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Monitoring Environmental Quality in Urban Gardens Using Moss Analyses of Heavy Metals and Pigments

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Urban gardening has become increasingly popular, raising concerns about the safety of food production in urban environments. As direct pollution measurements are often costly and time-consuming, this study evaluated the potential of the moss Syntrichia ruralis as a bioindicator of environmental pollution in Tallinn, Estonia. Concentrations of Zn, Cu, Ni, Cd, Pb, Hg, and photosynthetic pigments (chlorophyll a, chlorophyll b, and carotenoids) were measured in moss samples collected from 30 sites, including 22 community or educational gardens, in autumn 2019. Additional pigment measurements from eight sites in spring 2018 and soil heavy-metal data from eleven gardens were included. Long-term PM_{10} and NO_x concentrations were estimated using emission inventories and dispersion modelling. Most heavy metals in moss showed weak relationships with PM_{10} concentrations, except for Cu, which was significantly positively correlated with air pollution indicators. Concentrations of Cu, Cd, Ni, and Pb were strongly intercorrelated, and higher soil concentrations of Hg, Cd, and Cu were associated with elevated Hg levels in moss. Pigment content showed weak and inconsistent relationships with heavy metals. Instead, light availability, substrate type, and season had the strongest influence on pigment concentrations. The results suggest that Cu and Hg are the most suitable moss-based indicators of environmental pollution, whereas moss pigment content is not a reliable indicator of pollution in urban gardens.

Keywords: *bioindication, Syntrichia ruralis, bryophyte, PM_{10}, nitrogen oxides*

Introduction

Urban gardening has gained increasing popularity in recent years (Egli and Oliver 2016). This growing interest may be driven by several factors, including a desire for locally produced food and concerns about food safety. Pesticide residues are detected in commercially available food, and maximum residue levels are occasionally exceeded (Padur 2015). Urban gardens can also improve access to fresh food and provide a local strategy for addressing food insecurity (Tims et al. 2021). Furthermore, community gardens contribute to sustainable urban development and play an important role in enhancing both individual and community well-being (Huq and Deacon 2025). At the

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same time, the growing interest in urban food production raises an important question: is food grown in urban environments safe to consume?

Although advances in cleaner technologies have reduced emissions from many sources, traffic remains a substantial contributor to particulate matter (PM_{10}) pollution in urban areas. Previous research has demonstrated that environmental pollution, particularly PM_{10} containing heavy metals, poses significant health risks to residents of Tallinn (Orru et al. 2011). Heavy metals are among the most hazardous components of PM_{10} and contribute to its adverse effects on mortality and morbidity (Valavanidis et al. 2008). The presence of heavy metals in traffic-derived particles may partly explain the findings of Pindus et al. (2016), who observed significant health effects, particularly cardiovascular effects, associated with traffic-related particles but not with particles originating from wood smoke. Exposure to PM_{10} has also been associated with impaired cognitive performance in humans (Aretz et al. 2021, Künn et al. 2023). Furthermore, heavy metals bound to atmospheric particles may accumulate in plants and animals, creating a potential pathway for human exposure through the consumption of contaminated food products (Li et al. 2013).

Air quality in Tallinn is monitored at three permanent stations, where several pollutants, including PM_{10} and nitrogen oxides (NO_x), are regularly measured, whereas selected heavy metals are measured only intermittently at one station (Saare et al. 2019, Eesti Keskkonnauuringute Keskus n.d.). Estonia has three additional urban air-quality monitoring stations: one in Tartu, the country's second-largest city, and one in each of the industrial centres of Kohtla-Järve and Narva. Across all six urban stations, annual mean PM_{10} concentrations ranged from 9 to 20 $\mu g/m^3$ between 2016 and 2023 (Kliimaministeerium n.d.). However, the measurement programme of any of the three rural background stations does not include PM_{10}, but only fine particles ($PM_{2.5}$), which yearly average concentrations are about 4 $\mu g/m^3$ with small variability (Keskkonnaagentuur n.d.). We assume that background concentrations of PM_{10} in remote sites are nearly equal with $PM_{2.5}$, as sources of large dust particles are scarce.

