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Deer as sentinels of emerging environmental pollution: Assessing contamination patterns and seasonal variations

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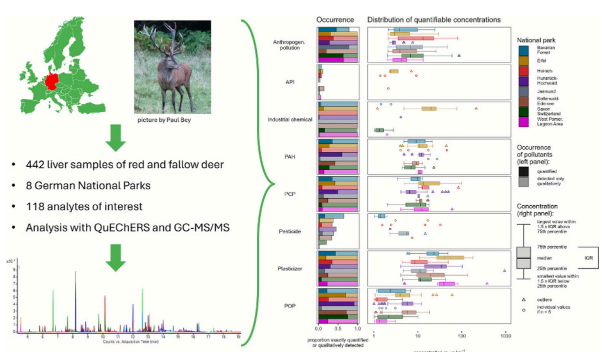
HIGHLIGHTS

- Red deer in German National Parks are polluted with a vast number of chemicals.
- Contamination was not susceptible to seasonal variations.
- Significant differences between parks were limited to individual substance groups.
- Determination of environmental chemicals with to-date unknown risk potentials
- First time reporting of plasticizer and PCP contamination in red and fallow deer

GRAPHICAL ABSTRACT



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ABSTRACT

Environmental pollution caused by various chemicals is a pressing issue that affects every ecosystem. National parks play a special role in protecting and preserving nature. However, despite their special status as protected

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DPHP
Tebuconazole
Bioaccumulation
Sustainability

areas, they are not immune to environmental pollution. We assessed the pollution burden of ungulate populations in eight national parks from all over Germany. We analyzed 118 compounds from eight pollutant groups (indicators for anthropogenic pollution, active pharmaceutical ingredients (APIs), polycyclic aromatic hydrocarbons (PAHs), personal care product ingredients (PCPs), pesticides, plasticizers, persistent organic pollutants (POPs), and industrial chemicals) in a total of 442 liver samples from *Cervus elaphus* and *Dama dama* taken between October 2023 and January 2025. Results revealed the presence of 61 different analytes in the samples. Parallel detected analytes in samples ranged from 14 to 33, (median 18). APIs and pesticides went largely undetected, whilst contamination with PAHs and PCPs was comparable among all eight parks and three age groups (fawn, subadult and adult). We are the first to report on such a wide range of specific compounds in ungulates, particularly emerging groups of pollutants. Determined concentrations of anthropogenic pollutants, industrial chemicals, plasticizers and POPs differed between parks. Statistical analyses and regression model fitting provided no evidence of seasonal variation in the contamination with anthropogenic pollutants, industrial chemicals, PAHs and POPs. The high number of analytes detected in parallel is alarming in terms of potential cocktail effects and underlines the importance of sustainable management of environmental pollution and further research into emerging pollutants.

1. Introduction

The negative impact of common, widely used chemicals is a major concern in terms of human health and the environment. A prominent example was the so-called "dirty dozen", twelve persistent organic pollutants (POPs), banned under the Stockholm Convention from 2004 (Stockholm Convention, 2019). The pesticide DDT, part of the dirty dozen, was prominently used in the 1950s and 60s. Later, it proved to be highly persistent in the environment, bioaccumulative, carcinogenic, and endocrine disruptive. Thus, its use was subsequently restricted, and it was banned by many countries. Since then, more substances have been included and subsequently banned as POPs (Stockholm Convention, 2023). Another pollutant group that has been in the focus due to its adverse effects on wildlife and the environment are pesticides. They are widespread, as they are crucial for agriculture and food production worldwide. However, they negatively affect pollinators, such as bees (Serrão et al., 2022) and bats (Guimarães Torquetti et al., 2021) to an extent that critically impairs biodiversity (Khan et al., 2023). When concerns regarding adverse effects on human health and the environment arise, the approval of pesticides that were previously important, like the neonicotinoid imidacloprid, may been withdrawn in the European Union (European Commission, 2020). Subsequently, new substances of unknown risk profile take their place. The same applies to other substance groups, like plasticizers. They are used in almost every plastic product available, reaching the environment through migration (Tüzüm Demir and Ulutan, 2013) or in microplastic particles (Fung et al., 2025). Phthalate ester plasticizers, like bis(2-ethylhexyl) phthalate (DEHP), were heavily relied on in plastic products, *e.g.* for food packaging and PVC (Haned et al., 2018), in previous decades. DEHP was subsequently classified as a substance of very high concern (SVHC) due to its endocrine disruptive properties by the European Chemicals Agency (European Commission, 2017). When the use of plasticizers is restricted, different substances emerge to replace them (Nagorka and Koschorreck, 2020). The substitutes are generally described as less harmful than their predecessors and are readily applied (Koch et al., 2015). In the case of bis(2-propylheptyl) phthalate (DPHP), concerns about potentially high exposure and risks to human health through endocrine disruption led to its inclusion in the Community Rolling Action Plan (CoRAP) of the European Chemicals Agency (ECHA) (European Chemicals Agency, 2014). This highlights the importance of monitoring the exposure of commonly used chemicals in the environment. Substances that are already known to be of concern can pose a risk to wildlife and biodiversity. Whereas chemicals that are currently considered not harmful and are thus used to a great extent without restrictions can later transpire to be harmful for the environment, nonetheless.

Commonly, contaminants do occur not in isolation, but as mixtures of many different substances, possibly leading to combined toxicological effects, so-called "cocktail effects". The mutual effects of multiple contaminants are even less well studied than those of single contaminants (Hernández et al., 2013). In mixtures, contaminants can lead to adverse effects at concentrations even below their actual effect thresholds (Kortenkamp, 2007). Determining the effects of chemical mixtures is challenging. Approaches to do so include modelling dose addition and independent action. However, as the effects of multiple chemical mixtures are not necessarily additive, but can be either independent, synergistic or antagonistic, these approaches can lead to inaccurate estimations. Thus, it is not feasible to investigate all possible combinations of potential environmental contaminants (Göbölös et al., 2024). Experiments showed that the presence of non- or low-toxic substances, like boscalid and terbuthylazine, can lead to significantly decreased LD_{50} values of pesticides and active pharmaceutical ingredients (APIs) (Göbölös et al., 2024; Tsvetkov et al., 2017), enhancing their toxicity. This highlights the potential of substances considered non-toxic or of low harm to contribute to mixture toxicity and adverse effects on human health and wildlife.

In this study, we examined the environmental pollution burden on red deer (*Cervus elaphus*) and fallow deer (*Dama dama*) in eight German national parks, with a total of 442 samples taken from October 2023 to January 2025. We analyzed the concentrations and occurrence of 118 compounds of interest, consisting not only of the well-known and long-time monitored POPs, pesticides, and polycyclic aromatic hydrocarbons (PAHs), but also of contaminant groups that are of more recent interest, such as plasticizers, personal care products (PCPs), active pharmaceutical ingredients (APIs), other industrial chemicals, and direct indicators for anthropogenic pollution. The aim of this study was to evaluate the presence of contaminants in deer populations in national parks across Germany, as well as assessing the different burdens over the life cycle of red and fallow deer, represented by three different age groups (fawn, subadult and adult), and concentration changes throughout the seasons. According to the IUCN (International Union for Conservation of Nature) category II definition (UN Environment Programme, 2024), national parks are extensive areas preserving major ecological processes and native biodiversity, while allowing suitable forms of public use (UN Environment Programme, 2020).

Due to the special protection of national parks, one would expect a low abundance of environmental pollutants in their territories. No pesticides are applied as there is limited agricultural use and general human presence is also limited, besides recreational activities. However, volatile environmental pollutants can migrate through the air. Persistent chemicals can also be inherited burdens, present since before the formation of national parks. Monitoring chemical pollution in most published research is focused on urban and agricultural areas. Air and water quality assessment play an important role in urban areas (Sicard et al., 2023) whereas in agricultural areas pesticides and their runoff are assessed (Andrade et al., 2021), as well as the prevalence of POPs and pesticides in agricultural soil (Plaza-Bolaños et al., 2012). Assessing the environmental pollution in nature conservation areas, such as national parks, is also important, as it can indicate the influx of contaminants from surrounding areas and ongoing effects of accumulation or slow degradation. Studies have also shown the presence of contaminants such as pesticides in distant areas like the polar regions or mountain areas in national parks in Brazil (Guida et al., 2018). Marine protected areas in the Persian Gulf have shown elevated levels of lipophilic POP contamination, indicating that the designation of nature conservation areas alone is not sufficient for pollution control (Ghaemi et al., 2024). The continuous, close monitoring of wildlife populations and included wildlife management allows for long-term sampling in a controlled frame.

Indicator species are a valuable tool for assessing environmental changes and the burden of environmental contaminants on different ecosystems. Popular indicator species include pollinators like bees (Parikh et al., 2021) and bats (Jones et al., 2009), other insects like beetles or ants (Parikh et al., 2021) or omnivores like raccoons (Lord et al., 2002). Ungulates have been used as bioindicator for PFAS and toxic metal contamination (Kowalczyk et al., 2018) and changing landscape quality (Tasser et al., 2023). As ungulate populations in German national parks are abundant (Warenik-Bany et al., 2019), closely monitored and regulated by wildlife management through hunting, we chose red deer as indicator species for this study. Where not enough *C. elaphus* specimen were available for sustainable sampling, fallow deer were used as substitutes. Both red and fallow deer, are considered as intermediate feeders, with similar diets, that only differ in the ratio of grass to woody browse during growing season (Spitzer et al., 2020). *D. dama* is also a very abundant species in Germany (Ludwig et al., 2012) and Europe (Bijl and Csányi, 2022) and part of ungulate management in Germany. The utilization of species that are hunted for population management purposes as an indicator species to monitor environmental pollution in German national parks provides the advantage of a minimal invasive monitoring strategy. An additional advantage of *C. elaphus* as an indicator species is its broad abundance in Europe (Skog et al., 2009), which enables extensive monitoring and comparison of environmental pollution in different countries. The large populations and broad hunting season timeframes allow for the monitoring of pollutant burden on *C. elaphus* over the course of summer and winter, enabling the monitoring of changes of pollutant occurrence, frequency and concentrations across the seasons.

