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Establishing a spatial framework for investigating PFAS in wild game animals: Evidence from wild boar livers in Brandenburg, Germany

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ABSTRACT

Per- and polyfluoroalkyl substances (PFAS) are a group of anthropogenic persistent pollutants, which are ubiquitously distributed in the environment and are linked to several adverse health effects. To monitor PFAS in the environment, wild boars (*Sus scrofa ferus*) have been proposed as bioindicator organisms, as their omnivorous diet can lead to intake of PFAS from their immediate environment. The study aimed to evaluate the influence of land use on the occurrence of PFAS in wild boar livers hunted in Brandenburg, Germany. For this purpose, 164 wild boars from 18 hunting districts were sampled and their livers were quantitatively analyzed for the presence of 16 PFAS. The hunting districts were characterized based on land use features using publicly available geodetic data. Additionally, geolocations of presumptive PFAS sources were used to evaluate the possible influence of their proximity to hunting districts on the PFAS burden. Statistical analyses revealed significant positive correlations between concentrations of PFOA, PFOS, PFNA, and PFDA and the proportional extent of urban and/or industrial areas. PFUnDA was statistically correlated with the extent of agricultural areas in the studied regions. Furthermore, the analyses indicated significantly higher concentrations of PFOA and PFNA in livers of wild boars hunted in districts located within 10 km from presumptive PFAS sources. In summary, the results demonstrate that PFAS concentrations in wild boar livers differ between hunting sites and indicate that land-use-based assessments are a feasible approach to locally characterize potential risks associated with the consumption of wild boar livers in terms of PFAS exposure.

1. Introduction

Poly- and perfluorinated alkyl substances (PFAS) are synthetic organic compounds in which some or all of the hydrogen atoms attached to carbon are replaced by fluorine. These substances have been produced industrially since the mid-20th century, valued for their unique technological properties, which make them effective additives in industrial processes and surface coatings for consumer goods. PFAS are commonly used in water- and stain-resistant treatments and as components in fire-fighting foams (Gaines, 2023; Glüge et al., 2020). PFAS are widely recognized as persistent organic pollutants due to their resistance to chemical and microbial degradation. These substances accumulate in the environment and food chain, and they have even been detected even in Arctic wildlife (Boisvert et al., 2019). In addition to their persistence,

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PFAS are associated with various health risks, making them an increasing focus of scientific research and political debate (ECHA, 2023; Ng et al., 2021; Buck et al., 2011).

PFAS primarily enter the human body through food, particularly animal products, as they contain higher levels of PFAS due to accumulation within the food chain (Schrenk et al., 2020). Considering the potential foodborne exposure for consumers, several studies have been conducted to investigate the uptake of PFAS by livestock and game animals (Arioli et al., 2019; Kowalczyk et al., 2018; Guruge et al., 2016; Vestergren et al., 2013; Müller et al., 2011). For instance, PFAS were detected in the plasma and skin of dairy cattle herds grazing on contaminated land or consuming highly PFAS-contaminated drinking water (Lupton et al., 2022). The transfer of PFOS from contaminated feed into dairy milk has also been documented (van Asselt et al., 2013). These findings align with experimental feeding trials where cattle and pigs exposed to contaminated feed and water absorbed PFAS (Numata et al., 2014; Kowalczyk et al., 2013). Studies by Kowalczyk et al. (2013) and Numata et al. (2014) further reported that PFAS accumulate to varying degrees in the liver, muscle tissue, and blood serum. Subsequently, the European Food Safety Authority (EFSA) re-evaluated PFAS and recommended the reduction of the health-based tolerable weekly intake of perfluorooctanoic acid (PFOA), perfluorononanoic acid (PFNA), perfluorohexanesulfonic acid (PFHxS) and perfluorooctanesulfonic acid (PFOS) to 4.4 ng/kg body weight (Schrenk et al., 2020). In response to growing health concerns, the European Union introduced limit values for four PFAS in meat and meat by-products in December 2022, which were later included in the Annex to the new Contaminants Regulation in May 2023 (Commission Regulation, 2023).

Although game meat represents only a small part of the animal protein consumption in Europe, it has gained the attention of researchers and regulatory authorities in the last decades in the context of PFAS contamination. As shown previously in hunted animals, the muscle and other organs of wild boars, especially the liver, can be contaminated with considerably high concentrations of different PFAS (Mertens et al., 2025; Mateus-Vargas et al., 2025; Schröder et al., 2024; Mikolajczyk et al., 2024; Draghi et al., 2024; Moretti et al., 2023; Felder et al., 2023; Stahl et al., 2012). While small mammals from heavily contaminated areas often exhibit a relatively uniform distribution of PFAS in their tissues, with blood and liver concentrations consistently an order of magnitude higher than muscle (Cartron et al., 2025; Witt et al., 2024), wild boars show more heterogeneous contamination patterns. This variability is particularly pronounced for short-chain and more hydrophilic PFAS, which differ in their accumulation among organs such as muscle and offal (Mertens et al., 2025). It may further be influenced by the level of exposure (Rupp et al., 2023; Felder et al., 2023), and the degree of anthropization of their habitats (Mateus-Vargas et al., 2025). Noteworthy, concentrations of PFAS in livers of wild boars may exceed the tolerable weekly intake recommended by the European Food Safety Authority (Rupp et al., 2023). Regarding the potential sources of PFAS for these free-ranging ungulates, there is strong scientific evidence that there is a strong correlation between the level of local environmental contamination with PFAS and the presence of these substances in the liver of individuals from these habitats (Rupp et al., 2023; Felder et al., 2023). While recent studies indicate that PFAS can have detrimental effects on arthropods, amphibians, and algae in both aquatic and terrestrial ecosystems, even at low concentrations (Brunn et al., 2023), data on the impacts of PFAS in wild ungulates, including wild boar, remain limited (Andrews et al., 2023). In controlled experimental settings, Numata et al. (2014) did not report health effects or pathological changes in the meat or offal of domestic pigs exposed to seven perfluoroalkyl sulfonic and carboxylic acids (PFAA) via contaminated feed over a 21-day period. Considering potential health risks to consumers, and despite significant recent advances, further investigation of PFAS contamination levels in wild boar game products remains essential for consumer protection (Mertens et al., 2025). Additionally, data on the impact of habitat anthropization on PFAS occurrence in game meat is crucial for accurate health risk assessments (Mateus-Vargas et al., 2025). Wild boars, with their omnivorous diet and soil-foraging behavior, have also been suggested as bioindicators of environmental PFAS contamination (Barola et al., 2020; Kowalczyk et al., 2018). A deeper understanding of the interaction of wild boar with contaminants in their habitat is therefore necessary to refine risk assessments for this species as a food source.

This study aimed to identify potential patterns in liver contamination with PFAS in wild boars hunted in the German federal state of Brandenburg, with a focus on possible links to anthropogenic factors. Using open-source data, the analysis examined both local land use characteristics and the proximity to presumptive PFAS point sources. The goal was to explore whether land use and nearby potential pollution sources might influence PFAS contamination in liver samples of wild boars in a region with no known pollution incidents.

