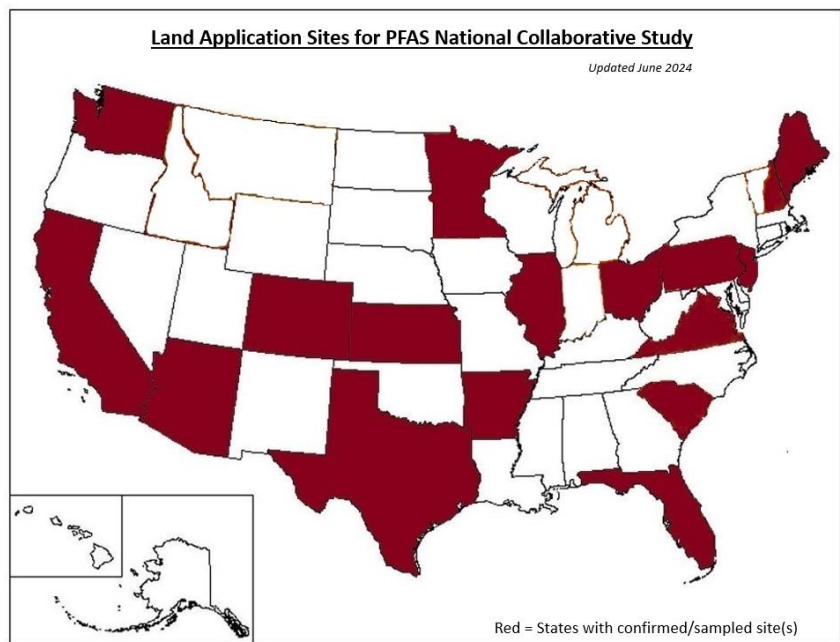
- 1) Evaluate the concentration of PFAS in surface soil following long-term land application of municipal biosolids.
- 2) Evaluate PFAS concentrations currently found in municipal biosolids.
- 3) Assess the potential mobility (leaching) of PFAS through soil.
- 4) Evaluate PFAS concentrations in groundwater in close proximity to land application sites to create paired datasets of soil and water PFAS concentrations.
- 5) Compare actual groundwater PFAS concentrations to predicted concentrations using a screening level model for PFAS leaching through soil and vadose zone.

The National Collaborative PFAS Project is unique in several ways. The study is truly nationwide in scope including a variety of different soils, depths to groundwater, and climates at 23 sites in 17 states. Land application sites from across the United States were identified, and soil samples collected from both irrigated and non-irrigated sites. Sampling methodology at each site was identical, allowing for direct comparison of data from a national set of real-world field sites. The study allows for robust calibrated model development, and quantitative data allows for risk assessments on specific land application sites. Importantly, only land application of municipal biosolids is has been considered, precluding industrially contaminated biosolids.

To ensure coordination of the research, a strict sampling and analysis protocol was conducted at all sites. An 18-minute video was provided to all site personnel to standardize sample collection and avoid contamination. In addition, all samples were sent to the University of Arizona prior to being processed and sent on to the University of Arizona Laboratory for Emerging Contaminants (ALEC) for PFAS analysis.

At each site, soil samples were collected at 1, 3 and 6 foot depths from the surface. Wherever possible, groundwater samples from close proximity to each site were also collected. Samples were collected from across the U.S. by farmers and academic researchers utilizing land application sites with records of known biosolid loading rates (See Map 1). Whenever possible, nine soil cores were collected from each site, three from control plots (no biosolids), and three each from plots with two different loading rates of biosolids (“low” and “high”). Lifetime loading rates are shown in Tables 1 and 2. Note that both Class A and B biosolid sites were included in the study. Collecting loading rate data from many years of land application was difficult, and not all sites could provide these data. At most sites, a total of 27 soil samples were collected: 3 plots per site x 3 cores per plot x 3 sample depths per core. Soils were analyzed for 25 different representative PFAS using Method EPA 1633.

Following analysis of all soils for PFAS, select soils will be chosen for characterization based on: i) unique PFAS profiles; ii) higher concentrations of PFAS; and iii) corresponding PFAS analyses of groundwater to create paired data sets of soil and groundwater. Soil characterization data plus corresponding soil PFAS concentrations will be inputted into a screening level model for PFAS leaching (Guo et al., 2022). This model will be used to predict the potential extent of leaching of PFAS into groundwater which will then be compared to actual PFAS groundwater concentrations. The methodology used for PFAS analysis is outlined below.



Map 1. States where samples were collected for the study.

Extracts for liquid chromatography-tandem mass spectrometry (LC-MS/MS) analysis of PFAS were prepared from soil samples and water samples separately, according to EPA Method 1633 guidance. Aliquots of soil (5 g) were mixed with PFAS Extraction Internal Standards (EIS), sequentially extracted three times with 0.3 % ammonium hydroxide in methanol, and centrifuged to combine supernatants before pH adjustment to 6.5, and finally clean- up by solid phase extraction. Water samples (250 ml) were mixed with EIS, adjusted to pH 6.5, and cleaned up by solid phase extraction using Waters Oasis WAX cartridges (also used for soil extractions). After addition of Non-extracted Internal Standards (NIS), extracts (20 ul) were injected onto a reversed phase analytical column (100 x 3 mm, 3 um), and separated with an aqueous 20 mM ammonium acetate - methanol gradient on an HPLC with delay column and Teflon fittings replaced, at 0.5 ml min⁻¹ flow rate. Twenty-five PFAS were detected using optimized transitions, collision energies, and declustering potentials on a high resolution, accurate mass quadrupole-time of flight (QToF) tandem mass spectrometer with negative mode electrospray ionization.

RESULTS

Datasets for each site were sent individually to site personnel, and all data will be analyzed in detail in preparation for peer-reviewed publications. In this report, we present an overview of the data that illustrates incidence and distribution of biosolid-derived PFAS in land application plots across the US. Data from 23 sites in 17 states are presented.

Incidence of PFAS analytes in soil samples at 1, 3, and 6 feet depths are illustrated in “Box and Whisker” charts in Figures 2-10. A schematic diagram of a “Box and Whisker” plot is shown below in Figure 1.

A “Box and Whisker” plot, sometimes referred to as a “Box Plot” is a simple way to visually display multiple values of a given parameter in terms of quartiles, where a quartile shows the data distribution for 25% of all data. In the diagram, the median value is the middle value that separates the upper 50% of the values (two quartiles) from the lower 50% (also two quartiles). For the upper 50% of the values, the Upper Quartile (25%) extends from the median value to the upper extremity of the box. The remaining upper 25% is shown as the chart’s whisker and extends from the Upper Quartile value to the Upper Extreme value. Outside of the Upper Extreme are Upper Outliers, whose values are excessively different from the median value. Whether a value is within the Upper Extreme range or is a true Outlier is related to its value relative to the standard deviation of the dataset. Analogous definitions exist for the Lower Quartile and Lower Extreme. In this plot, X represents the mean value of the dataset.

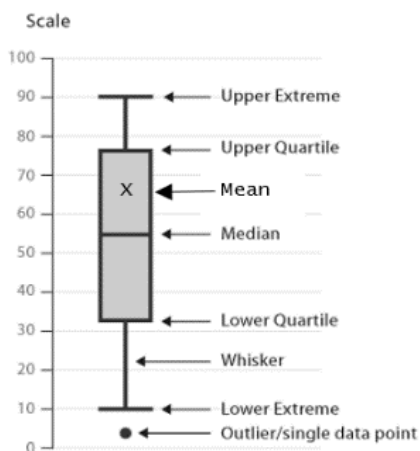


Figure 1. Schematic Box and Whisker

Figures 2-10 illustrate three Box and Whisker charts for each of the Control, Low Biosolid and High Biosolid plots. Each graph shows 25 PFAS analyte concentrations at 1, 3 or 6 feet depths. The color code for the 25 PFAS analytes is shown in Table 3. It is important to note that the concentrations displayed represent the individual concentrations from each site regardless of the actual loading rates, which vary from site to site. Actual biosolid loading rates for each site are shown in Tables 1 and 2. Despite the variability in loading rate, the Box Plots show tangible

and distinct differences in PFAS concentrations between the overall Control, Low and High Biosolid plots. Clear differences also exist between the 1, 3 and 6 feet soil samples.

a) Distribution of Soil PFAS Analytes in Land Application Plots Nationally

Figures 2, 3, and 4 show PFAS soil concentrations from Control plots at 1, 3, and 6 feet depths. For all plot types, there are high value outliers, including Control plots. Due to scaling issues related to data display, some outliers are not shown in Figures 2-10. However, overall concentrations of all analytes are low for Control plots as indicated by the mean and median values across all sites. Mean values of all analytes averaged over all sites are less than 1 ppb except for PFOS which is marginally higher than 1 ppb. Overall, PFAS concentrations are highest in the 1 foot control samples, when compared to 3 feet and 6 feet samples. Despite the overall low concentrations of analytes (See Discussion Section d), there are upper outlier values for several compounds.