2. Materials and methods

2.1. Study site description

Not all nature conservation areas in Germany that are called

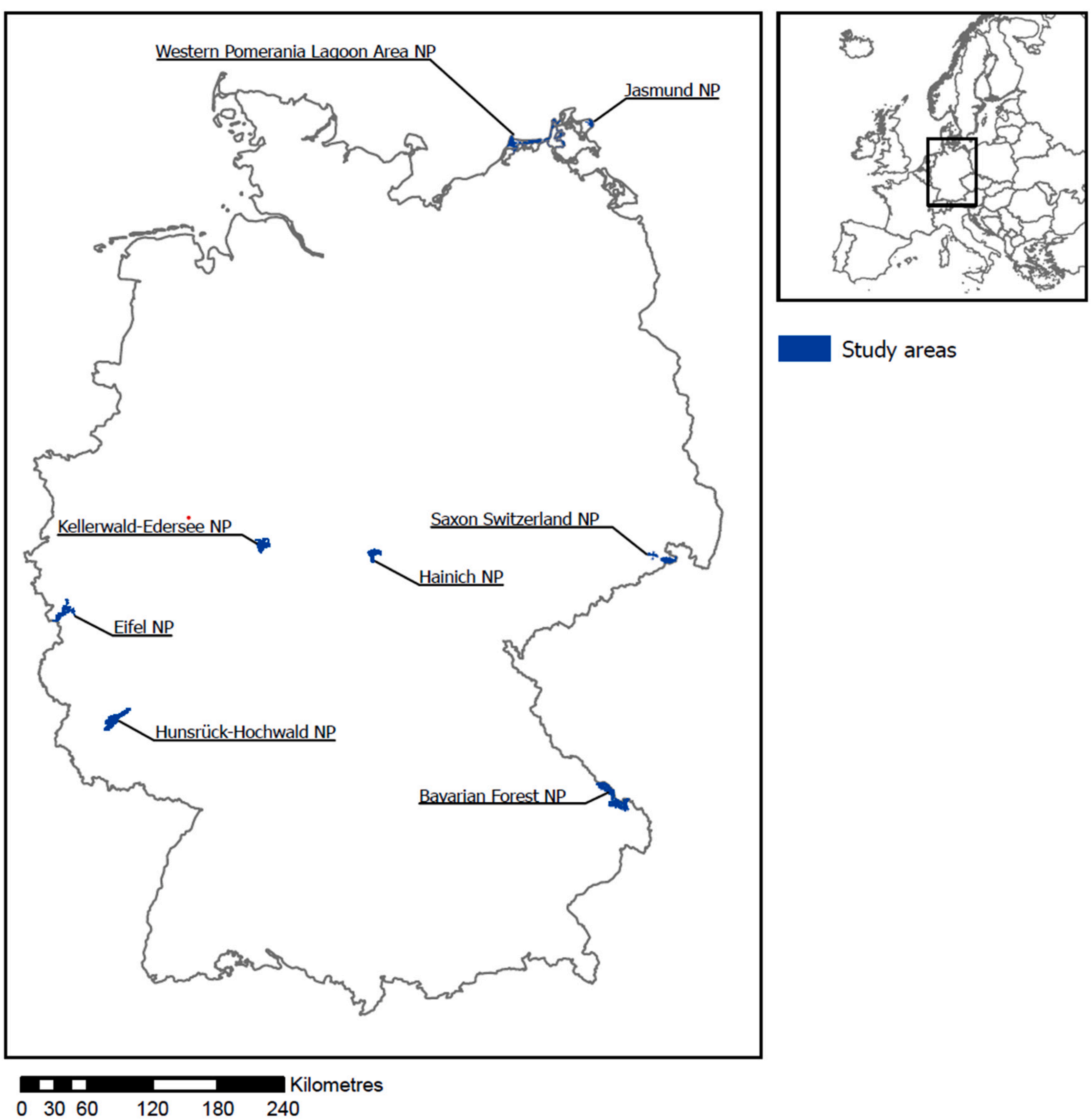

Fig. 1. location of the study sites in Germany.

“national parks” meet the criteria to be classified as category II according to IUCN. For better understandability, the term national park is used for all areas that are considered national parks according to German federal law (Bundesamt für Naturschutz, 2022). Considering this, there are 16 national parks in Germany. Three of them, belong to the German part of the Wadden Sea of the North Sea. These do not have any noteworthy ungulate populations and are therefore not considered in the present study. The national parks that contributed to this study covered a wide variety of habitats from low mountain ranges to coastal regions of the Northern and Baltic Sea (Fig. 1). Table 1 shows a detailed description of the study sites.

2.2. Sampling

The dataset for this study consists of 442 samples from red deer and fallow deer, collected in eight national parks from Germany, between November 2023 and January 2025. The population density of ungulates in German national parks is closely monitored and regulated by hunting if needed. The so-called wildlife management is applied for population regulation when damages in agricultural areas in the surrounding landscapes occur or to limit the spread of diseases. The regulation of ungulate populations in German national parks is necessary due to an incomplete variety of species required for self-regulation and the relatively small areas of the national parks in combination with their proximity to intensely used agricultural areas (EUROPARC Deutschland, 2012). Metadata of the samples includes age, sex, species, and date of sample collection (Supplementary Table S1). As not every Park was able to provide the age in the same resolution, we categorized the samples into three age groups according to the lifecycle of red and fallow deer: A fawn is defined as a juvenile deer from birth until 12 months of age, usually calculated from April 1 onwards. Subadult deer are in the transition stage prior to full maturity, *i.e.* between 12 and 24 months of age. Adult deer are considered fully mature with an age of 24 months or older. The age class of the sampled deer was determined by experienced hunters based on morphological characteristics such as fur patterns, body proportions and the form of the head. When there were not enough *C. elaphus* samples available, *D. dama* were used as a substitute. Hunting of red and fallow deer was carried out by game wardens within the national park wildlife management in compliance with legal requirements and all necessary permits. To ensure consistency, all samples were collected using 50 mL polypropylene centrifuge tubes from VWR Avantor (Radnor, PA, USA). The tubes were tested for extractables and leachables that might interfere with analysis prior to sampling. The liver samples of red and fallow deer were frozen directly after processing the dead specimens at −20 °C until analysis. Bovine liver from local grocery stores was used for method development, validation and procedural matrix matched calibration.

2.3. Residue analysis

Parallel analysis of 118 residues was performed according to a miniaturized QuEChERS method previously described by Schanzer et al. (2021). Liver samples were prepared with a modified, miniaturized QuEChERS based sample preparation, and analyzed with gas chromatography tandem mass spectroscopy (GC–MS/MS). As measurement mode, multi reaction monitoring (MRM) was applied, ensuring

Table 1
Description of study sites (Bundesamt für Kartographie und Geodäsie, 2021; Majewski et al., 2024).

National park	Founding year	Terrestrial area (ha)	Dominant terrestrial habitat types (>10%)	Non-intervention area (ha; forestry)	Strongly human-modified areas	Former use	Visitor days	Comments
Bavarian Forest	1970	24,968	Mixed forest (34%), Coniferous forest (25%), Grassland (20%), Deciduous forest (14%)	18,943	Sealed surfaces & buildings (0.06%), agricultural land (0.01%)	Commercial forest	760,000	
Eifel	2004	10,613	Coniferous forest (36%), Deciduous forest (35%), Grassland (16%)	5564	Sealed surfaces & buildings (0.05%), agricultural land (0.01%)	Commercial forest, military training area	450,000	Sewage treatment plant residues discharged into river Urft adjacent active military training area in Belgium (Elsenborn) Severely affected by the 2021 flood catastrophe
Hainich	1997	7508	Deciduous forest (67%), Grassland (27%)	6751	Sealed surfaces & buildings (0.04%), agricultural land (0.06%)	Military training area	295,000	Intensive agriculture on loess soils surrounding the NP
Hunsrück-Hochwald	2015	10,193	Deciduous forest (45%), Coniferous forest (35%), Mixed forest (11%)	3833	Sealed surfaces & buildings (0.01%), no agricultural land	Commercial forest	400,000	
Jasmund	1990	2444	Deciduous forest (80%)	3070	Sealed surfaces & buildings (0.30%), agricultural land (0.44%)	Commercial forest	679,000	
Kellerwald-Edersee	2004	7502	Deciduous forest (76%)	7028	Sealed surfaces & buildings (0.08%), agricultural land (0.71%)	Game reserve	200,000	Treatment plants discharge treated sewage into the Edersee
Saxon Switzerland	1990	9188	Coniferous forest (61%), Mixed forest (19%), Deciduous forest (11%)	7089	Sealed surfaces & buildings (0.21%), Agricultural land (1.58%)	Commercial forest and touristic area	1,712,000	Large-scale fire in 2022
Western Pomerania Lagoon Area	1990	13,445	Grassland (30%), Coniferous forest (20%), Deciduous forest (17%), Swamp (17%)	78,300	Sealed surfaces & buildings (0.21%), Agricultural land (2.07%)	Commercial forest, military training area	4,766,000	

unanimous identification of analytes at respective retention times. For quantification, matrix-matched procedural calibration samples were prepared in the same manner and batch as the samples. Samples and calibrants were spiked with deuterated internal standards prior to sample preparation and relative response ratios were used for quantification. The method was validated according to SANTE 11312. All details on residue analysis and method validation are described in Supplementary Text S1.