2. Material and methods

2.1. Study area

Wild boar liver samples were collected from 18 hunting areas in the state of Brandenburg. Brandenburg is a federal state located in the northeast region of the Federal Republic of Germany. Geologically, Brandenburg is part of the North German Plain. The Berlin/Brandenburg metropolitan area is centrally located within the state of Brandenburg. With 6.1 million inhabitants in 2020, this is the most populous center of the otherwise sparsely populated state (Amt für Statistik Berlin-Brandenburg AöR, 2021). Excluding the constituent state of Berlin, the federal state comprises approximately 14,426 km^2 of agricultural land (48.6 %), 10,320 km^2 of forested areas (34.8 %), followed by 2037 km^2 of human settlements (6.9 %), and 998 km^2 of surface water (3.4 %). In 2020, a total of 5413 farms in Brandenburg cultivated more than 1.31 million hectares of land, 38 % of which were used to grow animal feed [https://www.statistik-berlin-brandenburg.de/244-2021]. With an average utilized agricultural area of 242 ha, Brandenburg is one of the German federal states with the largest agricultural areas used by a single agricultural holding (Bundesministerium für Ernährung und Landwirtschaft, 2022).

2.2. Sample collection

Sampling activities were performed under a framework agreement involving the German Federal Institute for Risk Assessment (BfR) and the German Institute for Federal Real Estate (BImA). Details regarding the sampling strategy were previously reported by Maaz et al. (2022). For this study, 18 hunting districts, managed either by the German Institute for Federal Real Estate (BImA) or privately owned, were visited during driven hunts conducted by the German Federal Forest Division of the BImA in late autumn and winter over three consecutive hunting seasons from 2019/20 to 2021/22. The wild boars were legally hunted as part of a population management program, which obviated the need for official approval for carcass handling and sampling, and ensured compliance with ethical standards (Maaz et al., 2022). Game carcasses were intended for animal or human consumption. For our study, liver portions were collected from healthy free-ranging wild boar (*Sus scrofa ferus*) by the hunters during field evisceration and placed in a plastic bag provided by the visiting staff of the BfR. The body weight of the animals was determined after evisceration by the responsible persons of the BImA at the hunting day using a digital hanging balance to the nearest 0.1 kg. The age of the animals was reported in age classes based on characteristic features of physical development and appearance, according to Wacker (1978). Age class 0 and 1 include animals younger than one year and those aged between one and two years, respectively. Age class 2 stands for all adult animals older than two years. At the end of each hunt, liver samples were collected, chilled, and transported to the BfR facilities, where they were stored at −20 °C until further analysis. Data on sampled individuals regarding age class, sex, and weight was obtained in retrospect using the unique number of the certificate of origin assigned to every individual carcass.

2.3. Chemicals and materials

A PFAS mixed standard (Wellington Laboratories Inc., Guelph, Canada) was used for quantification. The standard contained the following perfluoroalkyl carboxylic acids (PFCAs) and perfluoroalkyl sulfonic acids (PFSAs): perfluorobutanoic acid (PFBA), perfluoropentanoic acid (PFPeA) perfluorohexanoic acid (PFHxA), perfluoroheptanoic acid (PFHpA), PFOA, PFNA, perfluorodecanoic acid (PFDA), perfluoroundecanoic acid (PFUnDA), perfluorododecanoic acid (PFDoDA), perfluorotridecanoic acid (PFTriDA), perfluorotetradecanoic acid (PFTetraDA), perfluorobutanesulfonic acid (PFBS), PFHxS, perfluoroheptanesulfonic acid (PFHpS), PFOS and Perfluorodecanesulfonic acid (PFDS). A monoisotopically labeled mixed standard (Wellington Laboratories Inc., Guelph, Canada) consisting of 13C-PFBA, 13C-PFHxA, 13C-PFOA, 13C-PFNA, 13C-PFDA, 13C-PFUnDA, 13C-PFBS, 18O-PFHxS, and 13C-PFOS was used as an internal standard. All other reagents and solvents used in the analysis were purchased from Carl Roth GmbH + Co. KG (Karlsruhe, Germany) and VWR International GmbH (Darmstadt, Germany). All chemicals met the purity requirements for highperformance liquid chromatography-mass spectrometry (HPLC-MS) grade.

2.4. Sample preparation

The collected liver samples were freeze-dried. For this purpose, the surfaces of the liver samples were cut off, and internal cross sections of 0.5 cm slices were chopped. Chopped liver pieces were weighed and spread out in aluminum trays and freeze-dried (Christ alpha i20) for at least 72 h. Freeze-dried liver samples were reweighted, and dry matter was calculated using the formula Bd. III 3.1 (5.1) published by the Association of German Agricultural Analytic and Research Institutes (VDLUFA) and frozen (−80 °C) until further processing. Deep-frozen, dried liver samples were homogenized using a porcelain bowl (130 mm) and pestled. Liver powder was stored in closed falcon tubes at room temperature until analysis. The preparation for PFAS analyses of the freeze-dried samples followed a slightly modified method based on the one described in a previous study (Felder et al., 2023). Briefly, 500 mg of the sample was weighed into a polypropylene tube, to which 10 mL of methanol was added, and the mixture was left overnight at room temperature. After extraction, purification via solid-phase extraction was performed using Chromabond HR-X cartridges (Macherey- Nagel GmbH & Co. KG, Düren, Germany) according to DIN 38407-42. The cartridges were each conditioned with 2 ml of methanol +0.1 % formic acid, methanol, and water. Subsequently, 1 mL of the sample extract was mixed with 1 mL of water +0.1 % formic acid and 50 μL of internal standard (0.02 ppm) in the cartridge. After sample addition, the cartridges were rinsed with 2 mL of water +0.1 % formic acid, acetone: acetonitrile (1:1) + 1 % formic acid, and methanol. The samples were eluted using 3 mL of methanol containing 0.1 % NH_3. The eluate was filtered through a Chromabond Carbon A cartridge (MachereyNagel GmbH & Co. KG, Düren, Germany), evaporated to dryness, and reconstituted with 1 mL of methanol:water (4:6). This was followed by measurement via high-performance liquid chromatography-tandem mass spectrometry (HPLC-MS/MS).

2.5. Instrumental analysis

Instrumental analysis was carried out using an LC-MS/MS system consisting of an Agilent Infinity II system coupled to an Agilent Ultivo mass spectrometer. Details can be found in the supplementary material.

2.6. Characterization of hunting districts regarding land use features

Hunting districts were initially characterized based on general land use features. In agreement with the characterization method previously described by Mateus-Vargas et al. (2022), datasets on land use characteristics obtained from the Corine Land Cover (CLC) database in its version for 2018 (data for 2018 available at https://land.copernicus.eu/pan-european/corine-land-cover/clc2018 [last accessed February 14, 2024]) were gathered and assigned to every hunting district. For analysis, the number of original land use categories contained in the CLC-dataset was dissolved by aggregating classes, ultimately distinguishing urban, industrial, and agricultural areas, as well as the areas covered by forest using the QGIS software (Prizren 3.34.11, QGIS.org, 2024). Considering the size of the home range reported for European wild boar (*Sus scrofa*) and in accordance with previous work (Mateus-Vargas et al., 2022), the aggregated land cover data were then intersected with areas generated from each middle point within a 4.4-km radius (in total 60 km^2) to calculate the relative extent of each land use type for each hunting district. For this study, aggregated land use data was additionally extracted for areas around the centroid of 130 km^2 (6.5-km radius) and 310 km^2 (10-km radius) to test further scenarios on exposure risk for this species. For all extracted data, a circular area was used for the sake of simplicity. Additionally, a roads layer from OpenStreetMap was added to the project (Geofabrik GmbH, 2024; OpenStreetMap contributors, 2017). Instead of all types of roads only motorways ("Autobahn") were projected. The corresponding class was selected by the "Select by Expression"-function ("fclass" = "motorway"), re-projected to UTM zone 32N by the Vector tool "Reproject layer", and clipped to the extent of Brandenburg using the "Clip"-function.

