

SUPPLEMENTARY INFORMATION

Residential history and drinking water type as predictors of serum PFAS in communities with a history of contaminated drinking water

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Site descriptions and contamination histories

Hyannis, MA

Hyannis is a village within the Town of Barnstable, located in Barnstable County on Cape Cod, Massachusetts (MA). The village has a year-round population of approximately 17,000 [1] that doubles during the summer season [2]. According to the 2022 U.S. Census, the median household income was \$63,432 and the population was 64% White, 13% Black or African American, and 15% Hispanic or Latino, with 11% reporting two or more races and 11% reporting some other race including Asian (Table S2) [1, 3]. Ninety-nine percent of residences are served by the Hyannis Water System (HWS), which draws groundwater from 11 municipal wells across three wellfields. The source of PFAS contamination to the most highly impacted wells is the Barnstable County Fire and Rescue Training Academy (BCFRTA), where aqueous film-forming foam (AFFF) was used for training [4]. Additional sources that likely impacted other Hyannis wells include a municipal airport, groundwater infiltration of effluent from a municipal wastewater treatment plant, and residential septic systems.

PFAS were first detected in HWS supply wells in 2010 [5, 6]. Results from the U.S. EPA's Unregulated Contaminant Monitoring Rule testing in 2013-2015 showed that several Hyannis wells had higher concentrations of PFOS and PFHxS than any other public water system in Massachusetts [7]. The HWS installed granular activated carbon (GAC) treatment systems on the most contaminated wells in 2015. By July 2016, all HWS wells with PFAS levels exceeding the 2016 EPA Lifetime Health Advisory (LHA) had either been shut off or had GAC treatment installed, so this marks the end of the "high exposure period" for Hyannis. Since 2022, all HWS wells have had GAC treatment systems in place to filter PFAS.

Ayer, MA

Ayer is a town located in Middlesex County in north-central Massachusetts, located west of Boston, with a population of approximately 8,000 [1]. According to the 2022 U.S. Census, the median household income was \$99,375 and the population was 77.5% White, 15.6% Hispanic/Latino, 2.9% Black or African American, and 1.6% Asian, with 13% reporting two or more races and 4.9% reporting some other race (Table S2) [1, 3]. More than 95% of Ayer residences receive drinking water from the Ayer Water Department (AWD), which draws groundwater from five wells across two wellfields. Due to the proximity of several wells to the former Fort Devens Army Installation, AWD began testing for PFAS in 2016 [8]. In February 2018, AWD began diverting water from one well that exceeded the EPA LHA away from the distribution system, while other AWD wells had lower levels of PFAS that did not exceed the LHA, so this marks the end of the "high exposure period" for Ayer. Since 2022, all AWD wells have had GAC or ion exchange treatment systems in place to filter PFAS.

PFAS drinking water concentrations

We compiled results from PFAS water testing for both the Hyannis Water System and the Ayer Water Department, starting in 2009 and 2016, respectively. Maximum PFAS concentrations were considerably higher in the Hyannis public water supply wells compared to those in Ayer (Table S1). The highest measured concentrations in any Hyannis well were 430 ng/L for PFOS and 270 ng/L for PFHxS, whereas the maximum concentrations for these PFAS in Ayer were 91 ng/L and 41 ng/L, respectively. Maximum concentrations were also higher in Hyannis compared to Ayer for PFOA (62 vs 33 ng/L) and PFNA (35 vs 1.4 ng/L). PFDA, PFUnDA, and MeFOSAA were infrequently detected in both systems, with maximum concentrations reported up to 14 ng/L (PFUnDA in Hyannis).

Prior drinking water concerns

In both communities, other drinking water quality concerns were identified years before PFAS contamination was discovered and may have shaped local perceptions about drinking water quality. A 1997 Town of Barnstable report noted that five HWS wells had been shut down due to contamination from volatile organic compounds [9]. In 2007, a HWS well was shut down to avoid pulling in nearby groundwater contaminated with perchlorate from the BCFRTA [10]. In Ayer, a 1998 health consultation conducted by the Agency for Toxic Substances and Disease Registry (ATSDR) noted community concerns about arsenic, lead, and manganese [11].

Table S1. Maximum PFAS concentrations (ng/L) in drinking water samples collected from municipal wells in Hyannis and Ayer, MA, and year of water sample collection.

These results represent drinking water entering the distribution systems and do not include samples collected when wells were shut off or samples of untreated water prior to PFAS filtration. These concentrations are higher than locations in the distribution system that contain a mixture of water from multiple wells. The table shows the year when these maximum concentrations were measured and the year when each of these PFAS were first tested by both water systems. Samples of treated water tested by both water systems after municipal mitigation were all <4 ng/L for the PFAS considered in this study.

	PFOS	PFHxS	PFOA	PFNA	PFDA	PFUnDA	MeFOSAA
Hyannis^a							
Maximum (ng/L)	430	270	62	35	2.8	14	<2
Year	2014	2014	2014	2014	2015	2015	2018
Year of first test	2009	2013	2009	2013	2015	2015	2018
Ayer^b							
Maximum (ng/L)	91	41	33	1.4	<2	<2	2.2
Year of maximum results	2017	2017	2020	2019	2018	2018	2019
Year of first test	2016	2016	2016	2016	2018	2018	2018

^aFor Hyannis samples, we reviewed all available water concentration results available online and provided by the Hyannis Water System to identify the highest concentrations. Data from [7].

^bFor Ayer samples, we reviewed all available water concentration results available on the MA Department of Environmental Protection Data Portal [9].

Table S2. Demographic characteristics of adult MA PFAS & Your Health Study participants by study site (n = 673).