2.4. Statistical analysis

In addition to detailed descriptive analyses, a statistical regression model was applied. Compared to the dataset shown in the descriptive analysis we excluded analytes which occurred very rarely according to criteria described in Supplementary Text S2. For the statistical analysis, we defined the response variable using a dose addition approach: for each sample, all measured concentrations within a pollutant category were summed. Due to the given instrument precision, not all measurements were exactly quantified. To account for the uncertainty in the measurement, the response was defined as interval censored values – intervals within which the sum of exact measurements lies. The bounds and widths of these intervals were determined using the limits of quantification of each pollutant (see Supplementary Text S2). We fitted a log-normal Accelerated Failure Time (AFT) model (Harell, 2015), which can handle such interval censored data (see model equation in Supplementary Text S2). Three explanatory variables were included: age group, park, and seasonal effects, the latter modeled as a smooth function of the day of year. In our main model no interactions between explanatory variables were assumed. To see how the estimated coefficients are affected by the model assumptions, we conducted several robustness checks. One involved refitting the model without the fallow deer samples to assess whether their inclusion introduced systematic patterns compared to a model restricted to the red deer samples. The modified model produced broadly compatible results, as did the other robustness checks. For more details on all the analyses conducted see Supplementary Text S2.

2.5. Interpretation of results

In the following, we will discuss estimated model parameters in terms of their statistical significance. In this context, it should be kept in mind that a non-significant parameter (and thus difference between two groups) merely indicates insufficient evidence for a difference, which is not to be confused with evidence of a lack of difference. An absence of significance may also be due to limited statistical power in our data set, related to the uncertainty following from the censoring and possibly insufficient sample size. Larger data collections may lead to statistically significant results. Moreover, it has to be noted that significance is always assessed with respect to the reference category. For each coefficient, we are interested in significance on the 5% level. Conversely, we report the 95% confidence intervals everywhere.

Concerning the regression analysis, all coefficients for categorical variables are presented on the response scale ($\exp(\beta)$). They are interpreted multiplicatively with respect to the reference categories, with values close to 1 indicating only slight differences compared to the reference category. The age category fawn was chosen as the reference level for age as we would suggest that most contaminants tend to accumulate over the lifespan, thus being most prominent in older animals. In the model specification, we selected the Bavarian Forest National Park as the reference category for the park explanatory variable, because it is the oldest national park in Germany, thus nature there had more time to return to an untouched state. It is also a rather large national park. For example, a point estimate of 0.45 for the Saxon Switzerland National Park in the plasticizer category (Fig. 5D) implies that, for two individuals with identical values of explanatory variables, the expected concentration of plasticizers in the Saxon Switzerland National Park is less than half of that in the Bavarian Forest National Park. Similarly, it is expected that for two samples from the same day and park, the concentration of POPs will be 0.77 times lower for a subadult than for a fawn. The fitted curve representing smooth temporal effects should be interpreted relative to value 1 with values above 1 indicating periods of increased pollution and values below 1 suggesting reduced pollution levels. Across all substance categories (anthropogenic pollution, PAHs, plasticizers, and POPs) the smooth seasonal effects exhibit slight variation over time. However, the 95% (pointwise) confidence intervals always include value 1, which means that there is no evidence for strong seasonal patterns in the data, or that any temporal variation in concentrations over the year is too weak to be detected from the available data.

3. Results and discussion

The presentation of results is structured as follows. We first summarize the provenience of samples across parks, time, species and other sample characteristics. Subsequently, descriptive graphical summaries of pollutant concentrations are provided. These are discussed in detail in the subsequent subsections on different analyte categories. These also summarize results from the regression model defined in the section statistical analysis and provide interpretations of the results. For the descriptive evaluation, we distinguish between mere detection without quantification and quantified values, summarizing only the quantified values by arithmetic sums over analytes.

3.1. Provenience and composition of samples

Fig. 2A shows the sample size of each National Park in each month of the sampling period (August to January). Notably, not all Parks were able to provide the same number of samples, due to differences in park size, red deer density and hunting periods. In Fig. 2B to D, the composition of the samples regarding animal species (B), sex (C) and age (D) is depicted.

3.2. Summarized descriptive analysis of substance occurrence and concentration

Figs. 3–6 show the results obtained in this study, organized by pollutant group. Due to the number of quantifiable observations, the statistical model was only applied to the four categories of anthropogenic pollution, PAHs, plasticizers, and POPs. The results of the other four contaminant groups (APIs, industrial chemicals, PCPs and pesticides) are shown in Supplementary Figs. S4-S7. Each figure is structured in the same way: The occurrence of pollutants is depicted by bar plots that represent detection and quantification (A). The box plots in part B visualize the distribution of determined concentration sums in each park and age group. The smooth seasonal effects are represented by the fitted spline curve (C), as described in the section interpretation of results, with the corresponding park and age regression coefficients (D). Parts C and D of the figures are only applicable when the statistical model was fitted.

Overall, no sample was free of pollutants. Most substance groups were detectable in almost every sample, only pesticides and APIs went largely undetected. Of the 61 detected analytes, a maximum of 33 were present in the same sample (Z070 from Eifel), whilst no sample exhibited less than 14 parallel detects. Overall, no clear trends regarding contamination could be identified between the parks or age groups.

In a first step, we determined whether the pollutant burden differed between the species *C. elaphus* and *D. dama* for the three parks (Hainich, Jasmund and the Western Pomerania Lagoon Area) where *D. dama* samples were necessary to reach a sufficient sample size. As both species are herbivores (Spitzer et al., 2020), it is not expectable to see major differences in contamination patterns. Indeed, contaminants from anthropogenic pollution, APIs, industrial chemicals, PAHs, PCPs and

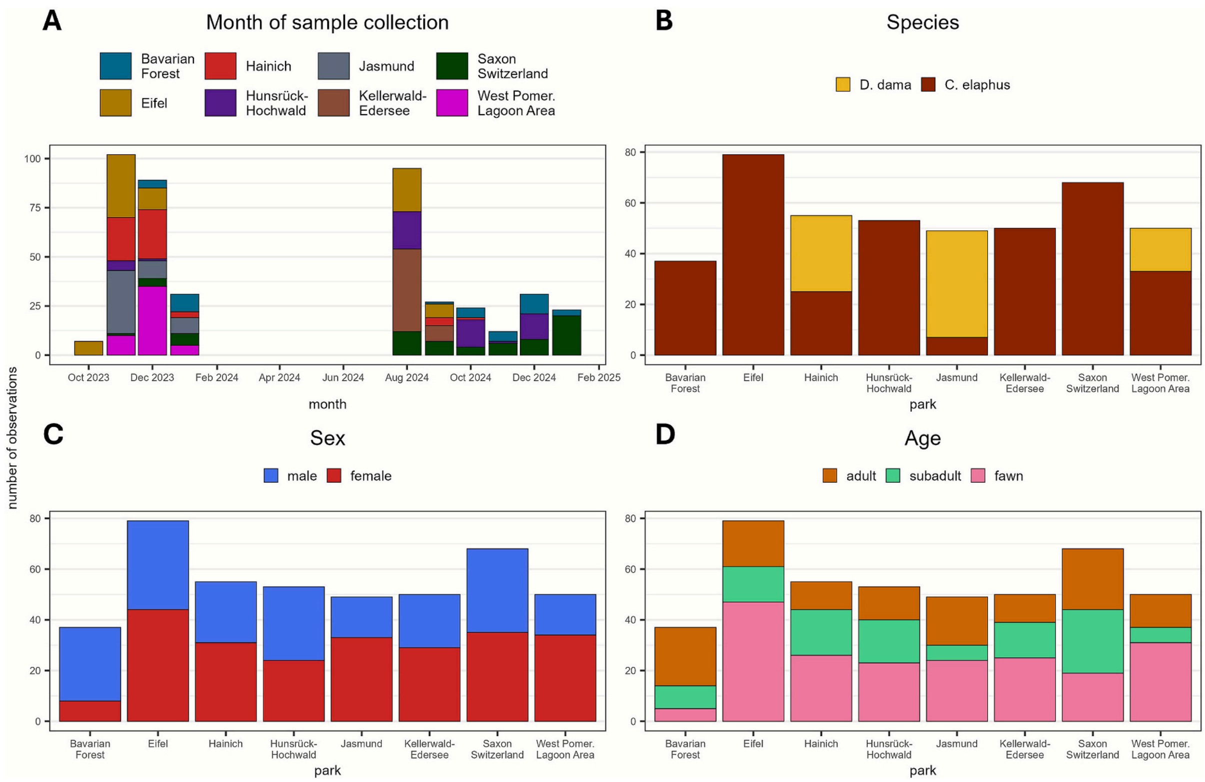

Fig. 2. Descriptive barplots of sample set composition; A shows amount of samples collected from each park at months from October 2023 to January 2025; B-D show distribution of species (B), sexes (C) and age groups (D) among samples from each park.

plasticizers were present in samples from both species in comparable amounts (Supplementary Fig. S1). For the pesticide and POP compound groups, only a slight difference in the frequency of detection and quantification was evident. As stated under Statistical analysis, the inclusion of the factor species into the fitting of the statistical model did not lead to significant regression coefficients on the species category. Our data thus did not provide evidence for differences between the two species. Therefore, for any further analysis, the samples of both species were treated equally.