Additional datasets were retrieved from the PFAS Data Hub. The dataset contains PFAS-data from different sources and is a continuation of the "Forever Pollution Project" (Source: CNRS Humanities and Social Sciences, 2024). The datasets were downloaded from the "Map" platform (available at: https://pdh.cnrs.fr/en/map/[last accessed October 04, 2024]). The data is already extracted, normalized and merged (for further detail see: https://pdh.cnrs.fr/en/data_doc/[last accessed October 24, 2024]). Data collection considers airports, as well as industrial, military and waste management sites as presumptive sources of PFAS contamination. Only data points to which coordinates were assigned were used. After loading the data into QGIS, the layer was reprojected to the coordinate reference system UTM zone 32N. Then, the datapoints were clipped to the extent of Brandenburg. For statistical analyses, linear distances from hunting districts (centroids) to every presumptive source of PFAS in Brandenburg were calculated using the vector analysis tool "Distance matrix". Additionally, the distances from hunting districts to motorways were determined using the tool „Distance to nearest hub (line to hub)". Then, hunting districts were assigned to categories considering 6.5 and 10 km as thresholds on the distance to presumptive sources. Thresholds were assigned based on the general proximity of presumptive sources to the centers of hunting districts in the study area.

2.7. Statistical analyses

For the statistical analyses, values below the limit of quantification (LOQ) were assigned the value of the limit of detection (LOD) to prevent potential overestimation of the actual concentration of the substance within the analytical range. Results below the LOD were treated as zero μg/kg freeze-dried liver. Statistical calculations were performed using SAS software version 9.4 for windows (SAS Institute Inc., Cary, NC, USA). For data analyses, the data on sampled wild boars was descriptively analyzed using the PROC FREQ statement by hunting district, sex, and reported age class. The Shapiro-Wilk and Kolmogorov-Smirnov tests were used to assess the normality of carcass weight data (PROC UNIVARIATE), and the MIXED procedure was used to determine whether the weight of sampled animals was influenced by age or sex. Considering the data reported for all animals, descriptive analyses of the PFAS concentration data were performed using the MEANS procedure. The UNIVARIATE procedure was used to test for normal distribution. An overall assessment of the influence of the factors “hunting district”, “age class”, and “sex” on results was made using a generalized linear mixed model (GLMM) for mixture distributions (PROC GLIMMIX). Additionally, spatial autocorrelation (Global Moran’s I) was calculated to assess spatial links between the sampled hunting districts and the median PFAS concentrations determined in the livers of wild boars (PROC VARIOGRAM). The Spearman’s rank correlation coefficient (PROC CORR) was used to determine whether the land use characteristics of the hunting districts were related to the PFAS concentrations recorded in wild boar livers. In cases where the GLMM identified a significant influence of categorical factors on the presence of a specific PFAS, the PARTIAL statement was used to control for potential confounding effects by those factors in the statistical correlations. Furthermore, Mann-Whitney tests were performed to compare PFAS contamination levels between categories defined by the presence of presumptive punctual PFAS sources within the set threshold areas. Results of the described statistical tests with $p < 0.05$ were considered significant. Additionally, Principal Component Analyses (PCA) were performed for all hunting districts where at least 10 animals were sampled, considering PFAS for which at least one liver contained concentration > LOD. In this study, the distance between the generated principal component coordinates (PC scores) represents the level of similarity in the overall PFAS profile between two animals. Visualization of generated PC scores for each sample was performed, with age class represented by color to evaluate the homogeneity of findings within each hunting district. PC scores by hunting district and further graphic visualization were performed using GraphPad Prism software version 10.4.0 for windows (GraphPad Software, San Diego, CA, USA).

3. Results and discussion

Original data on concentrations of selected per- and polyfluoroalkyl substances (PFAS) measured in wild boar liver samples from Brandenburg, Germany, as well as land-use characterization of hunting districts and distances between these districts and presumptive PFAS contamination sources, are available via Mendeley Data (10.17632/4dxvzbf3s7.1).

3.1. Data on the study population and liver samples

A total of 164 wild boar livers obtained from 18 hunting districts in the federal state of Brandenburg, Germany, were analyzed for the presence of 16 PFAS. This federal state was selected because, to the best of our knowledge, no extraordinary contamination events have been reported to date. Additionally, diverse landscapes create varying habitat types, microclimates, and resource distributions, leading to greater variability in wild animal behavior and dynamics (Johnson et al., 1992). This increased diversity may complicate isolating specific variable effects, raising the risk of confounding factors and complicating comparisons across studies or regions (Ullmann et al., 2023; Johnson et al., 1992), particularly in exploratory studies like the present one. Thus, the study focused on this specific federal state to avoid the influence of potential geo-anthropogenic confounding factors, which could complicate the comparative analysis of land-use-related effects on PFAS occurrence in wild boars from more diverse landscapes (Mateus-Vargas et al., 2022, 2025). The analyzed samples varied in the number, age class, and sex of the animals among the visited drive hunts. As expected, the weight of the animals was different between age classes ($p < 0.0001$), but no statistically significant differences were found between sexes of the sampled animals within the respective age classes. The number of animals analyzed, along with the age class categorization per hunting district and average weight, is summarized in Table S3. Regarding the basic characteristics of the liver, the median value for dry matter, ash, and fat content across the analyzed samples was 30.4 % (95 % CI: 30.0 %–30.8 %), 5.3 % (95 % CI: 5.1 %–5.4 %), and 11.1 % (95 % CI: 10.2 %–12 %). According to Spearman’s rank correlation coefficient (ρ), high fat content was frequently accompanied by high ash content ($\rho = 0.39$, $p < 0.0001$). In contrast, the dry matter content of the liver was negatively correlated to the ash content ($\rho = -0.21$, $p = 0.007$) but was not statistically related to its fat content. Based on the GLMM, dry matter content was not significantly influenced by sex or age class. However, despite some minor variations in the net content values, this parameter did show a statistically significant difference between hunting districts (GLMM; F-value = 1.8, p-value = 0.04). Similarly, fat content varied significantly across hunting districts (GLMM; F-value = 3.2, p-value = 0.0001), though no differences were observed between age classes or sexes. In contrast to both parameters, variations in ash content were not statistically significant for any of the tested factors. The statistically significant effect of the hunting district, particularly on liver fat content, was expected. However, the lack of any significant effect of age or sex on liver quality parameters, as reported by Ludwiczak et al. (2020), was unforeseen. This discrepancy may be attributed to differences in study design or other unaccounted factors. In our study, the observed differences in fat content may be related to a combination of habitat characteristics, such as land use and food availability. Additional potential influences on foraging behavior could include human activities and hunting practices (Kamieniarz et al., 2020). Interestingly, fat and ash contents of the liver were positively correlated with greater industrial land use within a 4.4 km radius ($\rho = 0.20$, $p = 0.01$ and $\rho = 0.16$, $p = 0.04$, respectively), while higher dry matter content was positively correlated with greater forest cover within 4.4 km and 6.5 km radii ($\rho = 0.22$, $p = 0.005$ and $\rho = 0.20$, $p = 0.013$, respectively). These findings suggest that land use features may influence dietary habits or nutrient availability. However, due to the heterogeneous distribution of ages and sexes within the sampled group as well as the general lack of studies on this specific topic, further biological interpretation remains speculative.