Characteristics ^a	Hyannis (n = 382)	Ayer (n = 291)
Median age (years)	62 (19-91)	58 (19-88)
Age		
18 to <45	74 (19%)	67 (23%)
45 to <65	141 (37%)	124 (43%)
65+	167 (44%)	100 (34%)
Biological sex		
Female	265 (69%)	184 (63%)
Male	117 (31%)	106 (36%)
Missing	0 (0%)	1 (0.3%)
Race and ethnicity		
White, non-Hispanic	319 (84%)	253 (87%)
Hispanic	21 (5.5%)	15 (5.2%)
Black, non-Hispanic	14 (3.7%)	7 (2.4%)
Other, non-Hispanic ^b	21 (5.5%)	14 (4.8%)
Missing	7 (1.8%)	2 (0.7%)
Formal education		
High school graduate or less	47 (12%)	23 (7.9%)
Some college or technical/trade school	102 (27%)	57 (20%)
College graduate or more	233 (61%)	211 (73%)
Household income		
Less than \$70,000	159 (42%)	64 (22%)
\$70,000 or more	182 (48%)	193 (66%)
Missing	41 (11%)	34 (12%)
Health insurance in the last 12 months		
Yes	368 (96%)	283 (97%)
No	13 (3.4%)	8 (2.7%)
Missing	1 (0.3%)	0 (0%)
Drinking water type ^c		
Filtered tap	172 (45%)	197 (68%)
Bottled water	115 (30%)	50 (17%)
Unfiltered tap	93 (24%)	43 (15%)
Missing	2 (0.5%)	1 (0.3%)

^a Age reported as median (range); all other variables reported as n (%)

^b Includes Asian participants and participants who reported more than one race

^c Based on most recent address in study area. Filtered tap = reported any type of home filtration and did not report “mostly” or “all” bottled water. Bottled water = reported “mostly” or “all” bottled water. Unfiltered tap = reported no home filtration and did not report “mostly” or “all” bottled water.

Table S3. Demographic characteristics of Hyannis and Ayer, Massachusetts.

Demographic Characteristic	Hyannis^a	Ayer^b
Population	17,178	8,118
Median age (years)	39.7	40.0
Sex		
Male	48.5%	49.0%
Female	51.5%	51.0%
Race and ethnicity		
One race	89.0%	87.0%
White	64.4%	77.5%
Black or African American	13.4%	2.9%
American Indian and Alaska Native	0.2%	0.1%
Asian	1.0%	1.6%
Native Hawaiian and Other Pacific Islander	0.1%	0.0%
Some other race	10.0%	4.9%
Two or more races	11.0%	13.0%
Hispanic or Latino origin (of any race)	15.0%	15.6%
White alone, not Hispanic or Latino	56.3%	75.7%
Education		
Less than high school graduate	14.3%	10.7%
High school graduate (includes equivalency)	35.2%	19.6%
Some college or associate's degree	25.3%	30.2%
Bachelor's degree	16.3%	24.5%
Graduate or professional degree	9.0%	15.0%
Median income	\$63,432	\$99,375

^aU.S. Census Bureau, 2018-2022. American Community Survey 5-Year Estimates for Hyannis (Zip Code 02601) [1, 3]

^bU.S. Census Bureau, 2018-2022. American Community Survey 5-Year Estimates for Ayer (Zip Code 01432) [1, 3]

Table S4. Serum PFAS concentrations (ng/mL) in adult MA PFAS & Your Health Study participants from Hyannis (n = 382) and Ayer (n = 291).

PFAS	Hyannis (n = 382)					Ayer (n = 291)				
	% >LOD ^a	25th Pctl ^b	Median	75th Pctl	Max	% >LOD ^a	25th Pctl	Median	75th Pctl	Max
PFOS	100%	3.7	7.0	10.8	51.9	100%	2.0	3.3	4.8	13.7
PFHxS	100%	2.5	5.0	10.2	45.4	100%	1.1	1.8	3.0	11.9
PFOA	100%	1.2	1.9	2.7	19.3	100%	1.2	1.9	2.6	8.9
PFNA	98%	0.4	0.6	1.0	4.4	97%	0.3	0.4	0.5	2.6
PFDA	70%	<0.1	0.2	0.3	1.7	55%	<0.1	0.1	0.2	1.6
PFUnDA	62%	<0.1	0.1	0.2	1.8	41%	<0.1	<0.1	0.1	0.6
MeFOSAA	30%	<0.1	<0.1	0.1	1.5	29%	<0.1	<0.1	0.1	1.4

^a LOD, limit of detection was 0.1 ng/mL for all target analytes.

^b Pctl, percentile

Table S5. Univariate models showing beta coefficients and p-values^a for associations with variables considered for the multivariable model among substudy participants (*n* = 399).

(a) Hyannis

	Beta coefficient Serum PFOS	p value	Beta coefficient Serum PFHxS	p value	Beta coefficient Serum PFOA	p value	Beta coefficient Serum PFNA	p value
Age (continuous)	0.021	<0.001	0.026	<0.001	0.012	<0.001	0.018	<0.001
Sex (referent = Female)								
Male	0.430	<0.001	0.355	<0.001	0.214	<0.001	0.168	0.019
Years in study area (referent = Less than 5)								
5 to <10	0.147	0.193	0.322	0.019	-0.095	0.293	-0.026	0.806
10 to <16	0.797	<0.001	1.234	<0.001	0.134	0.256	0.492	<0.001
16+	0.877	<0.001	1.444	<0.001	-0.011	0.907	0.371	0.001
Drinking water type (referent = Unfiltered tap)								
Filtered tap	-0.285	0.005	-0.481	<0.001	-0.084	0.264	-0.252	0.004
Bottled water	-0.332	0.006	-0.426	0.006	-0.238	0.008	-0.252	0.016
Race/ethnicity (referent = White, non-Hispanic)								
Other	-0.116	0.320	-0.321	0.031	-0.296	<0.001	-0.149	0.139
Education (referent = College graduate or more)								
Some college or technical/trade school	0.238	0.010	0.308	0.009	-0.029	0.676	0.075	0.353
High school graduate or less	0.313	0.020	0.441	0.010	-0.018	0.858	0.060	0.606
Household income (referent = \$70,000 or more)								
Less than \$70,000	0.159	0.067	0.426	<0.001	-0.041	0.528	0.029	0.697

Table S5 (continued)