Next, the effect of sex on the environmental burden was evaluated. We did not see clear differences in the contamination of samples from male or female animals (Supplementary Fig. S2), and the incorporation of the parameter sex into the statistical model did not yield significant differences, so any further analyses were conducted without differentiation between sexes.

Pollutant detection rates seemed to differ between the age groups of the samples from some national parks (*e.g.* PAHs, POPs and plasticizers, Supplementary Fig. S3). We defined three age groups according to the life cycle of *C. elaphus* as fawn (younger than 12 months), subadult (between 12 and 24 months) and adult (24 months and older). Fig. 2D shows the composition of samples taken from each park by age group. In most parks, the majority of samples were taken from fawns, except for the Bavarian Forest National Park, where more than 60% of samples were taken from adult animals, and the Saxon Switzerland National Park, where the distribution was equal among age groups. Hypothetically, one would expect that, especially for persistent pollutant groups like POPs and PAHs, more contaminants would be detectable in older animals due to bioaccumulation over time. We could not confirm this with our results. Interestingly, POPs showed an opposing trend, with decreasing expected contamination in subadults and adults, whilst for PAHs no significant difference in contamination between age groups could be found.

3.3. Anthropogenic pollution

Contaminants resulting from direct anthropogenic pollution (three analytes, caffeine, (−)-cotinine and 1,3 dinitrobenzene) were found in almost every sample, except for eight samples from Bavarian Forest (Fig. 3A). In samples from Eifel, Hunsrück-Hochwald and Kellerwald-Edersee, indicators of anthropogenic pollution were only quantifiable in less than 30% of samples. For Bavarian Forest, they were quantifiable in 46% of the samples and for Jasmund, Saxon Switzerland and the Western Pomerania Lagoon Area in 78%, 63% and 64% of the samples respectively. Determined concentrations were lowest in Hunsrück-Hochwald ($\sum$ anthropogenic pollutants 2.3 to 7.7 μg kg^{-1}, median 2.9 μg kg^{-1}), with the highest outliers at Saxon Switzerland (sample E052, $\sum$ 86.9 μg kg^{-1}) and Hainich (C035, $\sum$ 80.9 μg kg^{-1}) (Fig. 3B). From the descriptive point of view, neither detection rates nor concentration sums differed between the age groups.

Regarding the seasonal course (Fig. 3C) there is no clear trend visible. Contamination with anthropogenic pollutants appears to be relatively stable over time, with only a slight increase observed in August. Regression coefficients show that samples from Eifel, Hunsrück-Hochwald, Kellerwald-Edersee and the Western Pomerania Lagoon Area are expected to be exposed to fewer anthropogenic pollutants than samples from the Bavarian Forest National Part, with Hunsrück-Hochwald showing statistically significant lower contamination. Samples from Hainich, Jasmund and Saxon Switzerland may be exposed to more anthropogenic pollutants, with only Jasmund showing statistical significance. Between the age groups, there appeared to be no clear differences in contamination. Samples from subadult animals show a tendency to be more affected, but without statistical significance (Fig. 3D).

Considering the nature of anthropogenic pollutants, these findings are consistent, as caffeine and (−)-cotinine can be readily metabolized by mammals and only tend to bioaccumulate in aquatic ecosystems and their wildlife (Li et al., 2020a). Anthropogenic pollution was mainly

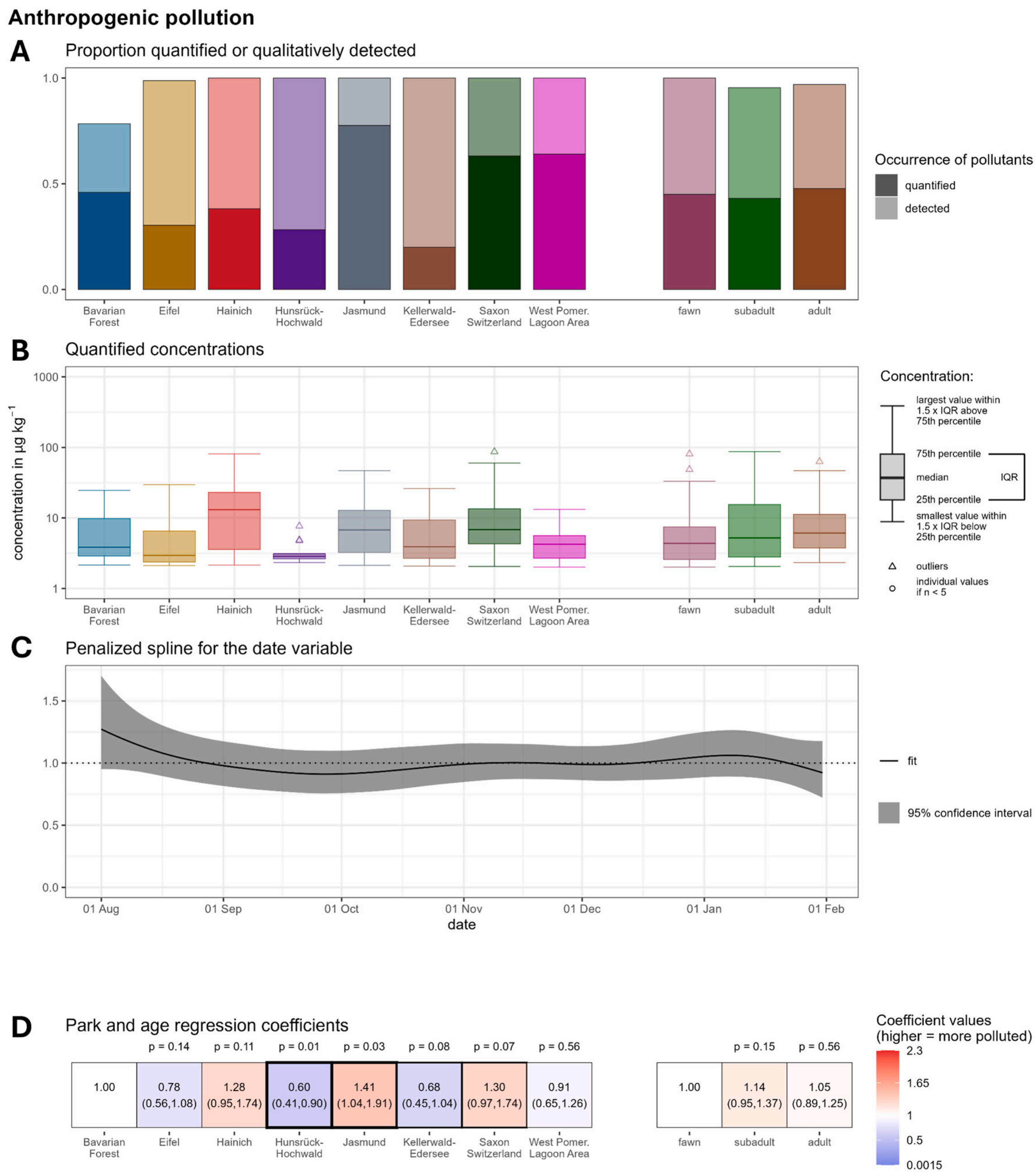

Fig. 3. Descriptive and statistical analysis of anthropogenic pollution; Barplots (A) show proportions of the total number of samples, where anthropogenic pollutants were detected and quantified, for the parks and age groups. Section B shows distribution of determined concentration sums of anthropogenic pollutants among parks. The boxplot represents the 25th to 75th percentile and the median, whiskers show the smallest and largest value within 1.5 times interquartile range, whilst outliers are presented as Δ. If less than five observations were quantified, individual values are presented instead. C shows the penalized spline and the 95% confidence interval for the date variable from August 1 to January 31. Corresponding regression coefficients and confidence intervals for park and age variables are shown in D; colors visualize deviation from reference park (Bavarian Forest) or age group (fawn), blue for lower and red for higher coefficients; statistical significance is expressed as *p*-value and indicated through bold lines.

driven by caffeine, followed by (−)-cotinine, a metabolite of nicotine. These two substances are commonly used as biomarkers indicating direct human impact (Benowitz, 1996; Buerge et al., 2003). Caffeine is found in fresh and surface water around the world (Diogo et al., 2023), often reported as originating from wastewater (Li et al., 2020b). Uptake through surface water could be a possible contamination route of indicators for anthropogenic pollution for *C. elaphus* and *D. dama*. Regional differences of anthropogenic pollution could be explained by different concentrations of pollutants like caffeine in surface waters. The high quantification rate in Jasmund (78%) and the Western Pomerania Lagoon Area (64%) national parks could possibly be explained by their proximity to the Baltic Sea, as studies have shown that seawater and sediment in coastal environments are contaminated with caffeine (Vieira et al., 2022). To evaluate this hypothesis, additional sampling of water sources in the national parks would be required. Another possible explanation could be the partially high touristic usage of these two parks. Chronic, high caffeine exposure has been linked to several negative impacts, including increased mortality in insects, induced oxidative stress in aquatic organisms and neurotoxic effects in fish (Li et al., 2020a). This highlights the role of caffeine not only as an indicator for human pollution, but also as an emerging pollutant itself.