Soil PFAS data for the Low Biosolid plots are shown in Figures 5, 6, and 7. Concentrations of PFAS analytes in 1 foot samples are still low, but higher than Control plots as evidenced by several mean values greater than 1 ppb, including PFDA, PFUnA, PFHps, 6:2 FTS and PFOS. However, median 1 foot concentrations were all less than 1 ppb. PFAS concentrations in 3 feet and 6 feet samples showed similar trends, but also significant attenuation with increased soil depth.

Samples from High Biosolids plots generally showed increased soil PFAS concentrations relative to Control and Low Biosolid plots (Figures 8, 9, and 10). Several compounds had mean values of soil PFAS concentrations greater than 1 ppb, including PFOA, PFDA, PFUnA, PFHpS and PFOS. PFOS concentrations are notable with a mean value close to 10 ppb. Yet again, significant attenuation occurred with increased soil depth. In addition, median values for all High Biosolid plot samples were less than 1 ppb.

b) Incidence of EPA Regulated Drinking Water PFAS in Soil

Mean, median, maximum and minimum soil concentrations of EPA regulated PFAS compounds are shown in Tables 4, 5, and 6. Values for 1 foot samples are shown since these are normally higher than 3 feet and 6 feet samples. Also shown in these tables are soil screening levels (for discussion of SSLs, see Discussion Section d), and EPA drinking water maximum allowable contaminant levels (MCLs). For Control plots (Table 4), all soil mean and median values are lower than corresponding soil screening levels except for PFOA, which is marginally higher (0.342 versus 0.3). For Low Biosolid plots (Table 5), all median values are less than corresponding soil screening levels except for PFOA. Soil mean values for PFOS, PFHxS and PFNA are lower than the SSLs, whereas the mean value for PFOA is higher than the SSL.

In High Biosolid plots, overall soil median PFAS values were always lower than mean values. PFOS, PFHxS and PFNA median values were lower than corresponding SSLs. The median value for PFOA (0.47 ppb) was slightly higher than the corresponding SSL (0.3 ppb). The mean values for PFOA and PFOS were greater than corresponding SSLs.

Finally note that GenX was not one of the analytes monitored in this study because when the study was initiated, it was not known that GenX would be one of the analytes regulated by EPA.

c) Recent Biosolids PFAS Concentrations

Biosolids samples collected during 2022-2024 were received from most (but not all) sites. PFAS analyte concentrations of these current samples are shown in Tables 7 and 8. Concentrations of analytes are universally low with the exceptions of samples from Site 7 and Site 19. For Site 7, six analyses were in excess of 100 ppb. For Site 19, three samples were in excess of 100 ppb.

d) Groundwater PFAS Concentrations of EPA Regulated Analytes

Table 9 shows the concentrations of PFAS in water samples provided by sites in the study. Note that only 10 sites out of the 23 were able to provide water samples. Additionally, sources and methods of collection of water samples varied from site to site. Concentrations of PFOA, PFOS and PFHxS were often in excess of the corresponding EPA MCL values, whereas PFNA concentrations exceeded the EPA MCL only once.

DISCUSSION

a) Soil PFAS Analytes in Land Application Plots Nationally

Figures 2-10 show the national incidence of PFAS averaged over all sites. This high elevation view of biosolid derived PFAS leads to the initial assessment that land application of municipal biosolids does not lead to unacceptably high levels of soil PFAS. In contrast, previous studies have shown that industrially contaminated biosolids result in very high levels of soil PFAS (Wilhelm *et al.*, 2008; Washington *et al.*, 2010). Interestingly, even Control plots that had never received land applied biosolids still showed detectable PFAS (Figures 2-4). The source of PFAS in these control plots is generally unclear, but their presence demonstrates the ubiquitous nature of PFAS. In fact, PFAS has been documented to be present in soils worldwide, even in remote areas far removed from obvious industrial inputs of PFAS (Brusseau *et al.*, 2020). Two potential explanations for this phenomenon are windblown deposits of PFAS, and documented rain and snow deposits (Johnson *et al.*, 2022).

The concentrations of PFAS in the 1 foot Control soil samples decreased with increased soil depth, showing attenuation of PFAS due to interaction with soil. The degree of PFAS attenuation will depend on many factors but two major factors are likely to be soil type and amount of rainfall and/or irrigation (see Section d later in Discussion). When viewed over multiple sites, attenuation of PFAS with increased soil depth is clearly observed.

Figures 5-7 show soil PFAS concentrations from Low Biosolid plots at soil depths of 1, 3 and 6 feet. A comparison of these data with Control plot values demonstrates increased PFAS, presumably of biosolid origin. However, it is important to note that cores from the Control plots and Low Biosolid plots are taken from physically separated locations, sometimes miles apart and with different soil types. Data from multiple locations clearly establish the correlation between land application of biosolids and enhanced soil PFAS. That being said, increases are modest and mostly below 1 ppb. Similar to Control plot values, PFAS concentrations decreased with increased soil depth. Of all analytes, PFOS mean concentrations from 1 foot samples at Low Biosolids plots were the highest at almost 2 ppb. Note also that mean values averaged over all sites are always higher than median values of the data. This is mostly due to the elevated concentrations at two sites (Sites 3 and 20) that skew the data. Median values reflecting 50% being lower, provide a clearer

indication of PFAS soil concentrations.

Figures 8-10 show data from High Biosolid plots. Data show the same trends as those from the Low Biosolid plots. The soil PFOS concentration at 1 foot resulted in the highest mean value of 8 ppb. However, removal of data from Sites 3 and 20 reduces the value to 3.2. Attenuation with soil depth continued to be observed, resulting in all mean concentrations of analytes being less than 2 ppb at the depth of 6 feet. However, the High Biosolid plots provided many more Upper Outliers than the Control and Low Biosolid plots. The source of these outliers is unclear because, in some cases, biosolids have been land applied since the 1980s.

Considering data from all plots nationally, an evaluation of mean and median concentrations shows that: i) land application of municipal biosolids rarely resulted in unacceptably high soil PFAS concentrations; and ii) attenuation of biosolid derived PFAS occurs rapidly within the soil profile and close to the surface.

b) Incidence of EPA Regulated Drinking Water PFAS Analytes

Incidence of EPA regulated PFAS compounds in soil are shown in Tables 4 - 6, along with mean, median, maximum, and minimum soil concentration from the National Study. For PFHxS and PFNA, all soil mean and median concentrations were below 1 ppb. For PFOA, all mean and median values were less than 1 ppb except for the 1 foot High Biosolids plot samples. For PFOS, all median concentrations were less than 1 ppb, but all mean concentrations exceeded 1 ppb and were as high as 8.5 ppb for the 1 foot High Biosolids samples. However, omitting soil PFAS data from Sites 3 and 20 results in a PFOS mean of 3.2 ppb.