(b) Ayer

	Beta coefficient Serum PFOS	p value	Beta coefficient Serum PFHxS	p value	Beta coefficient Serum PFOA	p value	Beta coefficient Serum PFNA	p value
Age (Continuous)	0.017	<0.001	0.018	<0.001	0.013	<0.001	0.015	<0.001
Sex (referent = Female)								
Male	0.510	<0.001	0.490	<0.001	0.219	0.004	0.191	0.021
Years in study area (referent = Less than 5)								
5 to <10	0.172	0.217	0.243	0.133	0.025	0.835	0.138	0.281
10 to <18	0.329	0.008	0.374	0.009	0.124	0.241	0.191	0.090
18+	0.454	<0.001	0.487	<0.001	0.211	0.047	0.275	0.015
Drinking water type (referent = Unfiltered tap)								
Filtered tap	0.103	0.420	0.013	0.932	-0.015	0.885	-0.010	0.934
Bottled water	-0.120	0.444	-0.111	0.545	-0.286	0.030	-0.148	0.295
Race/ethnicity (referent = White, non-Hispanic)								
Other	-0.204	0.125	-0.350	0.023	-0.249	0.026	-0.123	0.304
Education (referent = College graduate or more)								
Some college or technical/trade school	0.053	0.630	0.076	0.551	-0.048	0.604	0.015	0.877
High school graduate or less	-0.006	0.971	-0.069	0.742	0.023	0.879	-0.113	0.487
Household income (referent = \$70,000 or more)								
Less than \$70,000	-0.056	0.594	0.080	0.507	0.055	0.545	-0.049	0.615

^a p values <0.1 are shown in bold font

Table S6. Percent difference in serum PFAS concentrations (95% CI) in association with time lived in study area, sex, age, race/ethnicity, education, and primary drinking water type in (a) Hyannis and (b) Ayer for subgroup who completed residential history questionnaire (n = 399).

(a) Hyannis

	PFOS	PFHxS	PFOA	PFNA
Age (in years)	1.97 (1.29, 2.65)	2.28 (1.42, 3.15)	1.53 (0.98, 2.08)	2.07 (1.44, 2.7)
Sex (<i>ref = Female</i>)				
Male	59.13 (27.53, 98.56)	38.42 (4.55, 83.27)	26.58 (5.8, 51.45)	30.26 (6.14, 59.86)
Race/ethnicity (<i>ref = White, non-Hispanic</i>)				
Other	25.21 (-7.96, 70.32)	-0.94 (-32.93, 46.33)	-17.82 (-35.96, 5.45)	1.18 (-23.89, 34.49)
Education (<i>ref = College graduate or more</i>)				
Some college/technical school	17.33 (-7.8, 49.32)	8.61 (-19.99, 47.43)	1.22 (-16.74, 23.05)	-1.92 (-21.52, 22.58)
High school graduate or less	44.26 (4.32, 99.49)	59.42 (5.7, 140.43)	16.86 (-10.13, 51.96)	19.4 (-11.53, 61.15)
Time lived in study area in years (<i>ref = Less than 5</i>)				
5 to <10	-10.82 (-34.45, 21.33)	14.78 (-22.31, 69.57)	-29.52 (-45.08, -9.56)	-31.41 (-48.41, -8.81)
10 to 16	43.16 (3.96, 97.15)	107.74 (38.47, 211.67)	0.74 (-22.27, 30.55)	3.66 (-22.9, 39.37)
16+	32.21 (-1.3, 77.11)	117.78 (50.34, 215.46)	-21.36 (-37.95, -0.35)	-18.69 (-37.95, 6.56)
Drinking water type (<i>ref = Unfiltered tap</i>)				
Filtered tap	-25.21 (-41.66, -4.13)	-28.97 (-48.15, -2.68)	-18.69 (-33.51, -0.56)	-22.77 (-38.62, -2.82)
Bottled water	-37.34 (-52.52, -17.32)	-43.23 (-60.06, -19.32)	-17.2 (-33.86, 3.66)	-24.68 (-41.73, -2.66)

(b) Ayer

	PFOS	PFHxS	PFOA	PFNA
Age (in years)	1.36 (0.78, 1.95)	1.53 (0.84, 2.23)	1.08 (0.56, 1.61)	1.36 (0.79, 1.93)
Sex (<i>ref = Female</i>)				
Male	52.82 (29.49, 80.36)	55.43 (27.66, 89.23)	17.44 (1.15, 36.36)	12.26 (-4.46, 31.9)
Race/ethnicity (<i>ref = White, non-Hispanic</i>)				
Other	-12.42 (-30.76, 10.77)	-26.18 (-44.15, -2.41)	-18.73 (-34.25, 0.44)	-7.61 (-26.5, 16.14)
Education (<i>ref = College graduate or more</i>)				
Some college/technical school	-1.31 (-18.54, 19.57)	-0.96 (-21.15, 24.4)	-7.63 (-22.31, 9.81)	-3.28 (-19.76, 16.59)
High school graduate or less	-13.04 (-36.52, 19.12)	-18.95 (-44.23, 17.78)	-8.04 (-30.76, 22.13)	-18.5 (-40.01, 10.71)

Table S6 (continued)

Time lived in study area in years

(ref = Less than 5)

5 to <10	21.25 (-6.24, 56.8)	27.6 (-5.98, 73.18)	4.34 (-17.25, 31.56)	13.37 (-11.74, 45.61)
10 to 18	36.74 (9.56, 70.66)	40.07 (7.65, 82.24)	13.94 (-6.69, 39.14)	19.34 (-3.82, 48.07)
18+	33.66 (6.49, 67.76)	33.71 (2.08, 75.14)	11.61 (-9.07, 36.98)	17.26 (-6.01, 46.28)

Drinking water type (*ref = Unfiltered tap*)

Filtered tap	8.65 (-13.43, 36.36)	-2.63 (-25.66, 27.53)	-4.39 (-22.09, 17.35)	0.7 (-19.28, 25.62)
Bottled water	-4.25 (-27.45, 26.35)	-3.13 (-30.32, 34.67)	-20.02 (-37.71, 2.71)	-7.7 (-29.54, 20.91)

Figure S1. Enrollment and study procedures flow chart for adult participants in the MA PFAS & Your Health Study.