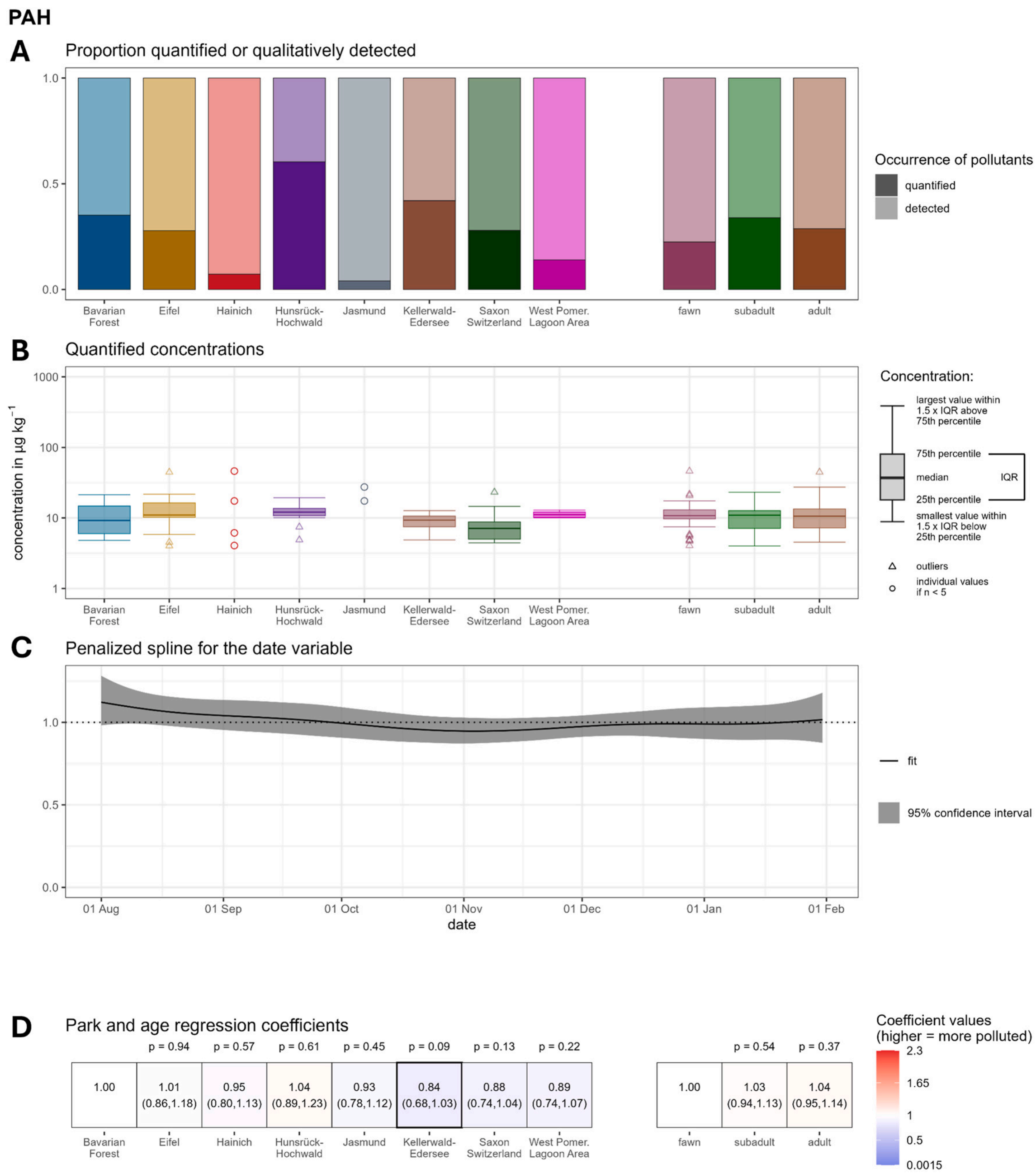

Fig. 4. Descriptive and statistical analysis of polycyclic aromatic hydrocarbons (PAHs); Barplots (A) show proportions of the total number of samples, where PAHs were detected and quantified, for the parks and age groups. Section B shows distribution of determined concentration sums of PAHs among parks. The boxplot represents the 25th to 75th percentile and the median, whiskers show the smallest and largest value within 1.5 times interquartile range, whilst outliers are presented as Δ. If less than five observations were quantified, individual values are presented instead. C shows the penalized spline and the 95% confidence interval for the date variable from August 1 to January 31. Corresponding regression coefficients and confidence intervals for park and age variables are shown in D; colors visualize deviation from reference park (Bavarian Forest) or age group (fawn), blue for lower and red for higher coefficients; statistical significance is expressed as p-value and indicated through bold lines.

3.4. Active pharmaceutical ingredients (APIs)

The 14 APIs were only present in very few samples across all national parks (Supplementary Fig. S4A) and quantifiable in even less. In Jasmund, no APIs could be detected, and quantifiable concentrations were only detected in Eifel, Hainich, and Kellerwald-Edersee. The determined concentration sums were also quite low, with the largest, measured in one sample from Hainich (C038), being $\sum$ 9.3 µg kg^{-1}(Supplementary Fig. S4B). As only very few observations regarding detection of APIs were made, and even less were quantified, the statistical model was not fitted for APIs. Regarding the distribution among age groups, the least detections were made in subadult samples, followed by adult and fawn samples. Found concentrations were highest in fawn.

The detected APIs were the hormones 17α-ethinyl estradiol and estrone, the analgesic codeine, the antiplatelet agent clopidogrel, the anxiolytic diazepam and the disinfectant triclosan, with only the two hormones, except for codeine in one sample from Kellerwald-Edersee (L055, $\sum$ 2.1 µg kg^{-1}) above quantification thresholds. Especially estrogen medication is among the most common APIs found in wastewater and fresh water (Almazrouei et al., 2023; Pal et al., 2010). 17α-Ethinyl estradiol is more persistent in the environment than natural estrogens, found in sewage treatment plants, manure that is used as fertilizer, as

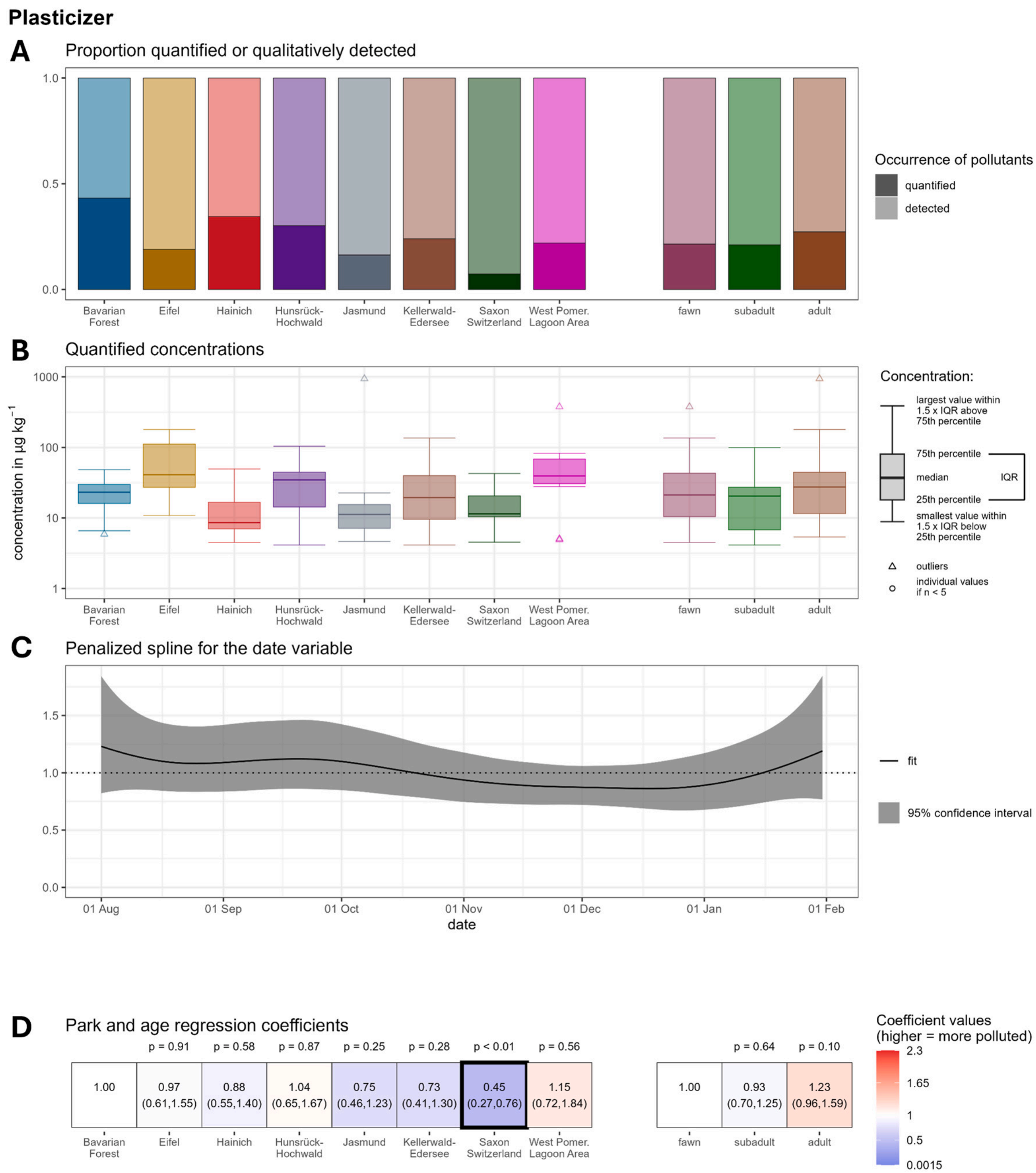

Fig. 5. Descriptive and statistical analysis of plasticizers; Barplots (A) show proportions of the total number of samples, where plasticzers were detected and quantified, for the parks and age groups. Section B shows distribution of determined concentration sums of plasticizers among parks. The boxplot represents the 25th to 75th percentile and the median, whiskers show the smallest and largest value within 1.5 times interquartile range, whilst outliers are presented as Δ. If less than five observations were quantified, individual values are presented instead. C shows the penalized spline and the 95% confidence interval for the date variable from August 1 to January 31. Corresponding regression coefficients and confidence intervals for park and age variables are shown in D; colors visualize deviation from reference park (Bavarian Forest) or age group (fawn), blue for lower and red for higher coefficients; statistical significance is expressed as p-value and indicated through bold lines.