Since median values for the EPA regulated analytes were all less than, or close to, the corresponding SSLs, these data indicate that land application of municipal biosolids is generally not a significant source of groundwater contamination. However, it is critical to point out caveats to this assessment. As noted previously, the degree to which PFAS may leach through soil and impact groundwater is dependent upon numerous factors, many of which are site specific. For example, one important factor is the source and nature of the biosolids. If industrially contaminated biosolids are land applied, this can lead to soil and groundwater contamination as demonstrated by studies in Decatur, Alabama (Washington *et al.*, 2010) and Sauerland, Germany (Wilhelm *et al.*, 2008). Other important factors include soil type, depth to groundwater, and magnitudes of natural and human-induced water inputs (See also Section D).

c) Biosolids and Groundwater PFAS Concentrations

With the exception of two sites, recent biosolids PFAS concentrations were relatively low and these levels in soil further decrease with attenuation. Thus, municipal biosolids, without industrial contamination, are unlikely to cause groundwater contamination since they result in soil PFAS concentrations lower than SSLs that are protective of groundwater. However, biosolids land applied several decades ago may have contained higher PFAS concentrations than recent samples of biosolids. Biosolids from Site 7 contained high PFAS concentrations, and following discussions with site personnel, it was discovered that inputs into the raw wastewater included a direct line with landfill leachate. The source of PFAS in Site 19 biosolids, the other site with higher PFAS concentrations, remains unclear.

In Table 9, groundwater PFAS concentrations are highly variable. At one site, Site 20, groundwater concentrations collected at the High Biosolids plot were higher than concentrations of PFAS in water collected at the Control plot. However, care must be taken in drawing conclusions about direct cause and effect for several reasons: 1) The hydrological conditions (e.g., depth to groundwater and direction of

groundwater flow) are unknown; and 2) The history of the site is unknown. The high variability of PFAS concentrations within groundwaters may be due to multiple anthropogenic inputs. For many years, the conventional wisdom was that groundwaters were pristine and free of chemical and microbial contaminants. However, in a major national study of groundwaters, samples of groundwater were collected from 448 sites in 35 US States (Abbaszadegan et al., 2003). Following analysis, it was shown that approximately 1/3 of all groundwaters had received anthropogenic contaminants. Nationally, if all biosolids were land applied, it would only require 0.5% of total cropland (National Biosolids Data Project, 2018). Thus, it is evident that other sources of contamination contributed to those anthropogenic inputs. Such sources could include irrigation water, leachate from sanitary landfills, effluent from industrial plants, and pesticides from agricultural soil or runoff.

d) Potential for Groundwater Contamination

Evaluating the potential for PFAS in soil to impact groundwater requires characterization of the leaching potential of PFAS for the site of interest. The leaching potential in turn is a function of many factors including soil infiltration rates, evapotranspiration, soil properties including texture, the amount of precipitation or irrigation, and the specific PFAS in question (Guo *et al.*, 2022).

Overall, the risk of significant PFAS contamination of groundwater from land application of biosolids would most likely be in a scenario where biosolids contaminated with industrial inputs of PFAS are applied to a coarse textured soil with a shallow depth to groundwater and high rainfall or irrigation (Pepper *et al.*, 2023). In contrast, risk of contamination would be less significant when municipal biosolids with lower PFAS content are applied to finer textured soils with large depth to groundwater. Finally note that there is greater risk of the more mobile short chain PFA analytes leaching, than longer chain PFAS.

To quantify the risk of leaching, a modeling approach is needed. A suite of mathematical models has been developed at The University of Arizona to simulate the migration, retention, and leaching of PFAS in the vadose zone (Guo et al., 2020, 2022; Brusseau and Guo, 2023; Smith et al., 2024). The models range in complexity and associated data-input requirements. The simplest version is based on the widely used EPA dilution-attenuation factor (DAF) soil screening model (EPA, 1996). The EPA model is based on determining the maximum concentration of the target constituent in soil (the soil screening level, SSL) that would be determined to be protective of groundwater (not exceed a selected concentration such as an MCL).

The standard EPA model considers retention of the constituent by sorption to soil solids as well as partitioning to the soil atmosphere. It does not consider adsorption at the air-water interface, which has been determined to be a critical source of retention for PFAS in certain conditions. Brusseau and Guo (2023) revised the EPA DAF model to incorporate adsorption at the air-water interface.

The simplified equation for the SSL is given by:

$$SSL = C_{soil} = C_{gw} DAF \frac{\theta_w}{\rho_b} R_d \quad [1]$$

where R in the original model is defined as:

$$R_d = \left(1 + K_d \frac{\rho_b}{\theta_w} + H \frac{\theta_a}{\theta_w} \right) \quad [2]$$

and R in the revised model is defined as:

$$R_d^{Rev} = \left(1 + K_d \frac{\rho_b}{\theta_w} + H \frac{\theta_a}{\theta_w} + K_{aw} \frac{A_{aw}}{\theta_w} \right) \quad [3]$$

and where DAF is the dilution-attenuation factor, ρ_b is porous-medium bulk density (M/L³), θ_a is volumetric air content (L³/L³), and θ_w is volumetric water content (L³/L³), $\theta_w + \theta_a = n$, where n is porosity, K_d (L³/M) is the sorption coefficient, H (-) is Henry's law constant, K_{aw} is the air-water interfacial adsorption coefficient (L³/L²), and A_{aw} is the specific air-water interfacial area (L²/L³).

The revised model can be used to calculate SSLs for any given PFAS at any land application site, provided soil characteristics at the site are known. Essentially the SSL for a given PFAS at a given site identifies the maximum allowable soil PFAS concentration that would maintain groundwater concentrations to less than or equal to any MCL such as the new EPA drinking water regulation of 4 ppt for PFOS and PFOA.

An example application of the revised DAF model is presented in Tables 10-13 for PFOA, PFOS, PFHxS, and PFNA, respectively. In these examples, a SSL for each PFAS is determined for a hypothetical soil with realistic estimates of soil characteristics such as 1.5 g/cc for bulk density and 1% organic carbon. For each of these calculations' parameters related to both the specific soil and the specific PFAS must be inputted either by estimation, calculation or physical measurement. The newly promulgated MCLs are used as the target groundwater concentration. The source of the various input parameters is noted in the footnotes. It is observed that the SSLs for the revised model higher than those determined with the original model. This is due to the impact of air-water interfacial adsorption. This example illustrates how the revised model can be used to determine SSLs for each site, with the relevant soil characterization data available. SSLs would be determined for each individual PFAS.

It is critical to note that the standard and revised DAF models have uncertainties and that the SSLs determined from the models are for screening purposes. The uncertainties and limitations are discussed in EPA (1996) and Brusseau and Guo (2023). It is also critical to note that the calculated SSL values are for illustrative purposes only. Actual SSL values will be site specific, and would need to be calculated using soil properties measured for the target site.

The site dependency of SSL originates from the influence of soil and PFAS properties on retention. Inspection of equation 1 reveals that C_{gw} and DAF do not change once selected. In addition, soil bulk density varies comparatively minimally across different soil types. Hence, the two parameters in equation 1 that will typically exhibit the greatest variability across sites are R_d and θ_w . Inspection of equations 2 and 3 shows that K_d , K_{aw} , and A_{aw} are the three parameters that cause R_d to exhibit variability, along with θ_w . The air-water interfacial area is a function of both soil properties and θ_w particularly the amount of fine-grained particles in the soil. K_d in turn, is a function of soil properties such as the amount of soil organic carbon as well as the properties of the individual PFAS (such as chain length). K_{aw} is also a function of the properties of the individual PFAS. In total, SSLs for a given PFAS can be anticipated to vary across sites due to differences in K_d and A_{aw} . For example, calculated SSLs for PFOS range from 0.5 to 21 $\mu\text{g}/\text{kg}$ when soil organic matter is increased from 0.1% to 10% (Table 14). The 0.5 value results from inputting a soil organic carbon value of 0.1%, decreasing the amount of PFOS sorbed. In contrast, increasing the soil organic carbon to 10% increases the amount of sorption and decreases the amount of PFOS available for leaching. Clearly

then, a suite of SSLs are feasible, depending on the particular soil. SSLs will also vary for different PFAS for a given site due to differences in K_d and K_{aw} among the PFAS. This is observed by comparing the SSLs in Tables 10-13 for the four example PFAS. Note that for most soils, organic matter contents are between 1 and 5%.

SUMMARY

The National Collaborative PFAS Study has successfully resulted in the largest U.S. dataset on incidence of soil PFAS concentrations resulting from municipal biosolids land application. The mean and median concentrations of PFAS were low. A set of illustrative SSL calculations were presented for four EPA regulated PFAS, along with a discussion of the site-specific variability that can be anticipated due to differences in soil properties. Overall, all mean and median PFAS soil concentrations measured nationally at land application sites were less than or close to calculated SSLs for specific EPA regulated PFAS analytes in typical soils with modest soil organic carbon content. These data will be utilized for modeling the potential risk of groundwater contamination following leaching of analytes through soil and vadose zone. Wherever possible, predicted groundwater PFAS concentrations will be compared to actual groundwater concentrations at specific sites. Potentially these data could be very useful to several States across the country by illustrating PFAS levels in soils within land application sites. Multiple peer review publications will be produced from Phase 1 of the research.