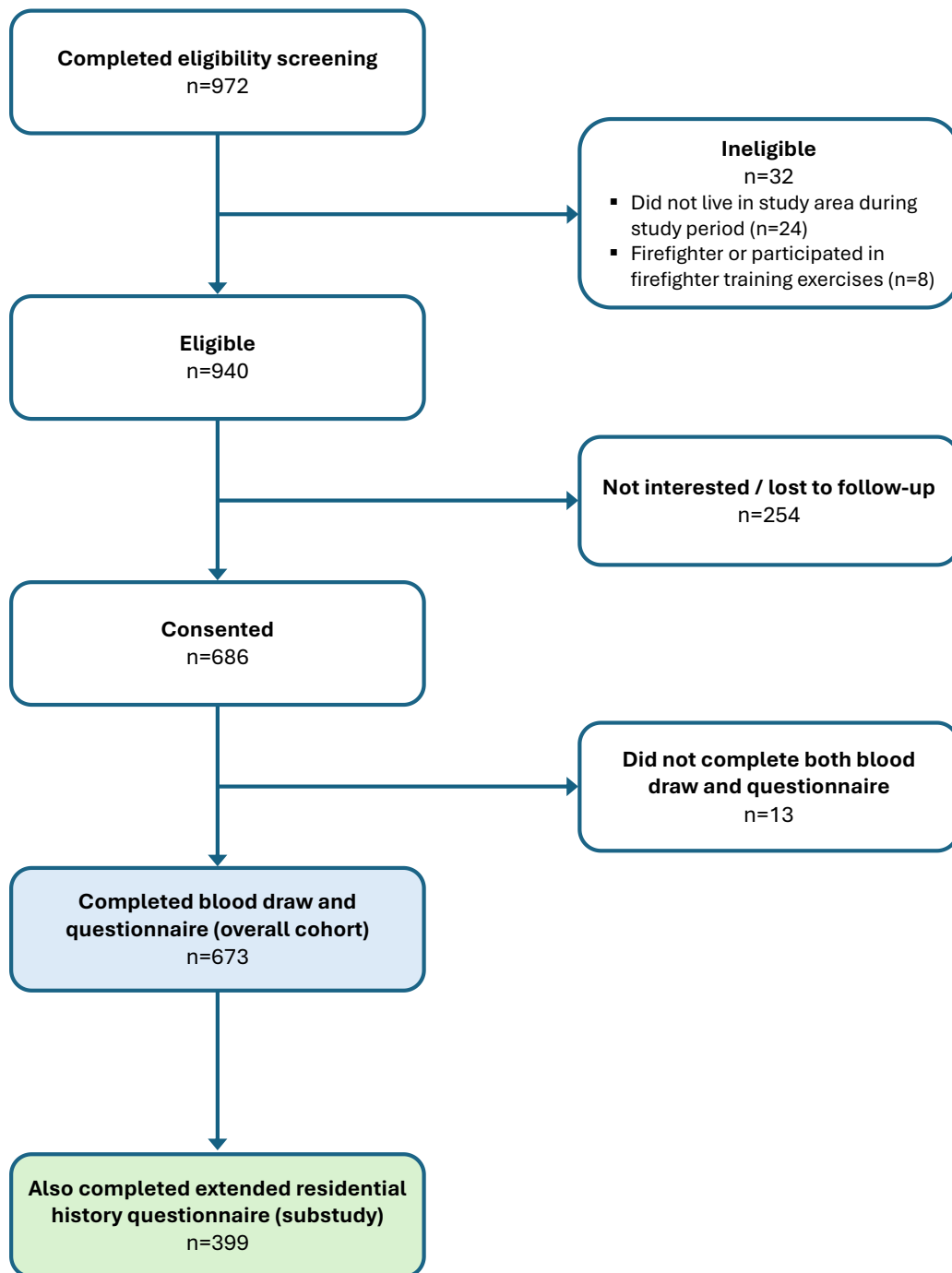
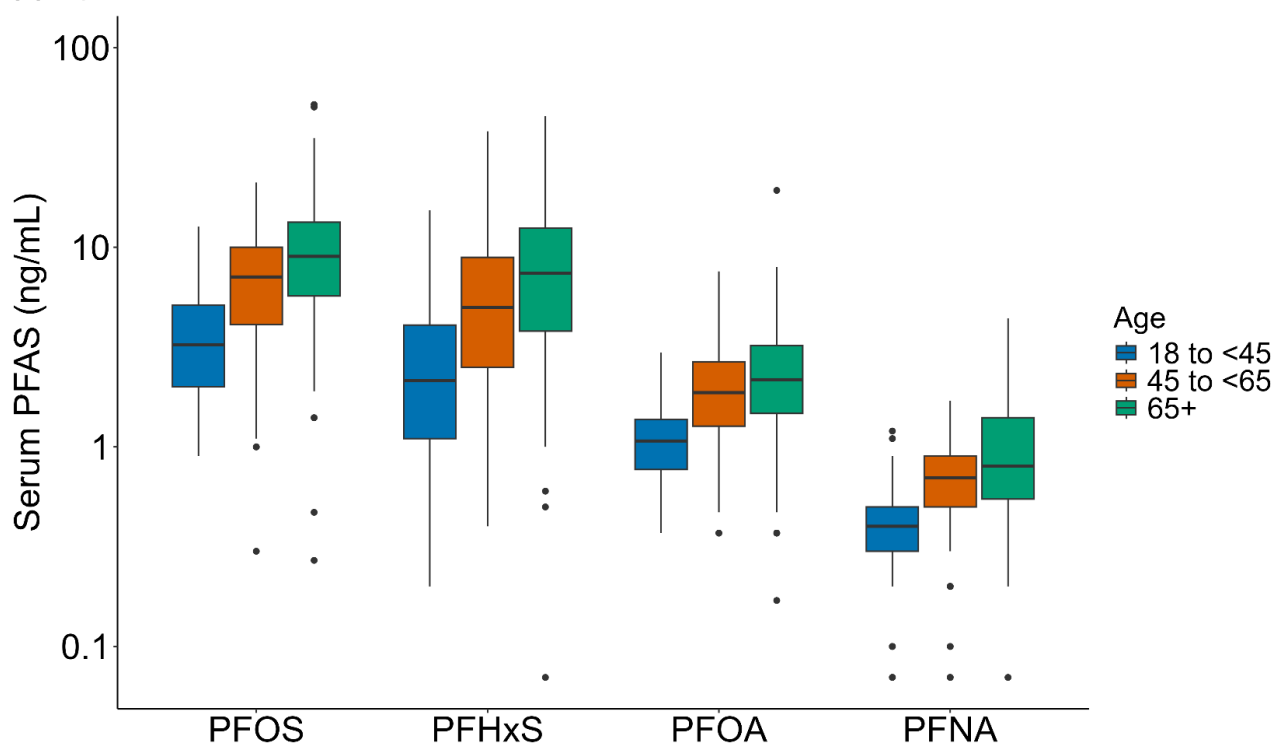


Figure S2. Serum PFAS concentrations among adult participants in three age categories in (a) Hyannis ($n = 382$) and (b) Ayer ($n = 291$).