3.2. PFAS concentrations in liver of wild boars in Brandenburg

PFAS were frequently detected in liver samples at concentrations above the LOQ. It is important to emphasize that PFAS concentrations were measured in freeze-dried liver samples. Methodologically, freeze-drying enhanced the detection sensitivity for all PFAS. This factor should be considered when comparing our results with those of other studies, as PFAS concentrations in freeze-dried liver may be expected to be approximately 2- to 3-fold higher than those reported for fresh liver samples. In this study, long-chain perfluorocarboxylic acids (PFCAs) and perfluorosulfonic acids (PFSAs) were detected in over 90 % of all samples. In this study, the lowest detected concentration was defined as the limit of detection (LOD), corresponding to 0.07 μg/kg in freeze-dried liver samples. As shown in Table 1, the detection rate for most substances was high (over 90 %) with only two exceptions. The lowest detection frequencies were observed for PFDS and PFHxA, which were detected in 21.7 % and 68.3 % of all samples, respectively. Although true zero concentrations may be unlikely in the study area, the combination of freeze-drying and the applied analytical methods substantially increased detection sensitivity. Additionally, both the Shapiro-Wilk test as well as the Kolmogorov-Smirnov test indicated that the data on PFAS concentrations was not normally distributed for all substances within hunting districts. Therefore, we chose not to substitute non-detected concentrations with values below the LOD for reporting or further statistical analyses, as these values did not provide additional insight for subsequent assessments and did not notably deviate from the median values. Methods such as maximum likelihood estimation (MLE), as recommended by Helsel (2006), seemed less adequate for statistically handling observations with values < LOD. Median concentrations were highest for PFOS, followed by PFNA, and PFDA. Although with slight differences in the net values, this pattern is consistent with previous findings from surveillance activities in three German federal states

Table 1
Detection rates, PFAS concentrations (μg/kg freeze-dried liver), and 95 % confidence intervals (CI) for each PFAS detected in 18 hunting districts in Brandenburg.

PFAS	Detection rate (%)	Median (μg/kg)	95 % CI (μg/kg)	Max. (μg/kg
PFBA	95.1	0.8	0.6–0.9	3.1
PFBS	92.7	0.7	0.6–0.8	3.4
PFPeA	99.4	0.5	0.5–0.5	1.8
PFHxA	68.3	0.1	0.1–0.1	1.7
PFHxS	96.3	1.6	1.4–1.9	35
PFHpA	93.9	1.3	1.2–1.5	11
PFHpS	95.7	1.7	1.4–1.9	17
PFOA	99.4	5.3	4.4–6.8	95
PFOS	97.6	235	220–260	2400
PFNA	98.8	15	12–18	310
PFDA	98.2	9.7	8.3–11	41
PFDS	21.7	0	0–0	10
PFUnDA	96.3	6.6	6–7	27
PFDoDA	95.1	6.1	5.6–6.6	27
PFTrDA	93.9	10	8.9–11	33
PFTeDA	95.7	5.9	5.3–6.5	23

(Mateus-Vargas et al., 2025). Regarding the physicochemical characteristics of the sampled livers, it is noteworthy that a higher ash content of the liver was positively correlated to higher concentrations of PFBS ($\rho = 0.17$, $p = 0.03$), PFHxA ($\rho = 0.17$, $p = 0.02$), PFHpA ($\rho = 0.23$, $p = 0.004$), and PFUnDA ($\rho = 0.21$, $p = 0.008$). Despite the strong correlation between ash and fat content in the sampled livers, the calculation of the Spearman's rank correlation coefficient (ρ) did not detect any statistically significant association between liver fat content and any PFAS. The overall detection frequencies, median values, 95 % confidence intervals (CI), as well as the maximum concentration detected for each PFAS, are listed in Table 1. Detailed information on detected PFAS per hunting district is summarized in the Supplementary Information (Table S4).

With few exceptions, PFOS concentrations were generally at least 10 times higher compared to other PFAS in the investigated liver samples. This is not unexpected, as PFOS tends to accumulate in wild boar liver more efficiently than other PFAS (Mertens et al., 2025), and PFOS levels above 1000 μg/kg have been reported in non-dried wild boar livers (Mateus-Vargas et al., 2025; Kowalczyk et al., 2018; Stahl et al., 2012). Given the long half-life of PFOS in pigs (Numata et al., 2014) and its low environmental mobility (Xing et al., 2021), such high concentrations may result from individual dietary factors, as PFAS accumulation varies across different food components (Rupp et al., 2023; Gerardu et al., 2023; Death et al., 2021). Interestingly, different European studies reported median PFOS concentrations ranging between 50 μg/kg and 90 μg/kg, as indicators of current background contamination in the environment (Mertens et al., 2025; Schröder et al., 2024; Tavoloni et al., 2023; Rupp et al., 2023). However, the median PFOS concentration in the analyzed freeze-dried samples from our study was 235 μg/kg, which may initially suggest contamination incidents in one or more of the sampled areas. However, analysis using GLMM revealed that PFOS contamination levels were not statistically associated with specific hunting districts (GLMM; $F = 0.86$; $p > 0.05$). Notably, the highest individual concentration (approximately 753.1 μg PFOS per 1 kg of fresh liver) was detected in a young wild boar (age class 0). Similar findings were reported by Mertens et al. (2025) in wild boars from Berlin and Brandenburg, where PFOS accumulation in juveniles was attributed to potential transfer through maternal milk. This pathway may also explain the elevated level in this particular individual, which weighed 15 kg (Briedermann, 1970). However, for other individuals among the top ten highest concentrations, all of which weighed more than 15 kg, a clear association remains difficult to establish. In addition to PFOS, PFNA was identified as one of the dominant PFCAs. Mertens et al. (2025) and Rupp et al. (2023) reported PFNA concentrations of 4.4 μg/kg and 11 μg/kg in livers of German wild boars, respectively, which is close to the median value of the samples analyzed in this study (15 μg/kg freeze-dried liver). In contrast, Schröder et al. (2024) reported a median value of 68 μg/kg in these matrices. The latter despite the probable point of source being as far as 140 km from the sampled region (Schröder et al., 2024). For liver samples obtained from wild boar in Italy, a mean concentration of 5.8 μg/kg for PFNA was reported (Tavoloni et al., 2023). Herzke et al. (2023) published data on PFAS in liver samples from various species from the Arctic region. Fig. 1 highlights the differences in long-chain PFCA patterns between wild boar populations from different European regions and those observed in Arctic mammals (Herzke et al., 2023). Based on previous observations and despite variations in final ratios (Fig. 1), wild boar livers seem to accumulate comparable patterns of long-chain PFCAs, with all these substances being detectable above the limit of quantification. In contrast to the livers of European wild boar populations, distinct PFCA profiles were reported in various Arctic mammals, probably linked to their different food sources, which may have led to a more diverse dietary exposures to specific substances (Herzke et al., 2023). For the wild boars, differences in PFCA profiles are likely more related to varying levels of exposure to different pollutants, rather than dietary variation, due to their similar metabolism and feeding preferences across Europe. This becomes clearer when specific pollution sources are identified (e.g. Schröder et al., 2024; Rupp et al., 2023; Felder et al., 2023), allowing for a more comprehensive understanding of contaminant distribution.

