Concentration and spatial distribution of PFASs and Metals in Swedish and German roadside soils

Concentrations et distribution spatiale des PFAS et des métaux dans les sols routiers en suédois et allemands

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RÉSUMÉ

La plupart des recherches sur l'infiltration routière et le cumul de polluants dans les sols en bordure de route se sont concentrées sur les métaux, malgré des preuves de plus en plus nombreuses indiquant que les eaux de ruissellement de voirie contiennent un éventail plus large de polluants. Cette étude vise à examiner et à comparer le cumul de PFAS et de métaux dans les sols en bordure de route, ainsi qu'à évaluer leur présence, leur concentration et leur distribution spatiale en fonction de la profondeur et de la distance de la route. Des échantillons de sol ont été prélevés en bordure de route le long de 12 routes en Suède et en Allemagne. Les tendances d'accumulation des métaux dans le sol étaient conformes aux études précédentes : les concentrations étaient généralement plus élevées le long des routes à forte intensité de trafic et diminuaient avec l'augmentation de la distance par rapport à la route et de la profondeur d'échantillonnage. Contrairement aux métaux, le PFOS — le composé PFAS le plus fréquemment quantifié — présentait des concentrations plus élevées à mesure que la distance à la route augmentait, sans variation notable selon la profondeur, ce qui reflète sa persistance et sa mobilité. Les concentrations élevées dans les échantillons de référence suggèrent une contamination de fond dans les zones densément peuplées plutôt que des apports directement liés au trafic par le ruissellement routier.

ABSTRACT

Most research on roadside infiltration and pollutant accumulation in roadside soils has focused on metals, despite growing evidence that road runoff contains a broader range of pollutants of emerging concern. Among these, PFASs in stormwater are attracting increased interest. This study aims to investigate and compare the accumulation of PFASs and metals in roadside soils to assess similarities and differences of their occurrence, concentration, and distribution with depth and distance from the road. Roadside soil samples were taken along 12 roads in Sweden and Germany. Metal accumulation patterns in the soil were in consistent with previous studies: concentrations were generally higher along roads with higher traffic intensities and decreased with increasing distance from the road and sampling depth. In contrast, PFOS, the most frequently quantified PFAS compound, showed increasing concentrations with distance from the roads and no considerable variation between sampling depths, indicating its persistence and mobility. Elevated concentrations in reference samples suggest background contamination in densely populated areas rather than traffic related sources in road runoff as specific source.

KEYWORDS

Metals, Perfluoroalkyl substances, Road runoff, Soil contamination, Stormwater infiltration

1 INTRODUCTION

Road runoff carries a wide range of pollutants that can be related to vehicular transportation (Müller et al., 2020). Roadside infiltration is a widely applied approach designed primarily for managing water quantity, yet it can also provide treatment functionality by different processes in the soil such as sedimentation, straining and sorption (Ekka et al., 2021). Pollutant concentrations in roadside soils can, hence, serve as a proxy for the occurrence of different pollutants. Additionally, pollutant distributions can deepen the knowledge about the sorption and fate of such pollutants in roadside soils.

For a long time, most studies on stormwater quality focused on a limited number of historical contaminants such as metals and hydrocarbons (Gasperi et al., 2022). In recent years, the focus of interest has also included emerging and organic pollutants (Gasperi et al., 2022). Perfluorinated substances (PFASs) are one example of a group of emerging stormwater and road runoff pollutants (Kali et al., 2025; Spahr et al., 2020). PFASs are chemically stable due to their strong carbon-fluorine bonds and more mobile in water due to their hydrophilic functional heads (Stahl et al., 2011; Alsadik et al., 2025). Few studies have evaluated occurrence and fate of PFASs in bioretention filter media indicating their higher mobility in stormwater infiltration facilities (Beryani et al., 2024; Furén et al., 2025). To date, no studies on PFASs accumulation in roadside soils exist. In contrast, metals have long been associated with road runoff given primary sources including wear and tear of tires, brakes, the engine and the vehicle body (Müller et al., 2020). Traffic intensity was found to be one of the key factors influencing metal concentrations in road runoff and roadside soil (Huber et al., 2016). In roadside soils, metal concentrations decrease with increasing distance from the road and with increasing soil depth (Werkenthin et al., 2014).