(a) Hyannis



(b) Ayer

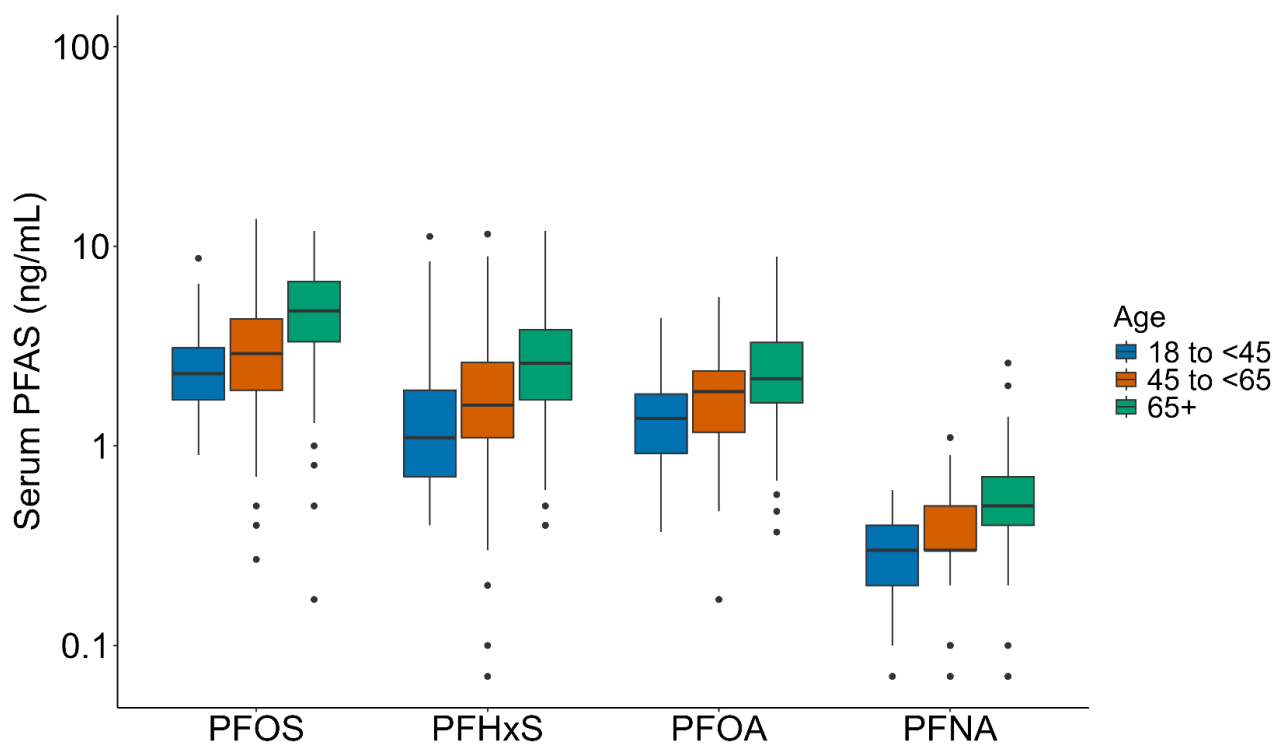
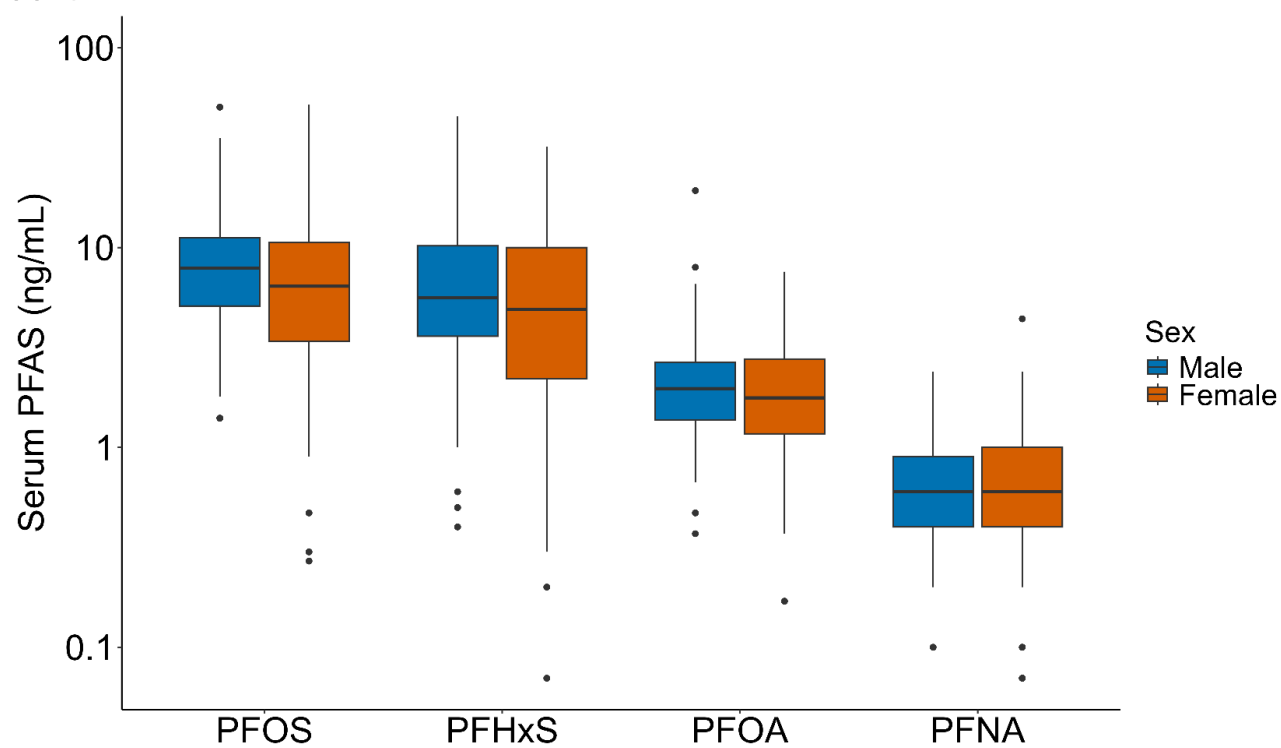


Figure S3. Serum PFAS concentrations among adult males and females in (a) Hyannis ($n = 382$) and (b) Ayer ($n = 291$).