Previous studies have reported that PFAS contamination levels in wild boar organs are influenced not only by the presence of these substances in the animals' habitats (Rupp et al., 2023), but also by intrinsic factors such as age and sex (Mertens et al., 2025; Felder et al., 2023). Consistent with these findings, data analysis was conducted using GLMM to assess the influence of the variables "age class" and "sex" across the complete dataset. The results indicated that neither sex nor age class (except for PFHxA: GLMM; F-value $= 3.4$, p-value $= 0.04$) showed a statistically significant relationship with the detected PFAS concentrations in the sampled wild boar population (Table 2). These findings were unexpected, as previous studies reported higher concentrations of different PFAS in livers of wild boar males sampled across various locations in Germany (Mertens et al., 2025; Schröder et al., 2024; Felder et al., 2023; Kowalczyk et al., 2018). However, those studies mostly focused on few limited regions and did not account for the potential influence of individual hunting localities on their observations. In the present study, GLMM analysis showed that the concentration levels of PFBA, PFBS, PFPeA, PFOA, PFNA, PFUnDA, and PFTrDA determined in the livers of the sampled wild boars were significantly influenced by the hunting district (Table 2). The variability in PFAS concentrations in wild boar liver between hunting districts was expected, since other studies reported regional variations in Germany (Mertens et al., 2025; Mateus-Vargas et al., 2025; Rupp et al., 2023; Kowalczyk et al., 2018). Noteworthy, according to the Moran's Index, no spatial autocorrelation was statistically determined for the all 7 PFAS highlighted by GLMM analyses. In contrast, elevated PFDA levels in the sampled wild boars appeared to be spatially clustered (Moran's $I = 0.014$; z-score $= 4.62$; $p < 0.0001$), with higher median values being present in hunting districts of the eastern site of Brandenburg. Interestingly, the occurrence of high median values of PFDA in the liver of wild boars did not appear to be disrupted by the motorway running from southern Berlin toward Poland (German denomination: A12), which shows a different distribution pattern as such of viruses within the wild boar population in Brandenburg (Simon et al., 2024). Recent discussions arise on the role of air emissions in environmental PFAS pollution (Schröder et al., 2024; Tian et al., 2018). In Europe for instance, Schröder et al. (2024) proposed a fluoropolymer production facility (located 120–140 km away) as a potential point source of PFNA for the Bohemian Forest, possibly through wind transport and atmospheric deposition. Given the prevailing wind direction in Brandenburg (predominantly westerly; Deutscher Wetterdienst, 2012), an airborne distribution of PFDA from significant sources, likely located in the Berlin

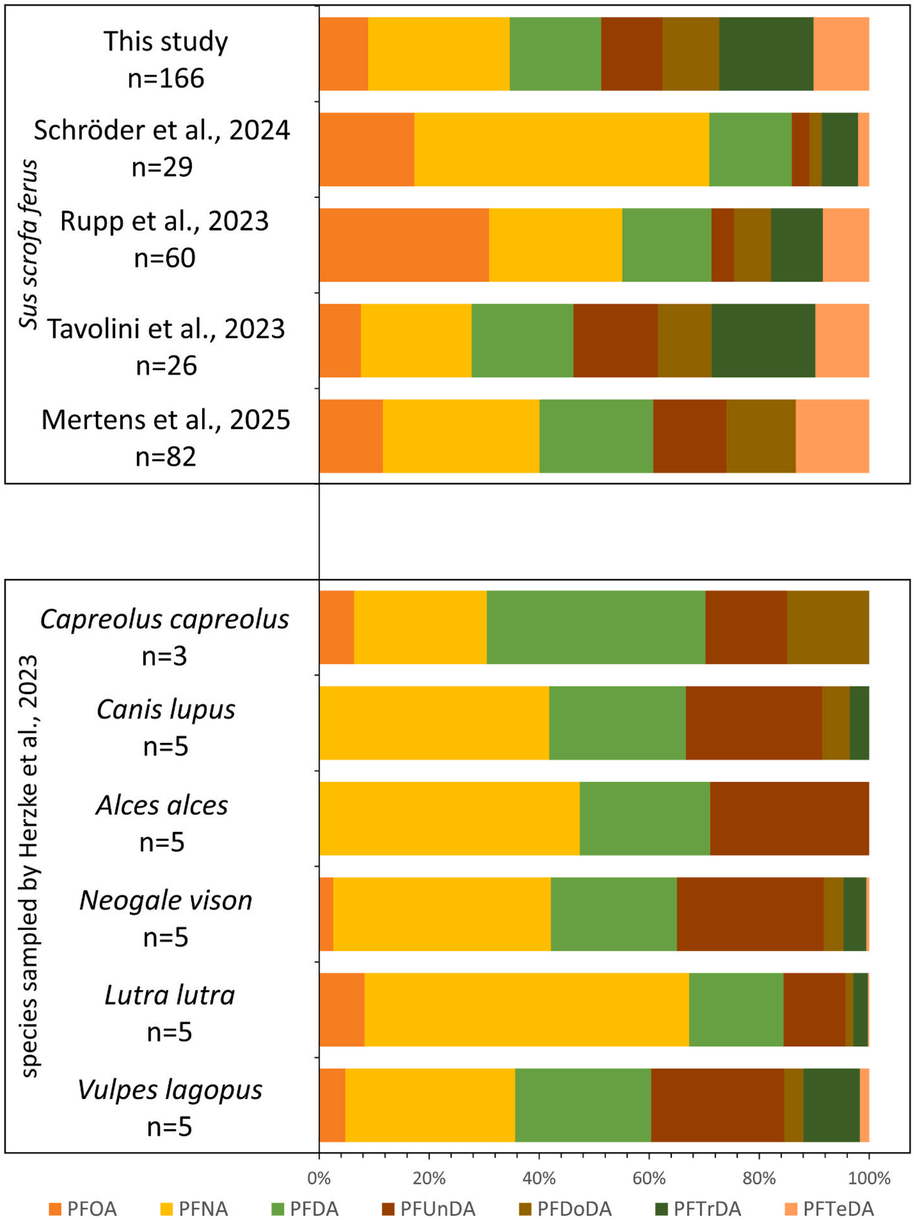

Fig. 1. Relative composition of the levels of long-chain perfluorocarboxylic acids (PFCAs) in the livers of various animal species. Data are represented as percentages (%) of total median PFCA concentrations.

metropolitan area, cannot be ruled out.