PHASE 2 of the National PFAS Study

Phase 2 will evaluate the indirect route of exposure to PFAS from the ingestion of foodstuffs from crops grown on land application plots. Phase 1 of the research project established a national network of land application plots where soil PFAS concentrations are now known. Capitalizing on this, an attractive concept is to establish a similar national network of plant uptake data across the U.S. by growing crops on the 23 land application plots already studied. This will allow for the creation of paired data sets of soil and crop PFAS concentrations. Multiple crop types will be grown including for example corn, oats and alfalfa. This will evaluate differential plant uptake of different PFAS analytes by different crops. In addition, planting the same crop at different national locations will allow for the influence of different soil types and climate regimes on plant uptake to be evaluated.

At each site, plant samples of roots, stems and leaves will be collected as well as edible crop produce. All samples will be sent to the University of Arizona for PFAS analyses at the Arizona Laboratory for Emerging Contaminants (ALEC). This will allow for crop uptake analysis. Using estimates of daily food intake and PFAS plant concentrations, the amount of PFAS exposure from ingestion of foodstuffs can be calculated and compared to recommended allowable PFAS exposure.

Currently, fundraising for Phase 2 is underway. Crop planting is anticipated in the spring of 2025, with crop sampling and harvesting undertaken in the summer and fall of 2025.

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Table 1. Low Biosolids Plots - Loading Rates^a

Site	Biosolid type (class)	Lifetime loading rate (dry tons/acre)	Application period	Application frequency (times)
S01	Class B	13	1987- 2001 (3 applications) and 2012-2019 (3 applications)	6
S02	Class B	13	1987 -2019	6
S03	Class B	36.4	1996-2016	76
S04	Class A	7.5	2017	1
S05	Class B (2016-2019), Class AA (2020-2022)	25.3	2016-2022	7
S06	Class A	24.8 wet tons/acre	2018-2022	3
S07	Class B	70	1980, 1981, 1982, 1984, 1989, 1991, 1993, 1996, 2001, 2006, 2011, 2016, 2021	13
S08	Class B	14	29	7
S10	Class B	10.8	2005-2019 ^b	12+
S12		19.4	2011 - 2022	6
S13	Class A	5	2023	1
S15	Class B	2.5	2023	1
S22	Class B	15 wet tons/acre	2024	1

^aPlot background information was provided by sites and is not standardized.

^bBiosolids application records date back to 2005, but biosolids were spread many years prior.

Table 2. High Biosolids Plots - Loading Rates^a

Site	Biosolid type (class)	Lifetime loading rate (dry tons/acre)	Application period	Application frequency (times)
S01	Class B	40	2014 - 2019	6
S02	Class B	46	1987 - 2016	13
S03	Class B	52.6	1997-2022	38
S04	Class A	25.5	2016, 2018, 2021	3
S05	Class B (2016-2019), Class AA (2020-2022)	31.9	2016-2022	7
S06	Class A	66.2 wet tons/acre	2018-2023	6
S07	Class B	92.4	1981, 1983, 1985, 1986, 1988, 1990, 1992, 1994, 1998, 2002, 2007, 2012, 2017, 2022	14
S08	Class B	31.5	29	7
S10	Class B	25.8	2005-2019 ^b	12+
S11		14.3	2007, 2010, 2014	3
S12		35.3	2013 - 2023	11
S13	Class A	20	2023	1
S14	Class B	126 wet tons/acre	2013-2022 (no application in 2014)	9
S17	Class B	82.38	1989 - 2023	35
S22	Class B	30 wet tons/acre	2024	1
S23	Class B	280	1996-2022	14

^aPlot background information was provided by sites and is not standardized.

^bBiosolids application records date back to 2005, but biosolids were spread many years prior.

Table 3. Code for PFAS Analytes in Figures 2-10

PFAS Analyte Key						
■ PFBA	■ PFPeA	■ PFHxA	■ PFHpA	■ PFOA	■ PFNA	■ PFDA
■ PFUnA	■ PFDoA	■ PFTriDA	■ PFTreA	■ PFBS	■ PFPeS	■ PFHxS
■ PFHpS	■ PFOS	■ PFNS	■ PFDS	■ 4:2 FTS	■ 6:2 FTS	■ 8:2 FTS
■ FOSA	■ NMeFOSA	■ NMeFOSAA	■ NEtFOSAA			

Table 4. Soil PFAS Concentrations of Analytes Regulated in Drinking Water by EPA

1 Foot, Control Plots

Compound	Soil Mean (ppb)	Soil Median (ppb)	Soil Max (ppb)	Soil Min (ppb)	Soil Screening Level (ppb)	EPA Drinking Water MCL (ppt)
PFOA	0.342	0.115	3.398	0.000	0.3	4.0
PFOS	1.066	0.091	20.906	0.000	3.7	4.0
PFHxS	0.060	0.000	0.898	0.000	0.41	10
PFNA	0.066	0.016	0.869	0.000	4.0	10
HFPO-DA (GenX Chemicals)	Not measured	Not measured	Not measured	Not measured	-	10

Table 5. Soil PFAS Concentrations of Analytes Regulated in Drinking Water by EPA

1 Foot, Low Biosolids Application Plots

Compound	Soil Mean (ppb)	Soil Median (ppb)	Soil Max (ppb)	Soil Min (ppb)	Soil Screening Level (ppb)	EPA Drinking Water MCL (ppt)
PFOA	0.740	0.387	3.269	0.000	0.3	4.0
PFOS	2.260	0.383	17.795	0.000	3.7	4.0
PFHxS	0.083	0.017	0.732	0.000	0.41	10
PFNA	0.122	0.054	0.767	0.000	4.0	10
HFPO-DA (GenX Chemicals)	Not measured	Not measured	Not measured	Not measured	-	10

* If values from S13 Pre Ap are excluded, max concentrations for PFOA is 3.269, for PFOS is 17.795, and for PFHxS is 0.732.

Table 6. Soil PFAS Concentrations of Analytes Regulated in Drinking water by EPA

1 Foot, High Biosolids Application Plots

Compound	Soil Mean (ppb)	Soil Median (ppb)	Soil Max (ppb)	Soil Min (ppb)	Soil Screening Level (ppb)	EPA Drinking Water MCL (ppt)
PFOA	2.410	0.470	19.263	0.000	0.3	4.0
PFOS	8.531	0.527	140.238*	0.000	3.7	4.0
PFHxS	0.252	0.050	3.323	0.000	0.41	10
PFNA	0.812	0.141	8.213	0.000	4.0	10
HFPO-DA (GenX Chemicals)	Not measured	Not measured	Not measured	Not measured	-	10

* If values from S3 and S20 are excluded, max concentration for PFOS is 17.950 and soil mean for PFOS is 3.188.