To understand the functionality of roadside infiltration, a broad analysis of several pollutant groups with different characteristics is needed which includes different climatic conditions and road types. Thus, this study investigates the occurrence, concentration and distribution of PFASs and metals in roadside soils from roads in Sweden and Germany focusing on PFOS and Zn. The study also aims to examine influencing factors, such as traffic intensity, climate, and land use.

2 METHODS

2.1 Sampling Sites and Procedure

Roadside soil was sampled along 12 roads in Sweden and Germany with different traffic intensity, speed limit, surrounding environment, and climatic condition. Five sampling sites were in and around Luleå, Sweden (two urban roads and three highways), two in Stockholm, Sweden (urban roads), one near Gothenburg, Sweden (highway), and four in Hamburg, Germany (motorways).

At each site, three cross-sections were sampled, consisting of three sampling points each according to Figure 1.

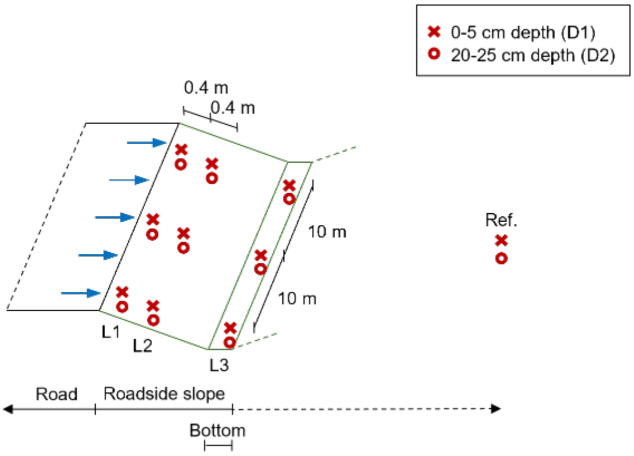

Figure 1: Schematic illustration of sampling design with sampling points (L1-L3) and soil depth (D1-D2)

2.2 Analysis

The samples were analyzed for 35 PFASs and 16 metals according to standard methods. Due to many PFAS nondetects (censored data), the NADA package in R was used to plot the probability distribution of the PFAS compounds, applying Regression on Order Statistics (ROS) model though the “*cenboxplot*” function.

3 RESULTS AND DISCUSSION

Of all PFAS, the long-chain PFAS legacy compound Perfluorooctanesulfonic acid (PFOS) was quantified most frequently (in 71.6% of 162 samples, excl. Ref.) and in highest concentrations (max: 2.2 µg/kg-DW, median: 0.135 µg/kg-DW). The highest occurrences and concentrations of PFOS were detected along the German motorways and the urban roads in Stockholm. Along the highways in Luleå, PFOS concentrations, when quantified, were low (≤ 0.37 µg/kg-DW). Comparing the highway sites in Luleå with the urban sites in Stockholm and the motorway sites near Hamburg suggests that diffuse background PFAS contamination (e.g., by atmospheric deposition) in proximity to urban areas and/or industry may be more important than traffic related sources in the direct road environment. A study about PFAS background concentrations in soils across Sweden found an exponential increase from north to south and west to east, which was explained by population density (Sörengård et al., 2022).

The highest Zn concentrations (max: 875 mg/kg-DW, median: 124 mg/kg-DW) were found along the German motorways, one of the Swedish highways and in individual samples from Stockholm. Overall, higher metal concentrations were observed along roads with higher traffic intensities, which is in line with previous studies (e.g., Werkenthin et al., 2014). Other factors (e.g. galvanized guardrails, vehicular speeds and braking and acceleration) might also play a role (Huber et al., 2016; De Silva et al., 2016; Loganathan et al., 2013). Zn concentrations decreased with depth and distance from the road (Figure 2). From L1 to L3 (Fig. 2) concentrations decreased by approximately 50%. This could be observed in the depth D1 as well as in D2, whereby the concentrations in D1 were proximately twice as high as those in D2 for the respective distances. Looking at individual sites, this pattern was particularly visible for the German motorways and Swedish highways. For the urban sampling sites in Sweden no pattern with distance from the road was visible, which can be attributed to seasonal snow storage and snow spreading over the roadside, as explained by Gavric et al. (2021). Moreover, commonly occurring snowmelt on frozen ground can result in surface runoff rather than infiltration close to the road. Similar patterns as for Zn were also observed for some other metals (e.g. Cu, Co), while Pb showed no clear variation with depth and distance, probably due to its historical use. Elevated Co concentrations along Swedish roads may be connected to the use of studded tires.