High levels of PFAS in animal livers have been reported primarily in connection with point sources. For wild rodents, for example, there are reports of PFOS levels of up to over 100,000 μg/kg (Cartron et al., 2025; Witt et al., 2024; Hoff et al., 2004). In comparison to published data on contamination in wild boars from areas with confirmed point sources, exceptionally high PFAS concentrations were determined in certain individuals, which markedly differed from the general levels found in other specimens within the same hunting district. Strikingly high contamination levels of PFOS were observed in hunting districts E, H, N, O, and P. In these districts, PFOS concentrations in freeze-dried liver exceeded 1000 μg/kg, while the upper limit of the 95 % confidence interval remained below 500 μg/kg (Table S4). Interestingly, a comparison of principal component (PC) scores based on PFAS concentrations revealed that most animals within a hunting district exhibited similar contamination patterns. Only few individuals of different age classes, including those with exceptionally high PFAS levels, deviated from the core group (Fig. S1). Due to the low number of animals sampled per hunting district, it was not possible to determine whether these were statistical outliers. Examples of PC scores for hunting districts with more than 10 sampled animals are provided in the supplementary information (Fig. S1). The results for most wild boars within hunting districts support the assumption that these animals are exposed to similar levels of PFAS in their local environments. Thus, individuals with exceptionally high contamination levels may have been hunted outside their usual territories. As previously reported, sampling was conducted during the fall and winter months, coinciding with the federal forest authorities' hunting season (Maaz et al., 2022), which spans three to four months and is often coordinated across neighboring districts to maximize the hunting bag. Intensive hunting practices, such as drive hunts or battue hunting, can prompt wild boar groups to move acutely from their original territories or temporarily expand their range (Keuling and Massei, 2021). According to Olejarz et al. (2024), wild boar may show more escape behavior as they gain hunting experience, especially in areas with frequent annual drive hunts. Although not noted in earlier studies on game animal contaminants, the unusual findings in this study

Table 2
Results of general linear model for mixture distributions (PROC GLIMMIX) for PFAS detected in wild boars of 18 hunting districts of Brandenburg. Statistically significant values are presented in bold and shadowed.

PFAS	hunting district		sex		age class	
	F-value	p-value	F-value	p-value	F-value	p-value
PFBA	**2.07**	**0.0135**	0.55	0.4598	0.78	0.4611
PFBS	**1.78**	**0.0414**	2.88	0.093	1.28	0.2816
PFPeA	**2.24**	**0.0072**	0.23	0.635	0.49	0.6112
PFHxA	1.51	0.1048	1.74	0.1895	**3.37**	**0.0383**
PFHxS	0.4	0.9835	0.02	0.8951	0.35	0.706
PFHpA	1.15	0.317	0.07	0.7963	0.68	0.5065
PFHpS	1.1	0.3628	0.11	0.7423	0.32	0.7293
PFOA	**4.8**	**<0.0001**	0.01	0.9082	0.62	0.5394
PFOS	0.86	0.6209	0.86	0.3554	0.93	0.3991
PFNA	**4.46**	**<0.0001**	0.09	0.7672	0.31	0.7307
PFDA	1.16	0.3082	1.44	0.2332	0	0.9974
PFDS	0.59	0.8934	0.36	0.5475	0.13	0.8747
PFUnDA	**1.98**	**0.0193**	2.11	0.1492	0.22	0.8038
PFDoDA	1.02	0.4472	1.17	0.2816	0.19	0.8291
PFTriDA	**1.74**	**0.0472**	3.26	0.074	0.89	0.4146
PFTetraDA	0.92	0.5529	0.46	0.4981	0.23	0.7946

may be due to increased animal movement caused by frequent drive hunts during sampling. Although still speculative, the extent of potential bias introduced by these hunting practices is difficult to assess with the current data. Nevertheless, it cannot be ruled out. While these considerations do not diminish the value of existing studies on the presence of chemical contaminants in wildlife, future research using wild boars as bioindicators should account for possible biases introduced by hunting-related animal movements. This may be particularly important when addressing more specific research questions, such as tracking the progression of a detected contamination event, which would require long-term monitoring to capture temporal and spatial variability more accurately.

Regarding the potential risks to humans, the presence of high PFAS concentrations has led to the establishment of maximum allowable levels for certain contaminants in food, as outlined in Commission Regulation (EU) 2023/915 (April 25, 2023). This regulation includes four PFAS compounds assessed by the European Food Safety Authority (EFSA): PFOA, PFOS and its isomers, PFNA, and PFHxS. Focused on the study of wild boars in Gerardu et al. (2023) showed that PFAS accumulate in offal, particularly liver. Despite significant knowledge gaps, the long half-life of PFAS in humans means that chronic exposure, even at low levels, could pose substantial health risks (Fenton et al., 2020). This maybe the case for the consumption of contaminated game products. For instance, the German Federal Institute for Risk Assessment has determined that consuming 125 g of wild boar liver, with average PFAS concentrations, once a year could exceed the tolerable intake level (Bundesinstitut für Risikobewertung, 2024). Consequently, the Federal Ministry for the Environment advises against the consumption of wild boar liver, particularly by children, pregnant women, breastfeeding mothers, and women of childbearing age (Bundesministerium für Umwelt, Klimaschutz, Naturschutz und nukleare Bundesministerium für UmweltKlimaschutzNaturschutz und nukleare Sicherheit, 2025). It is important to note that no perceptible changes in health, behavior, or organ appearance were reported by the hunters or the sampling staff in the wild boars of this study. Similarly, to the best of our knowledge, no pathological changes have been reported in highly contaminated wild boars of other studies. However, we remain cautious about these assumptions, given the challenges in accurately assessing chronic organ lesions, particularly in wild game animals during field evisceration. Furthermore, although the risk associated with liver consumption can be inferred from PFAS accumulation patterns and concentrations (Mertens et al., 2025; Rupp et al., 2023), the variability in contamination levels, habitat use, distribution among organs, and feeding behavior of wild boars across regions complicates drawing definitive conclusions about the risks of consuming their meat based solely on liver data. A differentiated approach is therefore essential: liver samples can serve as sensitive indicators for assessing environmental contamination and PFAS distribution, whereas meat samples provide more direct information on potential consumer exposure in specific geographical areas. This dual approach is crucial for accurate and context-specific risk assessment.

3.3. Analyses of results based on general land-use characteristics

In view of the variations observed during the initial analyses, a spatial analysis was conducted to further evaluate PFAS contamination levels in wild boar livers. First, the analyses were based on publicly available land use data. Similar approaches have been previously applied, including studies analyzing monitoring data from three German federal laboratories on PFAS in wild boar livers (Mateus-Vargas et al., 2025; Kowalczyk et al., 2018). In contrast to previous reports, this study has improved the descriptive accuracy of key habitat conditions by incorporating more detailed coordinates on the locations of the sampled hunting grounds. Additionally, as in a prior study on the occurrence of *Staphylococcaceae* with reduced susceptibility to cefoxitin in wild ungulates in Brandenburg (Mateus-Vargas et al., 2022), the land-use data was complemented by geodetic information from the Corine Land Cover dataset provided by the European Copernicus program. Despite local variability in land use, the results on PFAS concentrations of the present study were comparable between hunting districts due to the relatively homogenous topography of the Brandenburg region. Thus, the dataset allowed for a more focused evaluation of how different land-use types might influence the exposure of wild boars to anthropogenic PFAS contaminants at the local level. Fig. 2 shows the location of the sampled hunting districts in Brandenburg and the respective extent of coverage by land-use categories within a 4.4-km radius. Fig. S2 compares the hunting districts based on proportional land cover, including agricultural, forested, urban, and industrial areas.