Table 7. Recent Biosolids PFAS Concentrations, Sites 5 – 13 (ppb)

Analyte/Site	S5 #1	S5 #2	S6	S7	S10 #1	S10 #2	S11	S12	S13
PFBA	5.514	7.965	0.000	337.499	5.096	3.823	0.102	7.625	3.770
PFPeA	6.383	6.808	0.000	1282.833	1.014	ND	ND	27.963	1.120
PFHxA	18.041	16.464	0.000	1229.305	2.898	3.892	0.408	21.811	6.309
PFHpA	1.440	1.792	0.000	472.017	0.376	0.519	0.054	2.704	0.374
PFOA	9.569	8.960	0.000	996.770	1.601	2.721	0.392	20.148	1.862
PFNA	1.076	1.082	ND	8.341	ND	0.398	0.096	2.219	0.753
PFDA	7.883	7.458	NR	5.974	0.433	0.658	0.744	15.441	1.226
PFUnA	0.767	0.655	ND	0.889	0.255	ND	0.000	1.285	0.758
PFDoA	2.440	2.478	ND	ND	0.356	0.681	0.000	4.370	0.994
PFTriDA	0.370	0.509	ND	ND	ND	ND	0.000	0.827	0.211
PFTreA	2.338	1.707	0.000	1.896	0.307	4.745	0.086	2.114	3.533
PFBS	14.873	14.560	NR	1361.222	ND	ND	24.079	19.519	ND
PFPeS	ND	ND	NR	28.645	ND	ND	1.146	ND	ND
PFHxS	0.443	0.339	ND	201.801	ND	ND	1.026	1.899	ND
PFHpS	ND	ND	0.000	9.972	ND	ND	0.000	ND	ND
PFOS	10.082	8.509	ND	71.245	0.726	ND	4.138	37.565	9.806
PFNS	ND	ND	ND	ND	ND	ND	ND	ND	ND
PFDS	0.220	0.187	ND	ND	ND	ND	0.067	0.804	ND
4:2 FTS	ND	ND	ND	ND	ND	ND	ND	ND	ND
6:2 FTS	3.632	6.143	ND	ND	ND	ND	ND	3.777	2.298
8:2 FTS	1.076	0.000	ND	ND	ND	ND	0.157	0.000	1.448
FOSA	0.555	0.592	ND	ND	ND	ND	0.578	2.180	0.394
NMeFOSA	ND	ND	ND	ND	ND	ND	ND	ND	ND
NMeFOSAA	4.493	3.597	NR	ND	ND	1.657	0.000	6.801	2.070
NEtFOSAA	1.815	1.198	ND	ND	ND	ND	ND	2.249	1.551

Table 8. Recent Biosolids PFAS Concentrations, Sites 14 - 22 (ppb)

Analyte/Site	S14	S15	S16	S17	S18	S19	S21	S22
PFBA	0.273	5.189	12.239	NR	2.217	ND	15.676	NR
PFPeA	ND	5.492	ND	ND	7.261	53.511	ND	ND
PFHxA	NR	12.506	3.481	0.000	2.589	86.501	24.442	ND
PFHpA	0.127	1.083	0.943	NR	0.288	6.914	ND	NR
PFOA	0.618	6.618	4.636	NR	2.776	62.392	3.309	NR
PFNA	0.105	1.103	0.498	NR	0.000	23.782	ND	NR
PFDA	1.387	6.773	2.173	NR	1.907	152.773	ND	5.923
PFUnA	0.000	0.888	0.440	NR	0.214	15.295	ND	ND
PFDoA	0.000	2.709	0.825	0.000	0.598	32.989	0.740	1.980
PFTriDA	0.000	0.355	ND	0.000	1.124	13.959	ND	ND
PFTreA	NR	2.455	0.475	0.000	0.769	57.519	0.364	1.231
PFBS	NR	26.224	ND	NR	1.001	8.346	ND	4.488
PFPeS	NR	ND	ND	ND	ND	ND	ND	ND
PFHxS	2.054	0.793	ND	NR	ND	7.775	ND	1.064
PFHpS	0.000	ND	ND	0.000	ND	ND	ND	0.343
PFOS	2.802	7.585	6.596	NR	5.235	387.703	ND	31.886
PFNS	ND	ND	ND	ND	ND	10.178	ND	ND
PFDS	ND	ND	ND	ND	0.231	3.771	ND	4.820
4:2 FTS	ND	ND	ND	ND	ND	ND	ND	1.132
6:2 FTS	0.004	4.252	ND	NR	1.313	12.361	ND	1.309
8:2 FTS	ND	1.858	ND	ND	ND	16.351	ND	ND
FOSA	0.133	0.719	ND	ND	0.435	78.020	ND	ND
NMeFOSA	ND	ND	ND	ND	ND	ND	ND	ND
NMeFOSAA	ND	4.183	2.688	NR	1.766	230.255	ND	NR
NEtFOSAA	ND	2.461	ND	ND	0.000	70.759	ND	ND

Table 9. PFAS Concentrations of EPA Regulated Analytes in Water Samples (ppt)

Sample	Source and Collection Description	PFOA	PFOS	PFHxS	PFNA
S1 #1	groundwater; surface collection	16.006	109.484	88.932	NR
S1 #2	groundwater; surface collection	15.776	50.728	162.161	1.554
S2 #1	groundwater; surface collection	1.597	4.508	13.861	NR
S2 #2	groundwater; surface collection	2.777	2.527	10.194	0.189
S6 - C	canal water	ND	ND	ND	ND
S7 - H	groundwater; auger hole collection	ND	ND	ND	ND
S14 - H #1	groundwater; well collection	17.754	ND	5.132	ND
S14 - H #2	groundwater; well collection	NR	ND	1.063	ND
S14 - H #3	groundwater; well collection	ND	ND	1.554	ND
S17 #1	groundwater; well collection	0.565	ND	2.471	NR
S17 #2	groundwater; well collection	137.325	5.459	21.065	NR
S17 #3	groundwater; well collection	181.102	ND	11.411	ND
S17 #4	groundwater; well collection	0.649	ND	ND	ND
S17 #5	groundwater; well collection	24.362	0.880	6.337	NR
S17 #6	groundwater; well collection	0.321	0.262	2.264	NR
S20 - C	groundwater; auger hole collection	ND	ND	ND	ND
S20 - H	groundwater; auger hole collection	618.176	280.671	140.004	53.881
S21 - C	surface water in field	3.582	1.502	ND	0.346
S22	groundwater; well collection	ND	ND	ND	ND
S23 - H	spring water; surface collection	20.654	5.153	1.117	2.204
	EPA Drinking Water MCL	4.0	4.0	10	10

HFPO-DA (GenX Chemicals), with EPA Drinking Water MCL of 10ppt, was not measured in this study.

C = sample obtained close to control plots

H = sample obtained close to high biosolid plot

Table 10. Example Parameters and Calculated SSLs for PFOA Using the EPA Standard DAF model and the Brusseau and Guo Revised DAF model

Parameter	Standard Model	Revised Model	Notes
Dilution Factor (DF)	20	20	Default, EPA 1996
Attenuation Factor (AF)	1	1	Default, EPA 1996
Dilution-Attenuation Factor (DAF)	20	20	Default, EPA 1996
Bulk density (ρ_b , g/cm ³)	1.5	1.5	Assumed
Water content (volumetric, θ_w , -)	0.24	0.24	Example
Porosity (n, -)	0.4	0.4	Assumed
Sorption coefficient (K_d , cm ³ /g) ^a	1.3	1.3	Estimated
Air-water interfacial adsorption coefficient (K_{aw} , cm) ^b	NA	0.008	Measured
Air-water interfacial area (A_{aw} , cm ⁻¹) ^c	NA	450	Estimated
Distribution term (R_d , -)	8.9	23.9	Calculated
Target groundwater concentration (C_{gw} , µg/L) ^d	0.004	0.004	Set value
Soil Screening Level (SSL, µg/kg)	0.1	0.3	Calculated

^aRepresentative OC = 1%; log Koc from Brusseau, 2023a

^bMeasured value from Brusseau and Van Glubt, 2021

^cEstimated value from Brusseau, 2023b

^dThe target groundwater concentration is based on EPA MCL

Brusseau, M.L. (2023a). Differential sorption of short-chain versus long-chain anionic per- and poly-fluoroalkyl substances by soils. *Environments*, 10, article 175.

Brusseau, M.L. (2023b). Determining air-water interfacial areas for the retention and transport of PFAS and other interfacially active solutes in unsaturated porous media. *Science of the Total Environment*, 884, article 163730.

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Table 11. Example Parameters and Calculated SSLs for PFOS Using the EPA Standard DAF model and the Brusseau and Guo Revised DAF model

Parameter	Standard Model	Revised Model	Notes
Dilution Factor (DF)	20	20	Default, EPA 1996
Attenuation Factor (AF)	1	1	Default, EPA 1996
Dilution-Attenuation Factor (DAF)	20	20	Default, EPA 1996
Bulk density (ρ_b , g/cm ³)	1.5	1.5	Assumed
Water content (volumetric, θ_w , -)	0.24	0.24	Example
Porosity (n, -)	0.4	0.4	Assumed
Sorption coefficient (K_d , cm ³ /g) ^a	10	10	Estimated
Air-water interfacial adsorption coefficient (K_{aw} , cm) ^b	NA	0.12	Measured
Air-water interfacial area (A_{aw} , cm ⁻¹) ^c	NA	450	Estimated
Distribution term (R_d , -)	63.5	288.5	Calculated
Target groundwater concentration (C_{gw} , µg/L) ^d	0.004	0.004	Set value
Soil Screening Level (SSL, µg/kg)	0.8	3.7	Calculated

^aRepresentative OC = 1%; log Koc from Brusseau, 2023a

^bMeasured value from Brusseau and Van Glubt, 2021

^cEstimated value from Brusseau, 2023b

^dThe target groundwater concentration is based on EPA MCL

Brusseau, M.L. (2023a). Differential sorption of short-chain versus long-chain anionic per- and poly-fluoroalkyl substances by soils. *Environments*, 10, article 175.