(a) Hyannis



(b) Ayer

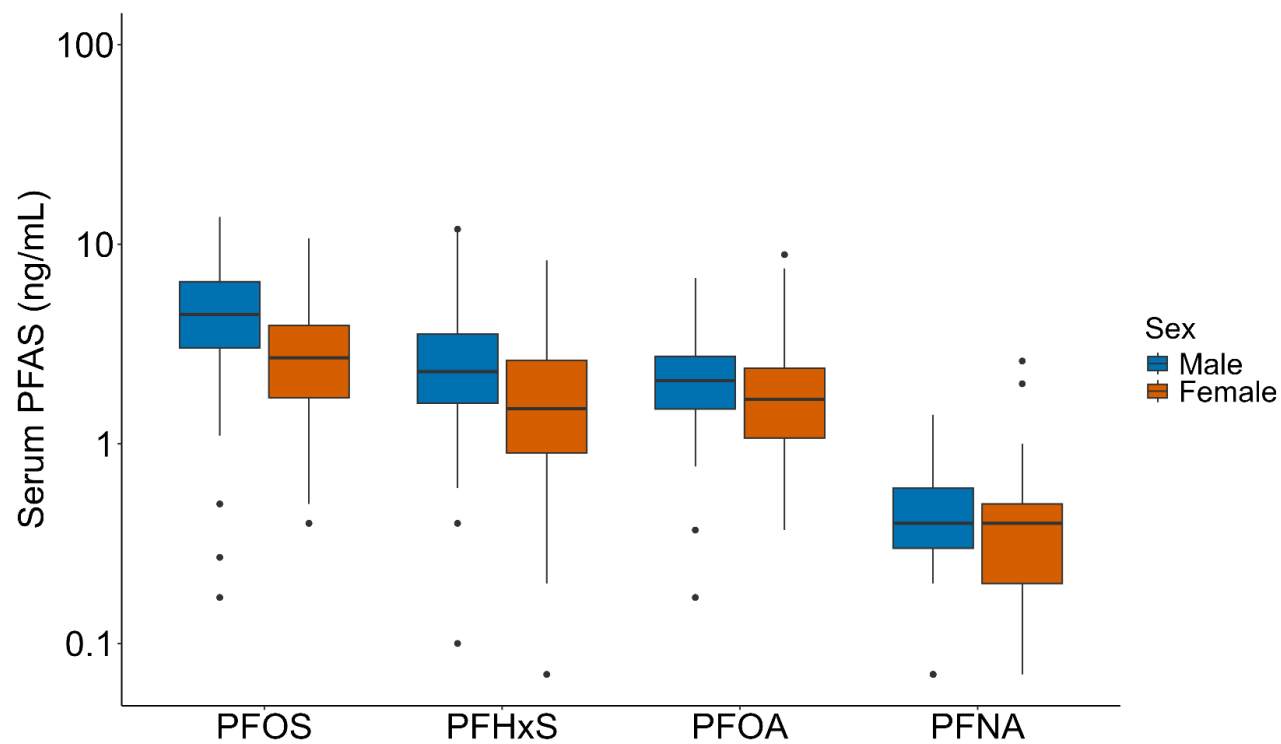


Figure S4. Comparison of age-adjusted median serum PFAS concentrations among adult participants from overall study cohort (n = 673) with NHANES.

Hyannis and Ayer median concentrations are adjusted to the age distribution of NHANES participants ages 20+ years. NHANES data from [13]. Error bars represent 95% confidence intervals around the weighted median.