The distribution pattern of PFOS differed considerably from the metals. Across all sites, increasing concentrations with distance from the road and no considerable difference between the depths D1 and D2 (Figure 2) were observed. From L1 to L3 (Fig. 2) concentrations increased considerably by approximately 10 times. Interestingly, the PFOS concentrations in Ref. samples (Fig. 2) were higher than for L1 and L2. Along German motorways, PFOS concentrations increased with increasing distance from the road, whereas at urban sites in Stockholm the accumulation pattern was more evenly distributed. These contrasting patterns highlight the unresolved role of road runoff as a pathway for PFASs to roadside environments. For all sites, PFOS concentrations in depth D2 did not vary considerably compared to D1, which indicates its persistency and mobility. Furthermore, the high PFOS concentrations even in the deeper layer could also be related to the transformation of their precursors (Beryani et al., 2024). Other PFASs were less frequently quantified and, particularly short-chain ones, in considerably lower concentrations. While this may indicate reduced presence in road runoff, it could also point to their even higher mobility in soil media (Beryani et al., 2025), resulting in reduced retention.

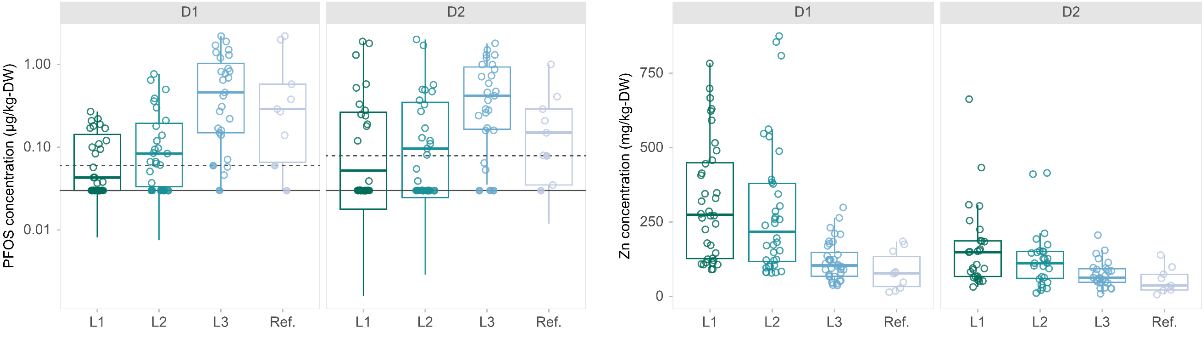

Figure 2: Boxplots for PFOS and Zn concentrations across the 12 sampling sites. The solid line marks the normal LOQ, while the dashed line marks the highest LOQ. Jittered points illustrate the measured values (detected values are displayed as

hollow circles, values <LOQ are filled with color and displayed =LOQ).

4 CONCLUSIONS

This study highlights the contrasting accumulation patterns of metals and PFASs in roadside soils across Sweden and Germany. Metals followed expected distributions, with higher concentrations near roads with higher traffic intensities and decreasing concentrations with distance and depth. Metal concentrations were further influenced by climatic conditions. In contrast, PFOS, a long-chain PFAS compound, showed increasing concentrations with distance from the road, with elevated levels in reference samples suggesting diffuse background contamination rather than direct road runoff as the dominant source. These results underline the importance of considering both traditional and emerging pollutants when evaluating roadside infiltration systems. While metals remain closely linked to traffic emissions, PFASs appear more mobile and influenced by broader urban deposition.

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