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Brusseau, M.L. and Guo, B. (2023). Revising the EPA Dilution-Attenuation Soil Screening Model for PFAS. *Journal of Hazardous Materials Letters*, 4, article 100077.

EPA 1996. *Soil Screening Guidance: User's Guide*. Publication 9355.4-23.

Table 12. Example Parameters and Calculated SSLs for PFHxS Using the EPA Standard DAF model and the Brusseau and Guo Revised DAF model

Parameter	Standard Model	Revised Model	Notes
Dilution Factor (DF)	20	20	Default, EPA 1996
Attenuation Factor (AF)	1	1	Default, EPA 1996
Dilution-Attenuation Factor (DAF)	20	20	Default, EPA 1996
Bulk density (ρ_b , g/cm ³)	1.5	1.5	Assumed
Water content (volumetric, θ_w , -)	0.24	0.24	Example
Porosity (n, -)	0.4	0.4	Assumed
Sorption coefficient (K_d , cm ³ /g) ^a	1.0	1.0	Estimated
Air-water interfacial adsorption coefficient (K_{aw} , cm) ^b	NA	0.003	Measured
Air-water interfacial area (A_{aw} , cm ⁻¹) ^c	NA	450	Estimated
Distribution term (R_d , -)	7.2	12.9	Calculated
Target groundwater concentration (C_{gw} , µg/L) ^d	0.010	0.010	Set value
Soil Screening Level (SSL, µg/kg)	0.23	0.41	Calculated

^aRepresentative OC = 1%; log Koc from Brusseau, 2023a

^bMeasured value from Brusseau and Van Glubt, 2021

^cEstimated value from Brusseau, 2023b

^dThe target groundwater concentration is based on EPA MCL

Brusseau, M.L. (2023a). Differential sorption of short-chain versus long-chain anionic per- and poly-fluoroalkyl substances by soils. *Environments*, 10, article 175.

Brusseau, M.L. (2023b). Determining air-water interfacial areas for the retention and transport of PFAS and other interfacially active solutes in unsaturated porous media. *Science of the Total Environment*, 884, article 163730.

Brusseau, M.L. and Van Glubt, S. (2021). The influence of molecular structure on PFAS adsorption at air-water interfaces in electrolyte solutions. *Chemosphere* 281, article 130829.

Brusseau, M.L. and Guo, B. (2023). Revising the EPA Dilution-Attenuation Soil Screening Model for PFAS. *Journal of Hazardous Materials Letters*, 4, article 100077.

EPA 1996. Soil Screening Guidance: User's Guide. Publication 9355.4-23.

Table 13. Example Parameters and Calculated SSLs for PFNA Using the EPA Standard DAF model and the Brusseau and Guo Revised DAF model

Parameter	Standard Model	Revised Model	Notes
Dilution Factor (DF)	20	20	Default, EPA 1996
Attenuation Factor (AF)	1	1	Default, EPA 1996
Dilution-Attenuation Factor (DAF)	20	20	Default, EPA 1996
Bulk density (ρ_b , g/cm ³)	1.5	1.5	Assumed
Water content (volumetric, θ_w , -)	0.24	0.24	Example
Porosity (n, -)	0.4	0.4	Assumed
Sorption coefficient (K_d , cm ³ /g) ^a	4.7	4.7	Estimated
Air-water interfacial adsorption coefficient (K_{aw} , cm) ^b	NA	0.05	Measured
Air-water interfacial area (A_{aw} , cm ⁻¹) ^c	NA	450	Estimated
Distribution term (R_d , -)	30	124	Calculated
Target groundwater concentration (C_{gw} , $\mu\text{g/L}$) ^d	0.010	0.010	Set value
Soil Screening Level (SSL, $\mu\text{g/kg}$)	1.0	4.0	Calculated

^aRepresentative OC = 1%; log Koc from Brusseau, 2023a

^bMeasured value from Brusseau and Van Glubt, 2021

^cEstimated value from Brusseau, 2023b

^dThe target groundwater concentration is based on EPA MCL

Brusseau, M.L. (2023a). Differential sorption of short-chain versus long-chain anionic per- and poly-fluoroalkyl substances by soils. *Environments*, 10, article 175.

Brusseau, M.L. (2023b). Determining air-water interfacial areas for the retention and transport of PFAS and other interfacially active solutes in unsaturated porous media. *Science of the Total Environment*, 884, article 163730.

Brusseau, M.L. and Van Glubt, S. (2021). The influence of molecular structure on PFAS adsorption at air-water interfaces in electrolyte solutions. *Chemosphere* 281, article 130829.

Brusseau, M.L. and Guo, B. (2023). Revising the EPA Dilution-Attenuation Soil Screening Model for PFAS. *Journal of Hazardous Materials Letters*, 4, article 100077.

EPA 1996. *Soil Screening Guidance: User's Guide*. Publication 9355.4-23.

Table 14. Soil Organic Carbon vs Calculated Soil Screening Levels (SSLs) for PFOS Using Revised EPA DAF Model