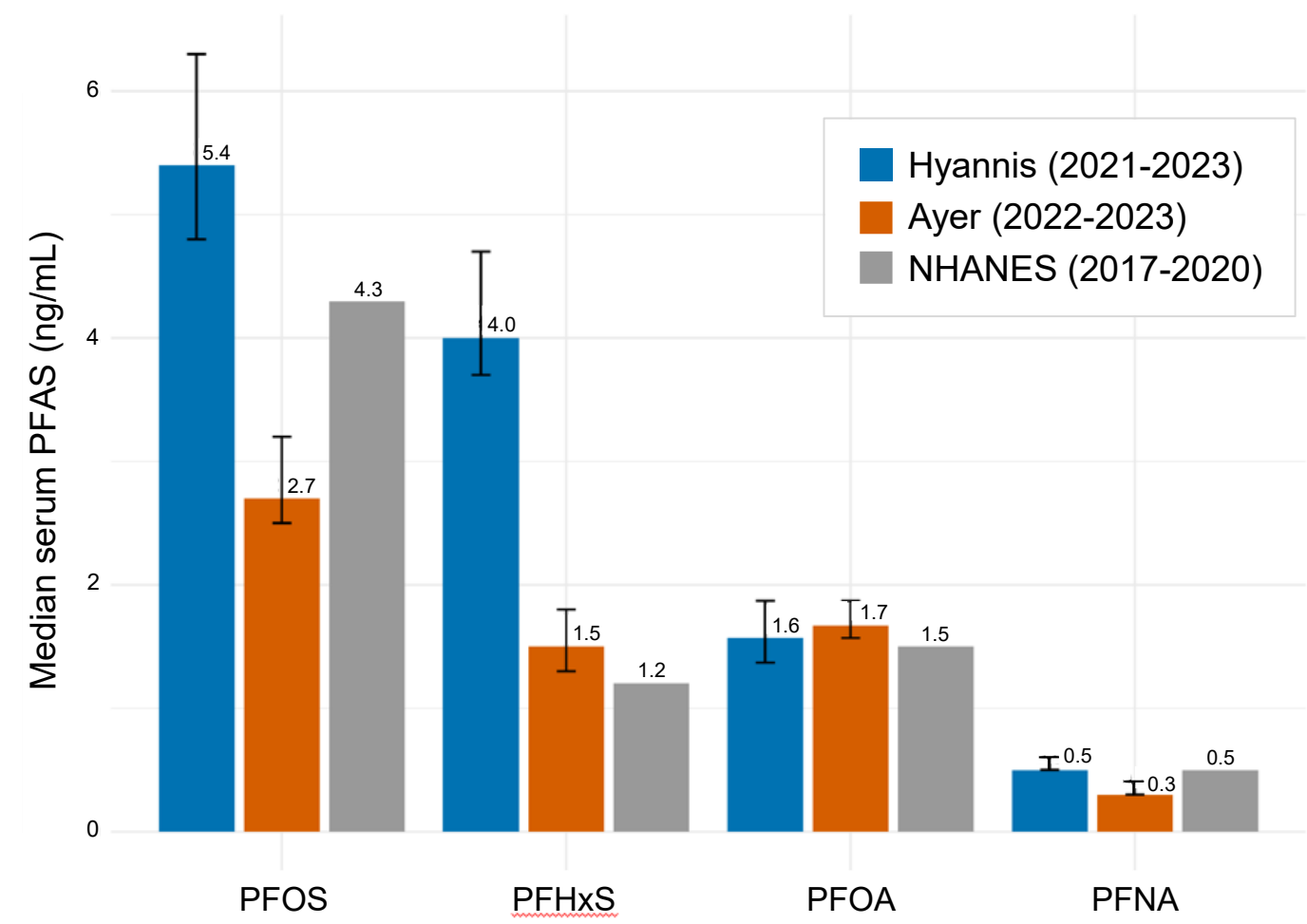
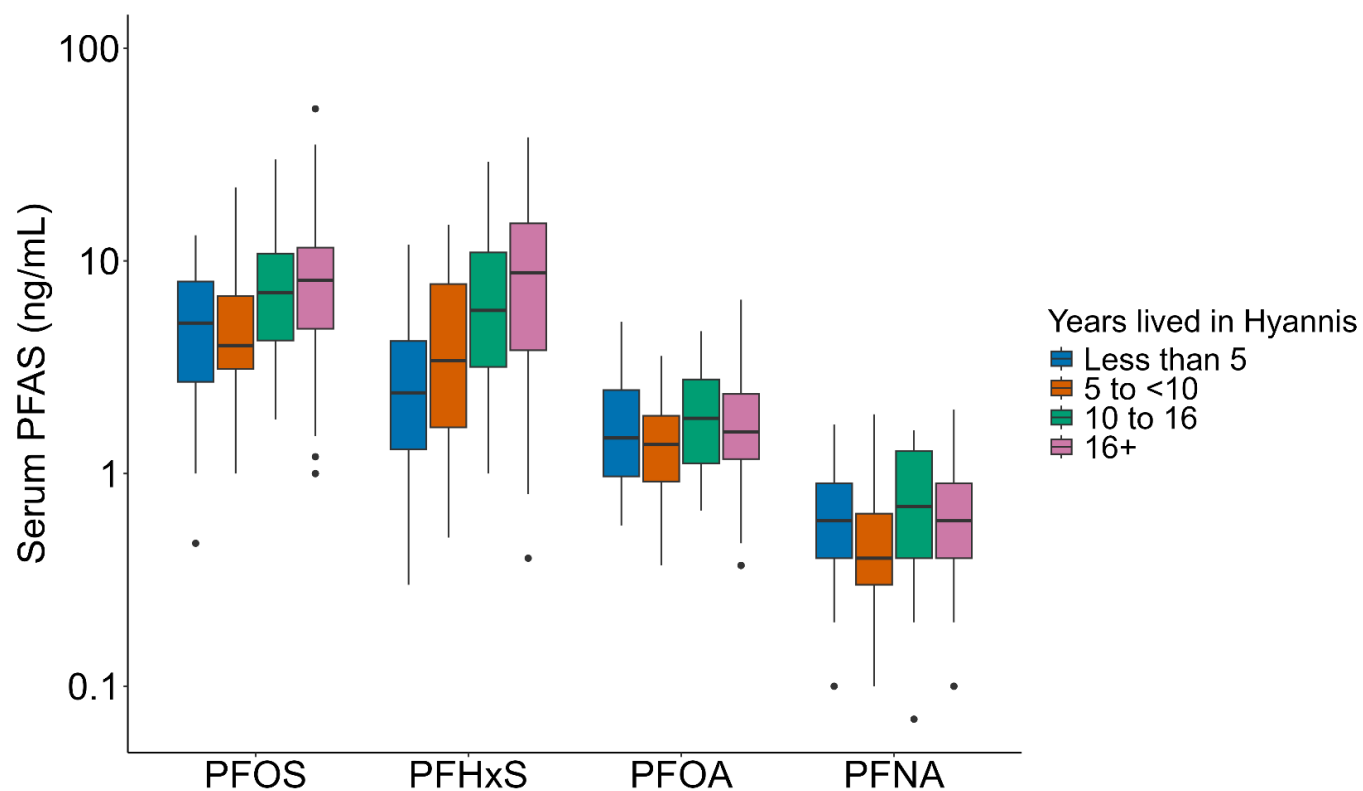


Figure S5. Serum PFAS concentrations among substudy participants by time lived in (a) Hyannis ($n = 169$) and (b) Ayer ($n = 230$).