Initially, the relationship between the land-use types and the overall detected PFAS concentrations was statistically tested. Regarding the land use characterization of hunting districts within the 4.4 km-radius, positive correlations were determined between the proportion of land covered by urban settlement and the concentrations of PFOA, PFOS, PFNA, and PFDA (Table 3). Additionally, the increasing concentration of PFOA and PFNA in livers was significantly correlated with a higher proportional coverage of hunting districts by industrial areas. Moreover, an effect of increasing agricultural land cover on PFUnDA concentrations was detected (Table 3). It is noteworthy that PFOA, PFNA, and PFUnDA showed a multi-focal occurrence across hunting districts according to GLMM, which distinguish them from other PFAS (Table 2). These findings suggest that local factors, such as the degree of urbanization and industrialization, or, in the case of PFUnDA, the predominant use of land for agricultural purposes, may have significantly influenced the variable occurrence of these substances in different hunting districts. Furthermore, PFDA clustering detected using Moran's Index appeared to be associated with urbanized areas within or close to the hunting districts. This observation appears to challenge the earlier hypothesis of potential airborne PFAS spread. However, it is also possible that both explanations, airborne transmission and local point sources, are valid and may act simultaneously. Future studies should specifically investigate this aspect to provide further clarity. Based on case studies on PFAS contamination around industrial plants, it is not surprising to find correlations between PFAS and industrial land use, both for studies conducted in Germany and outside of Europe (Sardiña et al., 2024; Göckener et al., 2023; Rupp et al., 2023; Smalling et al., 2023). A similar relationship may exist for agricultural areas. Recently, a number of studies have revealed the connection between pesticides and PFAS, highlighting that PFAS are used directly in pesticide formulations (Donley et al., 2024). Additionally, correlations between the use of pesticides and PFAS burdens in the blood serum of greenhouse workers

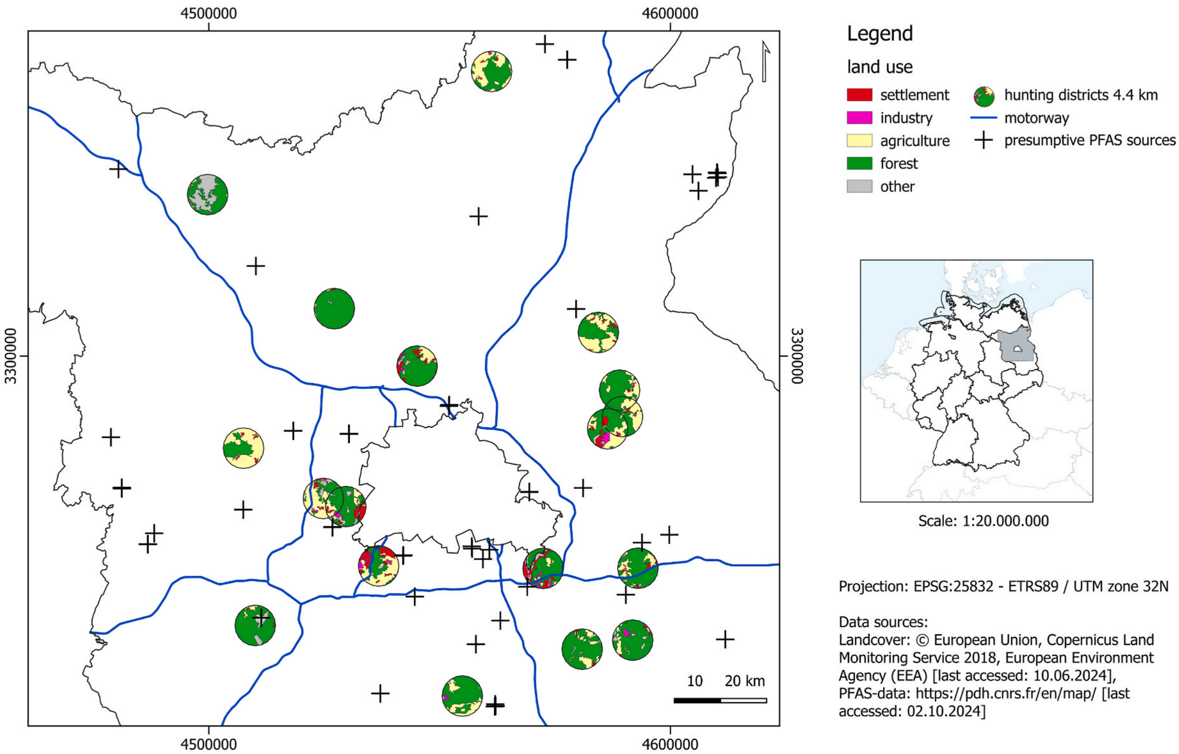

Fig. 2. Map showing the distribution of hunting districts where wild boars were sampled in the federal state of Brandenburg, Germany. Circles around the hunting district coordinates represent the proportional extent of land cover within a 4.4-km radius, categorized as settlement, industry, agriculture, forest, and other areas. Motorways are delineated in blue. Presumptive PFAS sources, as identified by the "Forever Pollution Project" (Source: CNRS Humanities and Social Sciences, 2024), are marked with crosses.

Table 3
Spearman's rank correlation coefficients (ρ) between PFAS concentrations in wild boar livers (μg/kg) and land-use features (%) within a 60 km^2 area. For clarity, only results with $p < 0.05$ are shown.

PFAS	Urban		Industry		Agriculture		Forest	
	ρ	*p*-value	ρ	*p*-value	ρ	*p*-value	ρ	*p*-value
PFBA	.	.	.	.	.	.	.	.
PFBS	.	.	.	.	.	.	.	.
PFPeA	.	.	.	.	.	.	.	.
PFHxA	.	.	.	.	.	.	.	.
PFHxS	.	.	.	.	.	.	.	.
PFHpA	.	.	.	.	.	.	.	.
PFHpS	.	.	.	.	.	.	.	.
PFOA	0.24	0.002	0.22	0.005	.	.	.	.
PFOS	0.18	0.02	.	.	.	.	.	.
PFNA	0.25	0.001	0.19	0.02	.	.	.	.
PFDA	0.24	0.002	.	.	.	.	.	.
PFDS	.	.	.	.	.	.	.	.
PFUnDA	.	.		.	0.16	0.04	.	.
PFDoDA	.	.	.	.	.	.	.	.
PFTrDA	.	.	.	.	.	.	.	.
PFTeDA	.	.	.	.	.	.	.	.

have been reported (Andersen et al., 2024; Donley et al., 2024; Lasee et al., 2022). In Germany, reports of PFAS contamination in an agricultural context have also been documented (Kotthoff et al., 2020; Söhlmann et al., 2018; Skutlarek et al., 2006; Wilhelm et al., 2008). However, it is important to note that the soil contamination incident in North Rhine-Westphalia documented only PFOS and PFOA (Wilhelm et al., 2008). By contrast, at the second contamination site in Rastatt (Baden-Württemberg), PFUnDA was found in higher proportions in the topsoil compared to the subsoil, likely due to its lower mobility caused by sorption (Röhler et al., 2021). Historically, the legal or illegal use of industrial or municipal waste sludges as a soil conditioner in agriculture (now prohibited in Germany) has led to land contamination, and the persistence of PFAS means that contamination from these past practices remain relevant in affected areas today (Brusseau et al., 2020; Hepburn et al., 2019). Given the predominance of agro-industrial farming in the study area, it is plausible that agricultural soils, when contaminated, contribute to PFAS burdens in wild boars. The potential influence of agricultural practices on environmental PFAS contamination in the study area requires direct investigation in future studies.