% Organic Carbon	Calculated SSL (ppb)
0.1	0.5
1	3.7
5	6.9
10	21.0

Figure 2. PFAS Concentrations
Control Plots, 1' Samples

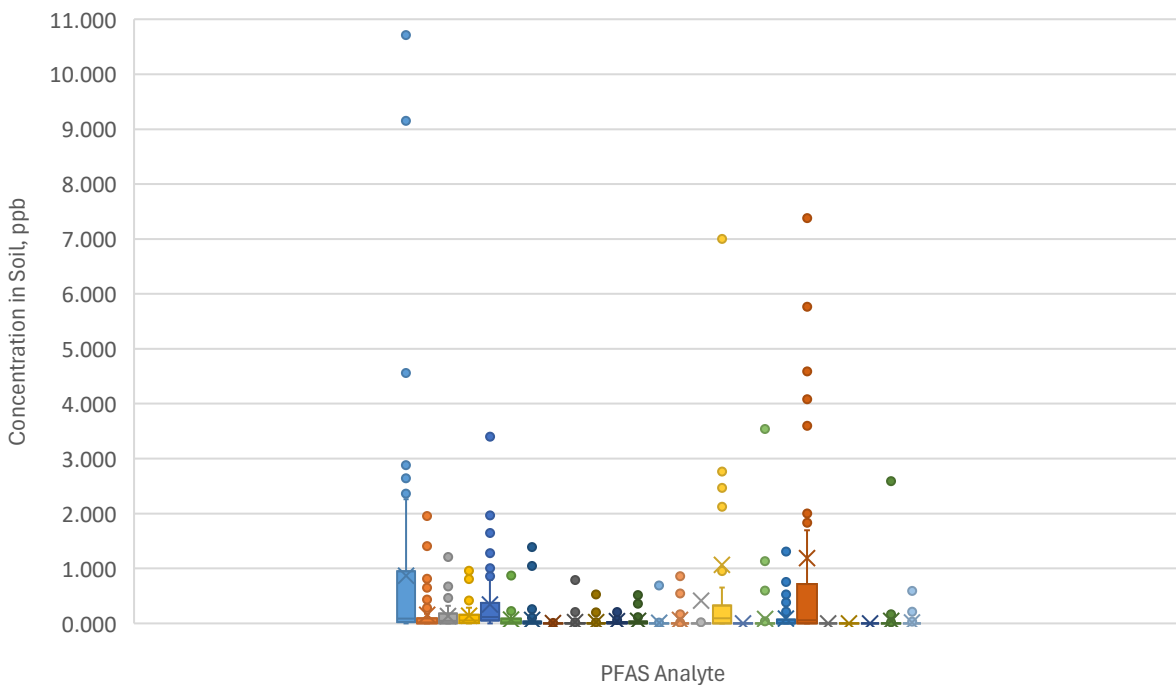


Figure 3. PFAS Concentrations
Control Plots, 3' Samples

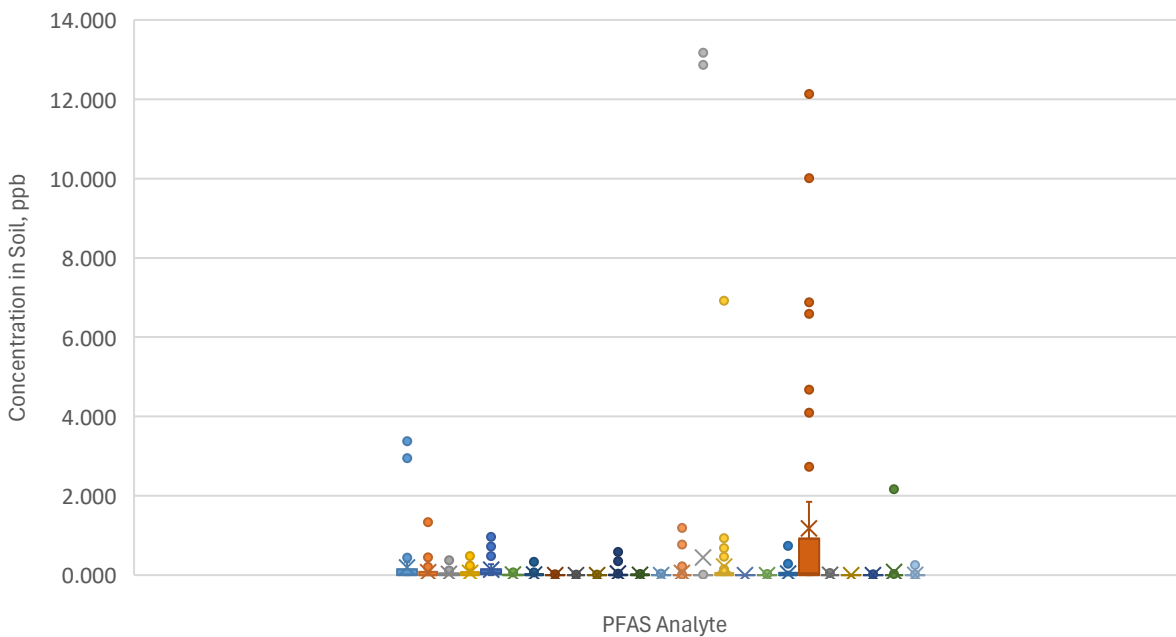


Figure 4. PFAS Concentrations
Control Plots, 6' Samples

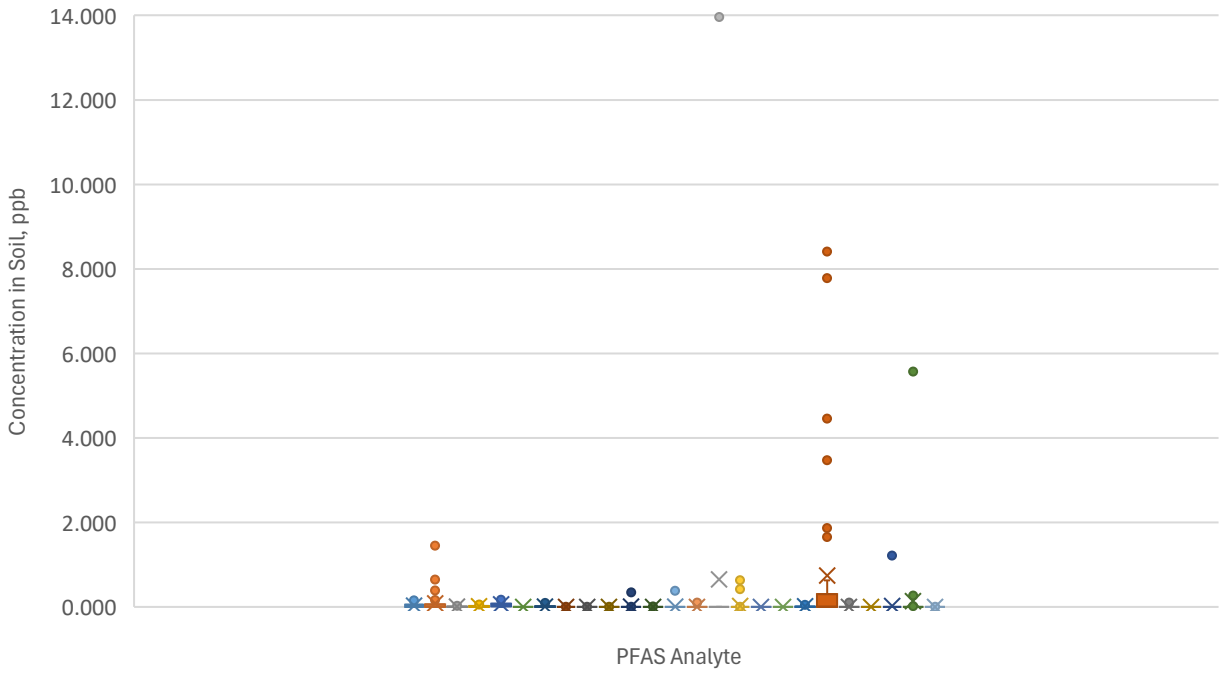


Figure 5. PFAS Concentrations
Low Biosoils Application, 1' Samples