well as in ocean water (Adeel et al., 2017). The presence of environmental estrogens all around the world is concerning, as they can interfere with reproduction cycles and pose the risk of disrupting sexual development and altering reproductive-associated behavior in aquatic species (Bhandari et al., 2015), even leading to feminization of male fish (Miedaner and Krähmer, 2023b). The low abundance of APIs in this study, despite their known presence in the environment, could also be attributed to the nature of gas chromatography. Many APIs are not suitable for underivatized analysis with GC–MS/MS due to their chemical properties (Sandra et al., 2002). This includes most analgesics, such as acetaminophen or ibuprofen, that are commonly monitored *via* liquid chromatography instead (Montaseri and Forbes, 2018). Despite the limited range of APIs accessible with our study design, the determination of estrogens in the environment is alarming, due to their impacts even at low concentrations.

3.5. Industrial chemicals

From the six included industrial chemicals diphenylamine, tris(1,3-dichloropropan-2-yl) phosphate (TDCPP), and triphenyl phosphate were detected in every sample analyzed in this study, except from one sample from Saxon Switzerland, although, in most cases, below

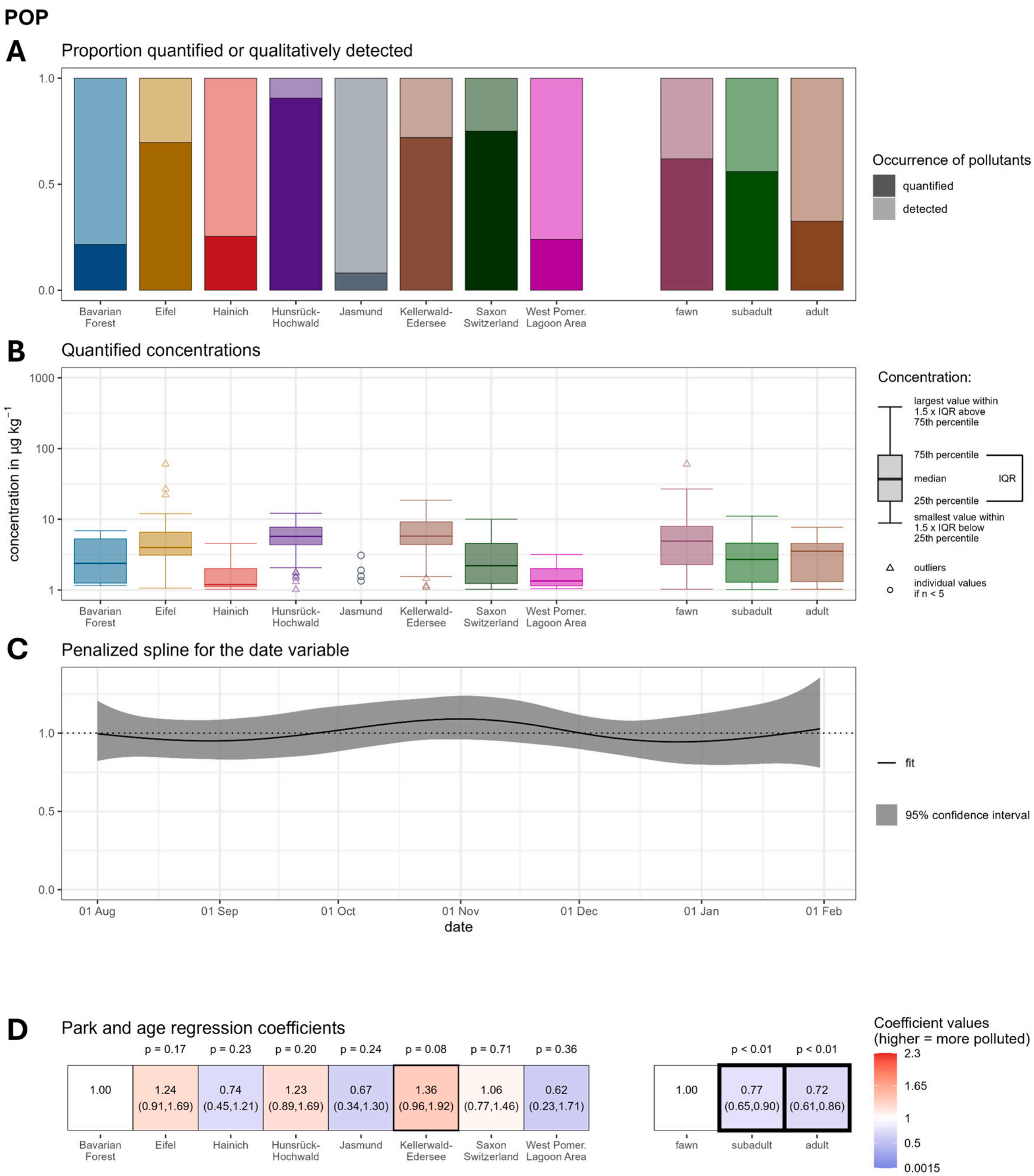

Fig. 6. Descriptive and statistical analysis of persistent organic pollutants (POPs); Barplots (A) show proportions of the total number of samples, where POPs were detected and quantified, for the parks and age groups. Section B shows distribution of determined concentration sums of POPs among parks. The boxplot represents the 25th to 75th percentile and the median, whiskers show the smallest and largest value within 1.5 times interquartile range, whilst outliers are presented as Δ. If less than five observations were quantified, individual values are presented instead. C shows the penalized spline and the 95% confidence interval for the date variable from August 1 to January 31. Corresponding regression coefficients and confidence intervals for park and age variables are shown in D; colors visualize deviation from reference park (Bavarian Forest) or age group (fawn), blue for lower and red for higher coefficients; statistical significance is expressed as p-value and indicated through bold lines.

quantification thresholds (Supplementary Fig. S5A). In five parks, quantifiable amounts were determined, namely in one sample from Hunsrück-Hochwald (D080, ∑ 4.1 μg kg^{-1}) and the Western Pomerania Lagoon Area (F004, ∑ 2.0 μg kg^{-1}) each, in two samples from the Bavarian Forest (∑ 1.5 and 2.5 μg kg^{-1}), as well as in a few from the Eifel and the Saxon Switzerland National Park (Supplementary Fig. S5B). Concentrations were highest in samples from Eifel (∑ 1.2 to 213.3 μg kg^{-1}, median 22.6 μg kg^{-1}). At a descriptive level, detection and quantification rates did not differ between age groups, but determined concentrations were higher in fawn and adult samples, with fawn sample Z018 containing the highest value of ∑ 213.3 μg kg^{-1}. As for APIs, the statistical analysis for industrial chemicals is not meaningful due to the insufficient number of quantifiable results.

The main contamination from industrial chemicals originated from the pollutant diphenylamine, which has many applications. It is used as a fungicide, but not authorized for use in the EU, as stabilizing agent in gunpowder, and in the manufacturing of synthetic dyes, rubber products, and as antioxidant (IARC Working Group on the Identification of Carcinogenic Hazards to Humans, 2022). Since it has numerous applications, it is difficult to track the origin of diphenylamine contamination. Diphenylamine contamination in Eifel could possibly be a legacy burden from its former intensive use as a military base. Studies have shown the contamination of ground water and soil at military sites with diphenylamine due to weapon and ammunition usage (IARC Working Group on the Identification of Carcinogenic Hazards to Humans, 2022). This hypothesis is contradicted by the fact that other National Parks, like Hainich and the Western Pomerania Lagoon Area (Table 1) were also at least partly military training areas before the national parks were established. Possible differences in pollutant burden of these parks could be explained by the different origins of the military forces, regarding German history. Additionally, the still actively used Belgian military training area of Elsenborn borders the Eifel region in the south.

3.6. Polycyclic aromatic hydrocarbons (PAHs)

In this study, polycyclic aromatic hydrocarbons (PAHs) were detected in every sample from every National Park and every age group (Fig. 4A). Three PAHs, acenaphthene, fluorene and phenanthrene, were detectable out of four, besides acenaphthylene which could not be found in any sample. All tested PAHs belong to the 16 so-called "priority pollutants" that are commonly used for monitoring PAH contamination (Howsam and Jones, 1998). In Hainich, Jasmund and the Western Pomerania Lagoon Area, only a few samples contained PAHs at quantifiable levels. Most quantifiable values were determined in samples from Hunsrück-Hochwald. Detected concentrations ranged in most Parks from $\sum$ (PAHs) 4 to 20 μg kg^{-1}, with higher concentrations in one outlier from Eifel (Z079, $\sum$ 44.6 μg kg^{-1}) and Hainich (C035, $\sum$ 46.2 μg kg^{-1}) (Fig. 4B).