3.4. *Occurrence of PFAS in relation to the presence of presumptive sources*

In alignment with most studies examining the impact of PFAS-using factories on surrounding environments, we further investigated potential relationships between PFAS concentrations in wild boar livers and the proximity to presumptive PFAS sources. To achieve this, geolocation data of potential PFAS sources were integrated into our analysis, and hunting districts were categorized based on the presence of these sources within radii of 6.5 km and 10 km, respectively. Within a 4.4 km radius, only one hunting district contains a presumptive source. In contrast, six hunting districts were identified as containing presumptive PFAS sources within the 6.5 km radius, such as military sites or waste management facilities, including those for non-hazardous waste treatment or sewage disposal. Expanding the radius to 10 km included four additional hunting districts, which contained waste management facilities, manufacturers of paper and paperboard products, or an airport (Fig. 2). Although only for PFOA and PFNA, statistical comparisons of the two categories within the defined geographic thresholds revealed significantly higher concentrations in the livers of wild boars from hunting districts with presumptive PFAS sources within a 10 km radius compared to those at greater distances (Mann-Whitney test; $p = 0.04$ and $p = 0.03$, respectively). Notably, statistical significance was even stronger for the 6.5 km range, with *p*-values of 0.015 for PFOA and 0.003

for PFNA. These results are in accordance with the land-use evaluations discussed above, which showed a statistically significant effect of industrial land coverage on the concentrations of these two substances found in wild boar livers, and further suggest a link to the presence of presumptive source facilities within a 6.5 km radius. In the case of Mertens et al. (2025), elevated PFAS concentrations (specially for PFOS) in wild boar livers were likely influenced by the presence of an abandoned airport within the hunting district. Previous studies have demonstrated that PFAS emissions from industrial activities can occur via water or air. For instance, research on PFAS concentrations in the air near fluorochemical manufacturing facilities in China identified PFOA as the dominant substance, followed by PFBA (Chen et al., 2018). Other study in China detected waste management sites, including garbage dumps, as point sources for airborne PFAS emissions, with PFBA and PFOA as the primary substances (Tian et al., 2018). Notably, Tian et al. (2018) observed an exponential decrease in deposited airborne PFAS concentrations with increasing distance from the source, a pattern that resembles the observations of the present study. However, data on airborne PFAS emissions in Europe remain limited, with most studies focusing on PFCA ≥ C7. Although there are few studies on short-chain PFCA, such substances have also been detected (Zhi et al., 2024; Rupp et al., 2023; Guckert et al., 2023; Herzke et al., 2023), emphasizing the need for more comprehensive research on this subject. Furthermore, the waterborne spread of PFAS often begins with their entry into wastewater treatment plants through municipal and industrial wastewater. During treatment processes, PFAS can undergo partial transformation, ultimately entering surface waters via effluent discharge or binding to sewage sludge (Fredriksson et al., 2022; Liu et al., 2022; Lenka et al., 2021). The limited or absent capture of PFAS by emission control systems underscores the need for further research into potential local-level inputs from various presumptive sources. Our findings indicate a possible general vulnerability of wild boars habiting near such sources to exposure in Brandenburg, at least to PFOA and PFNA. Although wild boars may theoretically be exposed to PFAS through air or water, previous studies suggest that rooting behavior and diet are likely more relevant exposure pathways. Potential exposure routes for wild boars include the ingestion of soil, plants, and small animals such as earthworms (Zhao et al., 2013; Rupp et al., 2023). Rupp et al. (2023) supported this hypothesis by showing that PFAS patterns in wild boar livers closely matched those in soils from both highly and weakly contaminated areas. Contamination of soil and their organisms may involve PFAS entering the soil through mechanisms such as water infiltration or dust sedimentation. Nevertheless, the precise distribution and exposure routes of PFAS within the hunting districts of Brandenburg have yet to be fully identified and mapped. A hypothesis-driven approach to selecting study areas, combined with time-course studies, could shed light on additional factors influencing PFAS distribution in the environment, as well as the interactions between animals and these contaminants. The impact of, for instance, extreme weather events, was previously shown for the occurrence of biological contaminants in wild boar populations (Günther et al., 2022).

3.5. Limitations

The analyses in this study focus on the contamination of wild boar livers by perfluorocarboxylic acids (PFCA) and perfluorosulfonic acids (PFSA). These compounds were selected as representatives of the broader group of per- and polyfluoroalkyl substances (PFAS) present in the environment. However, they only account for a fraction of the known PFAS compounds. For example, Rupp et al. (2023) identified PFCA precursors in wild boar livers, which are converted into PFCA through total oxidation of the samples (TOP assay). This suggests that the contamination patterns observed in the present study may underestimate the substances present in the liver samples.

4. Conclusion

As highlighted by this study and supported by previous reports, wild boar livers may contain varying PFAS concentrations, some of which raise consumer safety concerns (Mertens et al., 2025; Bundesinstitut für Risikobewertung, 2024; Rupp et al., 2023). The findings from Brandenburg highlight that local habitat characteristics have a stronger influence on contamination levels and PFAS patterns in wild boar livers than factors such as age or sex. Land-use-related analyses revealed that elevated PFAS concentrations in wild boar livers were statistically associated with areas of higher urban (PFOA, PFOS, PFNA, and PFDA), or agricultural coverage (PFUnDA). Furthermore, larger extents of industrial land coverage and the proximity to punctual anthropogenic sources within a 10 km radius were associated with higher concentrations of PFOA and PFNA in wild boar livers. These findings align with similar observations from other German federal states and emphasize the value of land-use-based analyses in combination with PFAS analyses organs of wild boar in identifying areas at greater risk of exposure to high levels of contamination. From the perspective of consumer protection, land-use-based assessments provide a promising tool for characterizing potential risks linked to the consumption of wild boar meat and offal. Such analyses can also enhance the planning and execution of risk-based monitoring programs, for instance by focusing efforts on urbanized or industrialized areas for long-chain PFCAs. Additionally, combining land-use data with precise information on the origins of sampled wild boars could help identifying detect unintentional or intentional releases, such as those linked to agricultural activities.

CRediT authorship contribution statement

Carsten Felder: Writing – original draft, Visualization, Investigation, Formal analysis. **Rafael H. Mateus-Vargas:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Ina Fischer:** Writing – review & editing, Visualization, Software, Formal analysis. **Dirk Skutlarek:** Writing – review & editing, Resources. **Harald Färber:** Writing – review & editing, Supervision, Resources. **Janine Kowalczyk:** Writing – review & editing. **Robert Pieper:** Writing – review & editing, Conceptualization. **Jana Rupp:** Writing – review & editing. **Maciej Durkalec:** Writing – review & editing. **Anneluise Mader:** Writing – review & editing, Methodology. **Julia Steinhoff-Wagner:** Writing – review & editing, Resources, Formal analysis, Conceptualization.

Ethics statement

Liver samples were obtained from wild boars legally hunted under annual population management plans established by the relevant authorities, in accordance with the applicable hunting law regulations, specifically the Brandenburg Hunting Act (Brandenburgisches Jagdgesetz, BbgJagdG) and the Federal Hunting Act (Bundesjagdgesetz, BJagdG). All samples were collected *post mortem*; therefore, no ethical committee approval was required.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2025.123583.

Data availability

Research data has been made accessible in Mendeley Data

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