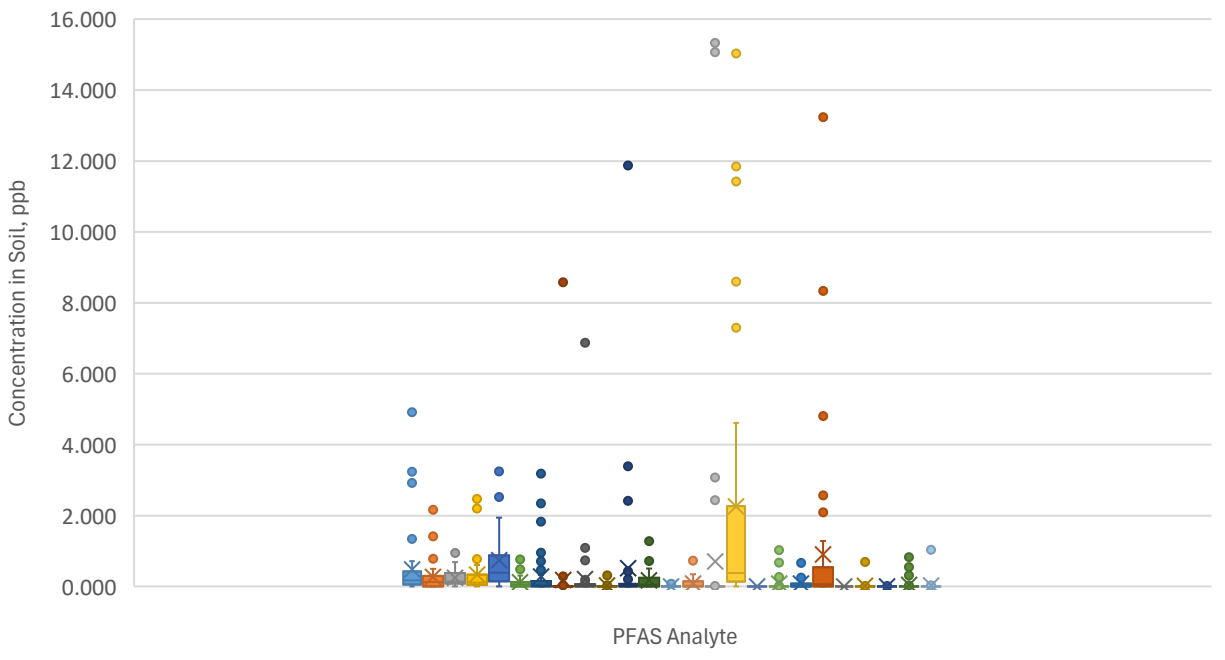


Figure 6. PFAS Concentrations
Low Biosoilds Application, 3' Samples

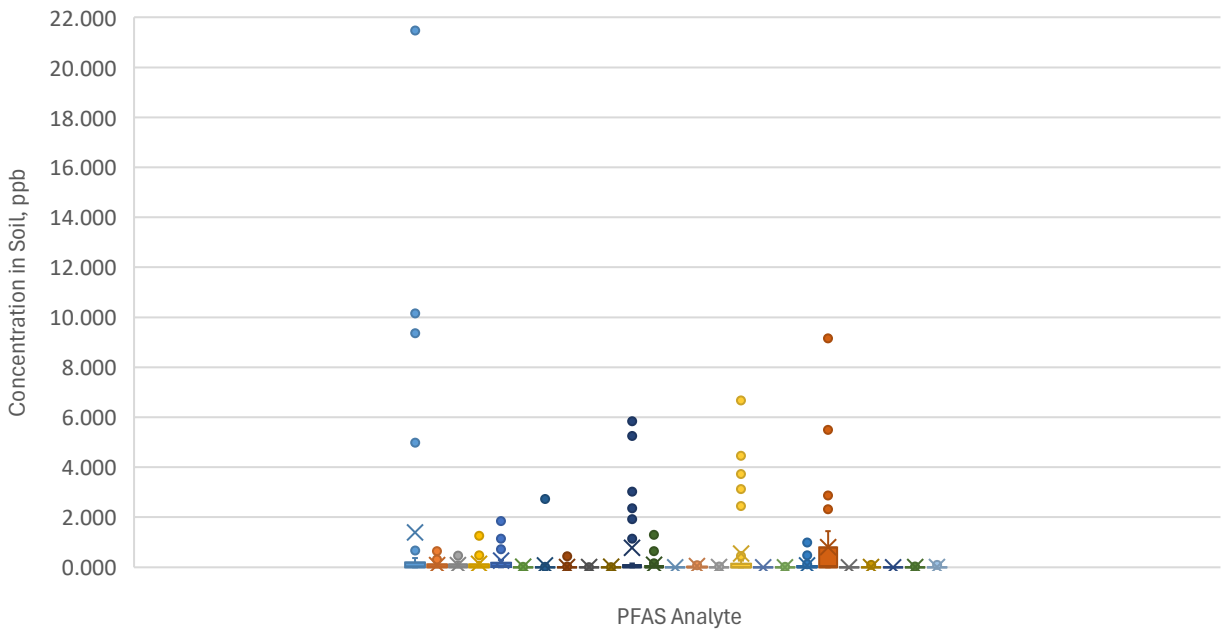


Figure 7. PFAS Concentrations
Low Biosoilds Application, 6' Samples

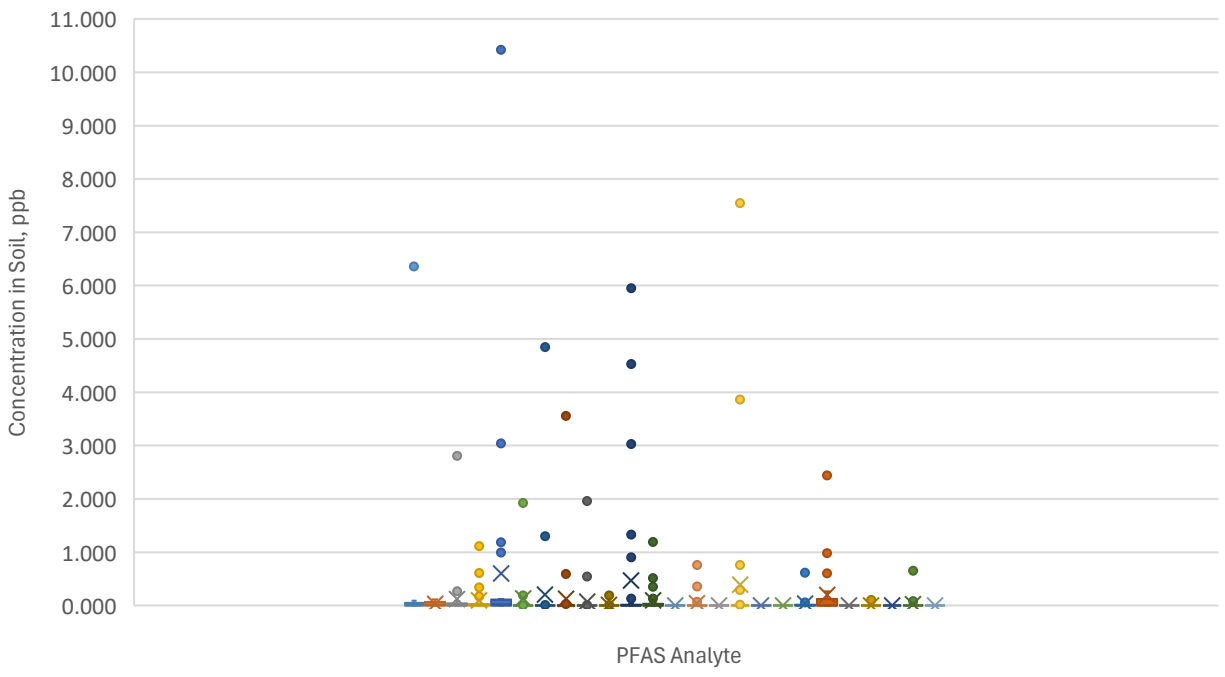


Figure 8. PFAS Concentrations
High Biosolids Application, 1' Samples

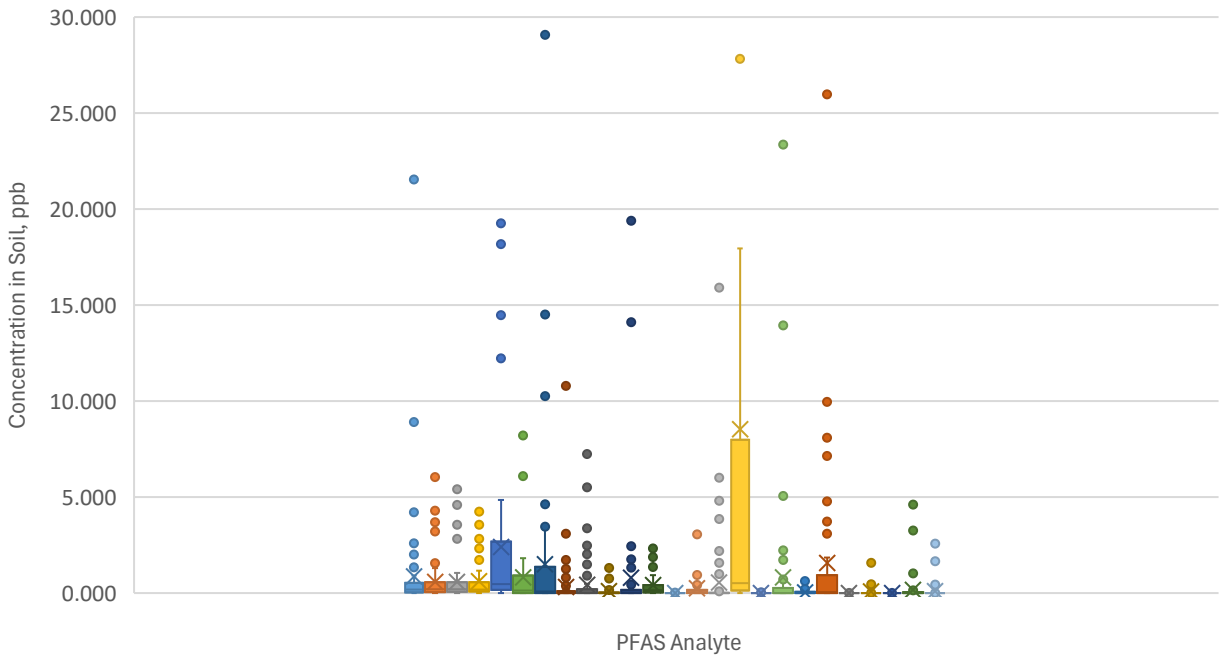


Figure 9. PFAS Concentrations
High Biosolids Application, 3' Samples