PAHs do not seem to be subject to seasonal effects, with a quite stable concentration course over the sampling period (Fig. 4C). Overall, contamination with PAHs appears to be relatively stable across the parks (Fig. 4D), with regression coefficients ranging from 0.84 at Kellerwald-Edersee to 1.04 in samples from Hunsrück-Hochwald, although this difference is not statistically significant. The concentrations determined in samples from all three age groups are also comparable, with coefficients of 1.03 for subadult and 1.04 for adult samples.

PAHs are a ubiquitous group of environmental, persistent pollutants. They are often analyzed for air quality assessment, health effects or environmental monitoring (Srogi, 2007). They are byproducts of incomplete combustion of organic matter (Montano et al., 2025), and can be found among other chemicals in fuels, coal tar or plastic products. They can be emitted into the environment due to power generation and heating, traffic or even forest fires (Miedaner and Krähmer, 2023a), with anthropogenic sources being more influential than natural sources (Patel et al., 2020). The primary uptake routes for PAHs are respiratory, but since they are ubiquitous, they can also be ingested with water or foodstuffs (Miedaner and Krähmer, 2023a). PAHs are not only very persistent in the environment, but they are also known carcinogens and toxic for development, reproduction as well as neurotoxic (Patel et al., 2020). The frequent detection of contaminants at low concentrations, which are comparable across parks and age groups, supports the hypothesis of ubiquitous contamination. Regionally elevated levels of PAHs could be caused by nearby major roads, industrial areas or inherited burdens.

3.7. Personal care product ingredients (PCPs)

Another pollutant group that was detected in each sample was personal care products (PCPs, 12 analytes). Some parks (Hainich 9%, Jasmund 12%, Saxon Switzerland 9% and Western Pomerania Lagoon Area 10%) had quantifiable amounts of PCPs in only a few samples, with slightly more for Kellerwald-Edersee (24%). In the Bavarian Forest, Eifel and Hunsrück-Hochwald, PCPs could be quantified in more samples, up to 49% of samples in Hunsrück-Hochwald (Supplementary Fig. S6A). The concentration medians of most Parks ranged around $\sum$ 10 μg kg^{-1}, with the lowest median in Hunsrück Hochwald ($\sum$ 6.5 μg kg^{-1}) and the highest in Eifel ($\sum$ 13.2 μg kg^{-1}). The highest concentration was also measured in Eifel, sample Z016 with $\sum$ 99.7 μg kg^{-1}, followed by one sample from Hainich (C002, $\sum$ 84.1 μg kg^{-1}) and Western Pomerania Lagoon Area (F032, $\sum$ 60.3 μg kg^{-1}), along with a few values from Hunsrück-Hochwald (D048 and D042, $\sum$ 49.9 μg kg^{-1} and 42.8 μg kg^{-1}). The lowest values were determined in Saxon Switzerland with a minimum of $\sum$ 2.0 μg kg^{-1} (=LOQ, E022) (Supplementary Fig. S6B). Quantification rate and detected concentrations did not differ between the age groups. All three age groups showed outliers towards higher concentrations, with a median around 10 μg kg^{-1}. The statistical model was not fitted for PCPs.

The PCPs in this study were mainly UV blockers and to a lesser extent, fragrances. Some analytes, like the fragrant galaxolide and the UV blockers octocrylene and oxybenzone were detected in almost each sample from each park, mostly at concentrations below LOQ, thus posing some kind of background contamination. Octocrylene was only quantifiable in samples from the Bavarian Forest. The UV blockers Uvinul® A plus and 2-ethylhexyl salicylate (EHS) were also present in nearly every sample, but more often at concentrations above LOQ. Lastly, avobenzone was present at some samples from each park, also more often at quantifiable levels, whereas benzophenone-1 and the fragrant tonalid were only present in samples from Eifel and Hainich, respectively. UV blockers are present in the environment worldwide, especially in water bodies, entering through bathing, manufacturing runoff or urinal excretion, besides being added to limit UV degradation in plastics *etc.* (Shetty et al., 2023) Oxybenzone, octocrylene and EHS have been identified in the influent and effluent of wastewater treatment plants in Brazil (da Silva et al., 2015) and other countries across the world. Oxybenzone was among the most frequent detected PCPs in environmental water samples from Slovenia (Cuderman and Heath, 2007) and has also been found in dolphin blubber from specimen stranded at the Canary Islands (González-Bareiro et al., 2023). Several negative effects were previously linked to environmental contamination with PCPs. As contamination with UV blockers is especially relevant at the Sea, their influence is mainly studied on aquatic life forms, such as coral reefs, where they can lead to bleaching and increased mortality of some coral species (Shetty et al., 2023). In the marine food web, the UV blockers did not tend to bioaccumulate (Wang et al., 2022), which is consistent with our own results, showing rather low median concentrations and similar patterns across age groups. The potential negative effects of UV blockers on mammals and their potential pollution with PCPs are to date not sufficiently understood. As we have detected and quantified several PCPs of interest for the first time in *C. elaphus* and *D. dama*, further research on their potential negative impacts on terrestrial mammals is needed.

3.8. Pesticides

The assessment of pesticides as environmental pollutants is quite common, as they have been categorized as dangerous for the environment, animal and human health, and are closely monitored (Miedaner and Krähmer, 2023c). Pesticides were also the largest pollutant group in this study, with 57 analytes. In samples from the Western Pomerania Lagoon Area National Park, only the fungicide tetraconazole was detected in one sample, below LOQ (Supplementary Fig. S7A). In the other Parks, several pesticides could be detected, but mostly under LOQ. Interestingly in the Bavarian Forest, pesticides were present in more than 50% of samples. Only very few samples overall contained pesticides at quantifiable concentrations. If so, the sums were quite low compared to other pollutant groups (Supplementary Fig. S7B), with only samples from Eifel (Z079, $\sum$ 17.0 μg kg^{-1}), Hainich (C017 and C018, $\sum$ 32.6 and 14.6 μg kg^{-1} respectively), and Jasmund (G007, $\sum$ 14.8 μg kg^{-1}) reaching concentration sums above 10 μg kg^{-1}. The sample with the highest pesticide burden originated from Hainich and mainly contained tebuconazole, which was among the most often detected pesticides, except for Kellerwald-Edersee. Pesticides were detected and quantified more frequently in subadult and adult samples than in fawns. As only a few observations were made, statistical analysis would not be beneficial.

This underlies the bioaccumulation of pesticides, particularly of fungicides which have a higher prevalence in this study (Hvězdová et al., 2018). Generally, the low occurrence of pesticides is a positive finding, but individual substances can still be harmful. The detected pesticides consisted mainly of fungicides such as azoxystrobin, difenoconazole, epoxiconazole or propiconazole. The fungicide tebuconazole has been shown to negatively affect offspring growth and reduce chick survival in farmland birds (Bellot et al., 2025).

3.9. Plasticizers

The next pollutant group that could be detected in every sample from every National Park was plasticizers. Out of the six analytes from this group, three were detectable. Quantification rates differed between parks, ranging from 7% of samples from Saxon Switzerland to 43% of samples in the Bavarian Forest (Fig. 5A). Regarding the detected concentrations, Hainich (median $\sum$ 4.5 μg kg^{-1}), Jasmund (median $\sum$ 4.6 μg kg^{-1}) and Saxon Switzerland (median $\sum$ 4.5 μg kg^{-1}) depicted similar low concentration ranges (Fig. 5B), with one considerable outlier in Jasmund (G032, $\sum$ 941.4 μg kg^{-1}). The second-highest concentration was measured in one sample from the Western Pomerania Lagoon Area National Park (F011, $\sum$ 376.6 μg kg^{-1}), which was the park with the second highest median ($\sum$ 39.4 μg kg^{-1}), second to Eifel ($\sum$ 41.0 μg kg^{-1}). When it comes to age groups, we did not determine any significant differences in concentrations, and the medians were comparable. However, the detection rate and maximum for adult samples are higher than for subadult and fawn samples.

The seasonal course of plasticizer contamination remains quite stable over time (Fig. 5C), with a slight decrease from November to January. Regarding regression coefficients (Fig. 5D), the Bavarian Forest is among the more polluted parks, similar to the Eifel and Hunsrück-Hochwald National Park with comparable regression coefficients of 0.97 and 1.04 respectively. Only samples from the Western Pomerania Lagoon Area National Park are expected to be exposed to more plasticizer pollutants with a regression coefficient of 1.15, but without statistical significance. Samples from other parks would all be expected to be less polluted, with the Saxon Switzerland National Park showing a significant reduction of estimated pollution to 50% compared to the Bavarian Forest. Adult samples showed higher coefficients than fawns, and subadults are expected to even lower contamination with plasticizers, but without statistical significance.