(a) Hyannis



(b) Ayer

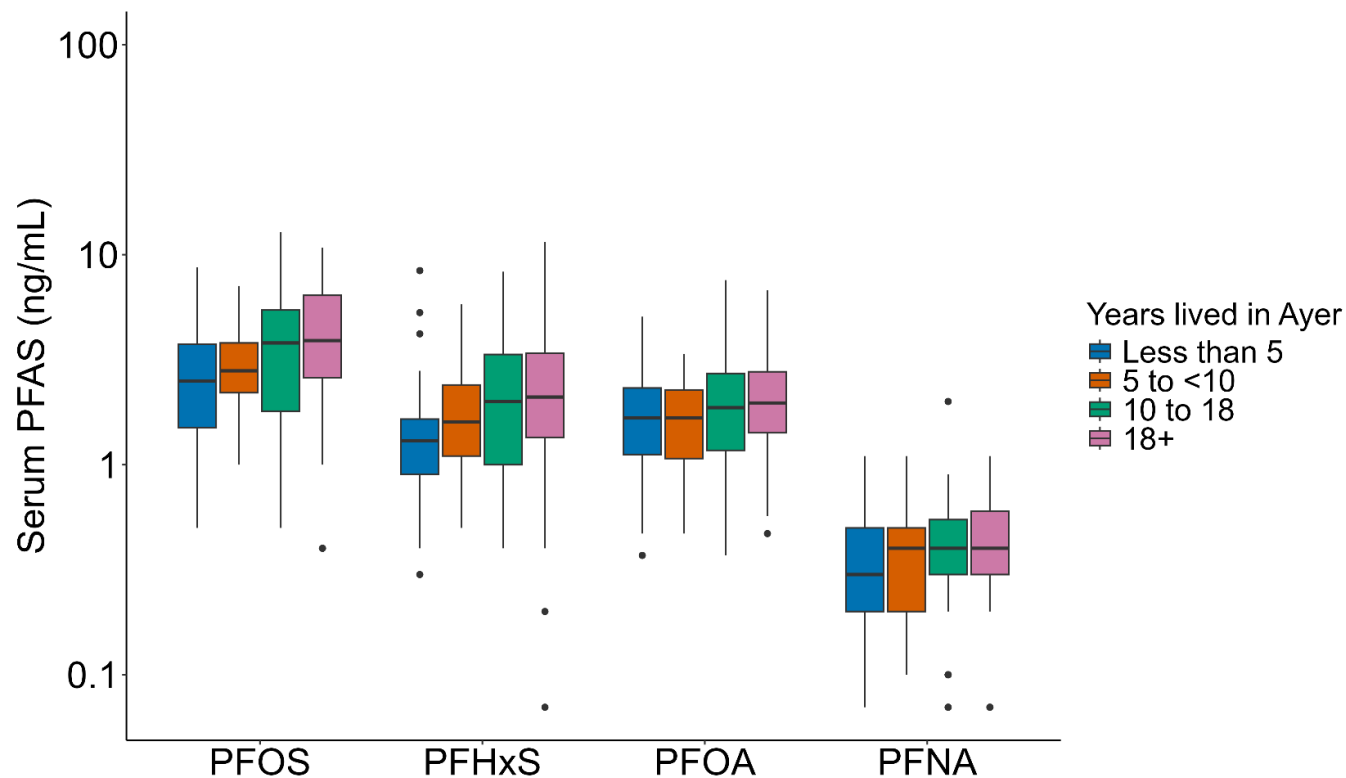
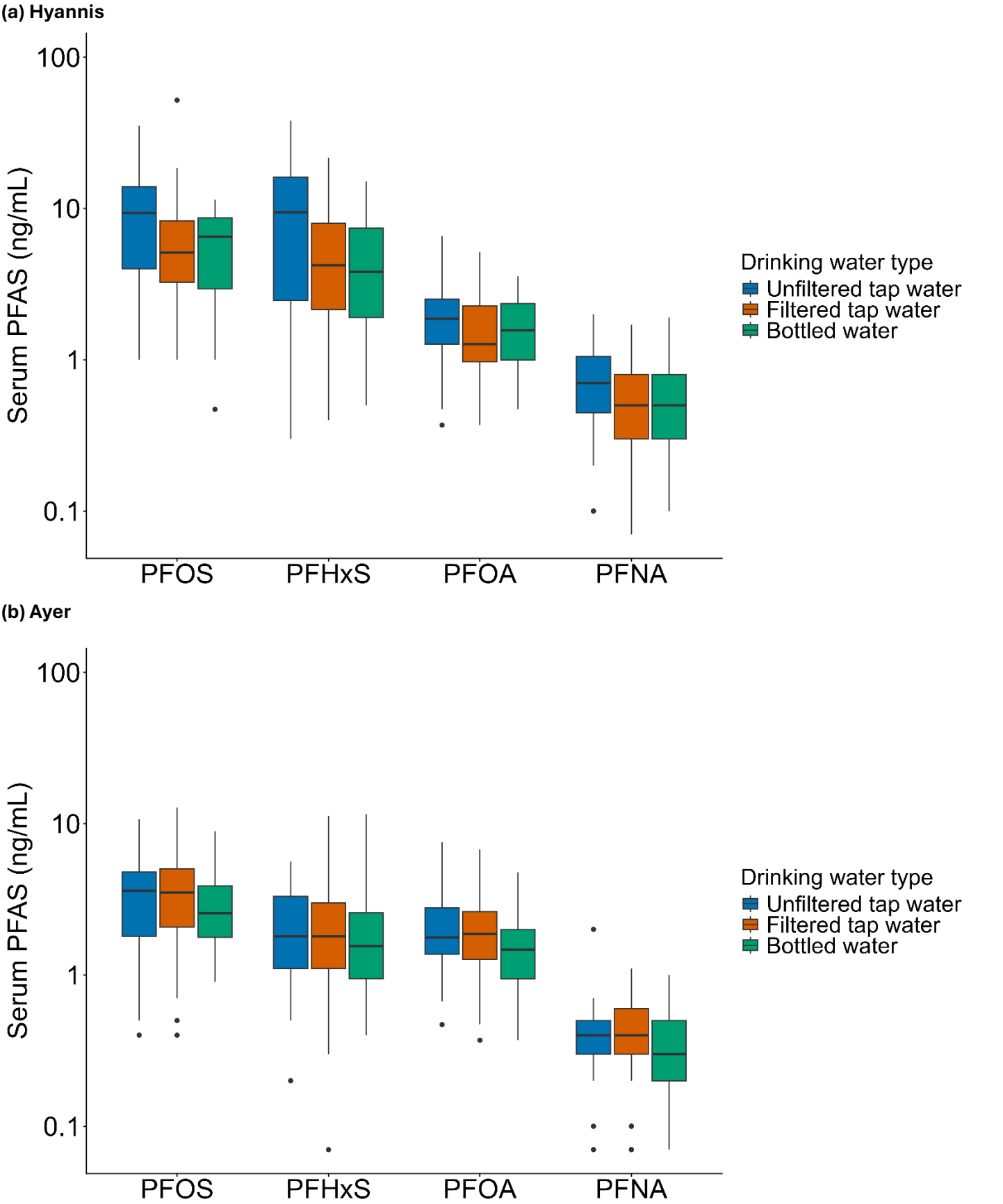


Figure S6. Serum PFAS concentrations among substudy participants according to drinking water type in (a) Hyannis (*n* = 169) and (b) Ayer (*n* = 230).



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