Out of the six plasticizers analyzed in this study, three could be detected and bis(2-ethylhexyl) adipate (DEHA) and DPHP were found in almost every sample, and DINCH occasionally. DEHA was the most often quantified plasticizer and responsible for the outlier in the Western Pomerania Lagoon Area, whereas DPHP was the substance that led to the highest quantified value in this study, in Jasmund (913.1 μg kg^{-1}). DPHP has been shown to be among the main substances to replace DEHP and other regulated phthalates in water samples from Germany (Nagorka and Koschorreck, 2020). Emerging plasticizers are considered less dangerous than their, now regulated or banned, predecessors, although concerns have risen regarding their potential adverse effects on the environment. DPHP was added to the Community Rolling Action Plan (CoRAP) of the European Chemicals Agency (ECHA) due to potential endocrine disruption, high aggregated tonnage and subsequent high exposure and wide, dispersive use. A potential risk to the environment was identified by the ECHA due to the interference of DPHP with the thyroid system in rat studies, and further data were requested to clarify this concern (European Chemicals Agency, 2022). The impact of the plasticizer pollution detected in this study cannot therefore be evaluated, however the high concentrations found in individual samples are alarming.

3.10. Persistent organic pollutants (POPs)

Persistent organic pollutants were found in every sample from every national park and every age group (Fig. 6A). Out of the 18 POPs in this study, 15 were detected. Their presence in nearly all environmental samples collected worldwide is well-documented. In samples from Jasmund, POPs were almost only present at concentrations below the LOQ. This also applies to samples from Bavarian Forest, Hainich and the Western Pomerania Lagoon Area, where only up to 27% of samples contained POPs at quantifiable concentrations. In the Eifel, Hunsrück-Hochwald, Kellerwald-Edersee and the Saxon Switzerland, POPs were quantifiable in the majority of samples. When POPs were quantifiable, their concentration sums were comparable between the parks, with the mean and 25th to 75th percentile below $\sum$ 10 μg kg $^{-1}$ for all parks (Fig. 6B). Only in the Eifel, some outliers range as high as $\sum$ 60.3 μg kg^{-1} (Z002).

The concentration of POPs did not significantly change over the year (Fig. 6C). This reflects a stable background contamination of POPs in the samples over the course of the months, as one would expect due to their ubiquitous presence. Expected POP contamination of samples is comparable in Saxon Switzerland National Park to the Bavarian Forest. The Eifel, Hunsrück-Hochwald and Kellerwald-Edersee National Parks show higher contaminations, whereas samples from Hainich, Jasmund and the Western Pomerania Lagoon Area are potentially exposed to fewer POPs. None of the regression coefficients, however, showed statistical significance. POP contamination was significantly lower in subadult and adult samples (regression coefficients of 0.77 and 0.72, with 5% significance) than in fawn (Fig. 6D).

This outcome is unexpected, as to date, most studies have found higher contamination levels of POPs in areas from the former GDR (German Democratic Republic) compared to areas that belonged to FGR (Federal German Republic) (Schanzer et al., 2022). This would include samples from Hainich, Jasmund, Saxon Switzerland and the Western Pomerania Lagoon Area (see locations in Fig. 1). We do not observe this trend in our study, neither for the aggregated sum of POPs nor for individual substances like DDE (Supplementary Table S1). The trend that the age groups display is also contrary to our expectations. As POPs are prone to bioaccumulation and biomagnification, we would have expected to find higher concentrations in samples from older individuals, but our findings did not support this hypothesis, as the age groups adult and subadult are expected to be significantly less contaminated than fawn samples. One possible explanation could be maternal transfer during nursing. A longitudinal study in dolphin mother and calf pairs has shown a similar trend, where the serum and milk POP concentrations of the mothers decreased post-partum, whilst serum POP levels of the corresponding calves were rising (Noren et al., 2024). Although POP burdens and distributions are species-specific, the transfer of the female after birth to the fawn could also be an explanation for the trend observed in this study. Another possible explanation could be a difference in metabolic activity or distribution of POPs in the tissues of the specimen. Meanwhile, growth dilution is an unlikely explanation for the observed results, as it would be more likely to occur in very fast-growing organisms, such as microalgae (Herendeen and Hill, 2004), as opposed to terrestrial mammals. A similar trend, as well as the general low POP concentrations observed are consistent with findings from deer populations in Croatia (Herceg Romanić et al., 2012).

3.11. Summarized results

Despite their special status as protected areas, National Parks are not safe from contamination with environmental pollutants. This may be due to external sources, but it may also be because the park areas still contain legacy pollutants from before the parks were established. APIs and pesticides were rarely detected, and if so, only in individual samples and mostly below the LOQ. Nonetheless, specific substances can pose risks to individuals, such as the pesticide tebuconazole. Caffeine was among the substances with the highest individual concentrations found, indicating it to be an emerging pollutant itself, rather than just a biomarker for direct anthropogenic presence. The main contamination found in samples from all eight national parks in this study can be classified as background contamination that was found in almost every sample, mostly below individual LOQs. This is particularly evident for PAHs and PCPs. Quantifiable contamination of anthropogenic pollutants, industrial chemicals, plasticizers and POPs differed between parks, but without a clear tendency. Interestingly, no significant difference was observed in POP prevalence in samples taken from parks that are on the territory of former East and West Germany. Previous studies have shown higher concentrations of DDT and DDE, *e.g.* in bat liver (Schanzer et al., 2022) in samples from the former GDR. Similarly, the expected accumulation of POPs over the lifespan of deer could not be demonstrated, contrary, fawn samples were exposed to more POP contamination than subadult and adult samples. Neither anthropogenic pollutants, PAHs, plasticizers, nor POPs showed to be affected by seasonal variations. As mentioned in the Results section, the fact that many parameters in our statistical model (and thus many differences between groups) were statistically insignificant should not be interpreted as proof of no difference but merely indicate that the available data were compatible with the assumption of no difference. The confidence intervals in many cases being rather wide, there may be effects which could be determined with larger data sets. Despite the often-low concentrations, possible adverse effects on red and fallow deer cannot be ruled out, as the mutual influence of pollutants on each other is mostly unknown. These cocktail effects can range from additive to even synergistic, making it virtually impossible to assess potential impacts, especially regarding the large number of co-occurring chemicals reported in this study. This makes the large number of 61 substances that could be detected even more alarming. We have refrained from evaluating the pollutant concentrations in the samples with regard to potential negative effects based on limit values. With the currently available data, carrying out this assessment on a scientifically sound basis is not possible. Firstly, the available limit values are often inconsistent and frequently refer to human consumption rather than the risk to animals. Secondly, no limit values are available for many of the pollutants examined. Thirdly, the evaluation of individual substances only provides incomplete results if one does not want to neglect the mutual influence of the substances' modes of action in terms of cocktail effects.

4. Conclusion

In this study, we provide an extensive monitoring of persistent and emerging environmental pollutants in red and fallow deer samples from eight National Parks located all over Germany. We were able to determine a wide range of different pollutants. Many of them, to our best knowledge, had not been previously monitored in deer populations. This includes the pollutant burden of plasticizers, APIs, PCPs and industrial chemicals on red and fallow deer. When environmental pollution in *C. elaphus* populations is determined, the focus lies clearly on toxic metal and metalloids (Oropesa et al., 2022), as well on fluorides (Zakrzewska et al., 2005). We present the first study that deals so thoroughly and comprehensively with the exposure of red and fallow deer to such a wide range of persistent and emerging contaminants.

Our findings show that deer populations in national parks are susceptible to widespread contamination, despite the special focus on nature conservation. Results revealed a background of various contaminants present in every sample, although at mostly low concentrations. Individual pollutants were present at concerning levels. Regional differences were determined only for individual pollutant categories, and no strong seasonal patterns could be revealed.

The high prevalence of pollutants in our study emphasizes the importance of continued monitoring. To trace the origins of contaminants and gain a deeper understanding of contamination routes and exposure, a more detailed sampling approach including water, soil and leaf samples from each National Park would be necessary. For risk assessment of the reported contaminants, further research is essential, as to this date, no evaluation of the combined toxicity of such complex pollutant mixtures can be achieved.

However, this study gives insight into the present environmental pollution in deer populations in German national parks. It provides a valuable starting point for monitoring the changes of the contaminant burden. Continued monitoring will enable the early detection of emerging pollutants as well as the observation of deviations in pollutant composition, allowing for improved contamination control in the parks and serving as an early indicator of changing pollution levels. Monitoring strategies are an important tool, particularly regarding the sustainable management of environmental pollution and chemicals. Our extensive data set allows for comparison with red and fallow deer populations from other countries, as we present comprehensive data on the pollutant burden in German national parks.

CRediT authorship contribution statement

Michelle Peter: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Barbora Němcová:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **Sönke Twietmeyer:** Writing – review & editing, Resources, Investigation, Conceptualization. **Nico Schumacher:** Writing – review & editing, Resources, Investigation. **Alisa Klamm:** Writing – review & editing, Resources, Investigation. **Valentin Luckas:** Writing – review & editing, Resources, Investigation. **Maik Henrich:** Writing – review & editing, Resources, Investigation. **Stephanie Puffpaff:** Writing – review & editing, Resources, Investigation. **Tobias Rönitz:** Writing – review & editing, Resources, Investigation. **Anja Schneider:** Writing – review & editing, Resources, Investigation. **Odilian Adamczak:** Writing – review & editing, Resources, Investigation. **Annika Busse:** Writing – review & editing, Resources, Investigation. **Johannes Bracher:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Marco Heurich:** Writing – review & editing, Supervision, Resources, Investigation, Conceptualization. **Christoph Müller:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

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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.scitotenv.2026.181415.

Data availability

Data will be made available on request.

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