In Tallinn, however, only three permanent stations are available to represent air quality across the entire city. Although these stations are suitable for monitoring general trends and compliance with air-quality standards, they cannot capture fine-scale spatial variation among individual locations. This limitation is particularly relevant to community and educational gardens, which may be situated at varying distances from major roads, former industrial areas, and other local pollution sources. Consequently, the monitoring network alone cannot provide site-specific information on environmental contamination at individual gardens or potential garden sites. Moreover, pollutant concentrations measured at monitoring stations do not necessarily represent the longer-term accumulation and deposition history of heavy metals at a particular location. Expanding conventional instrumental monitoring to a much larger number of sites would also be time-consuming and expensive. A cost-effective and spatially detailed complementary screening method is therefore needed to identify sites where more comprehensive analyses of air, soil, or edible plants may be warranted.

The preliminary assessment of environmental contamination is particularly important when selecting sites for urban food production. Measuring contaminants in edible plants requires crops to be cultivated first, by which time substantial effort may already have been invested in establishing the garden. Soil analyses alone may not fully represent the relevant exposure conditions. Urban crops are often grown in raised beds amended with imported uncontaminated soil, which can have lower metal concentrations than beds established directly in the original urban soil (Mitchell et al. 2014). In such cases, historical contamination of the original soil may be less relevant to contaminant uptake by crops, while ongoing atmospheric deposition from traffic and other local sources can still affect cultivated plants (Säumel et al. 2012).

Mosses already growing at or near a proposed garden site may provide an important complement to soil-based assessments. Changes in metal concentrations, particularly Pb, may be detected more rapidly in moss than in soil, potentially enabling earlier identification of changes in environmental contamination (Meyer et al. 2015). Temporal variation in metal deposition may partly reflect variation in airborne particulate matter (Bozkurt et al. 2017). Moss analysis could consequently serve as an early screening step for identifying locations where more detailed soil, air, or edible-plant analyses are warranted.

Bryophytes lack true roots and a protective cuticle and obtain most of their nutrients directly from atmospheric deposition. These characteristics make them particularly sensitive to air pollution and valuable bioindicators of urban environmental quality (Vanderpoorten and Goffinet 2009, Govindapyari et al. 2010, Oishi and Hiura 2017, Plášek et al. 2026). Atmospheric metals can reach the surfaces of terrestrial bryophytes through precipitation or dry deposition, after which they may be retained, solubilised, or washed away. Although terrestrial bryophytes obtain most deposited substances from the atmosphere, soil particles may also contribute significantly to their heavy-metal content (Stanković et al. 2018).

Many bryophyte species are highly sensitive to environmental pollution and are absent from heavily contaminated habitats; for example, 87% of British and Irish moss species have been classified as having no tolerance to heavy metals (Hill et al. 2007). Conversely, pollution-tolerant species may accumulate metals in their tissues and thereby integrate information on environmental conditions over the period represented by the sampled tissue. Although mosses can accumulate substantial quantities of heavy metals, this accumulation may affect their physiological functioning (Kaur et al. 2010). Świsłowski et al. (2022), for example, showed that exposure to Cu, Zn, Cd, Pb, Mn, Fe, and Hg affected photosystem II functioning in mosses.

Chlorophyll content is frequently used as an indicator of plant physiological condition and photosynthetic capacity. Several controlled-exposure studies have demonstrated that heavy metals can affect chlorophyll concentrations and photosynthetic functioning in bryophytes, although the magnitude and direction of the response depend on the moss species, metal, concentration, and duration of exposure (Tremper et al. 2004, Shakya et al. 2008, Tuba et al. 2010, Kaur et al. 2010, Stanković et al. 2018, Świsłowski et al. 2022, Phaenark et al. 2023). Using metal concentrations representative of field conditions, Tremper et al. (2004) found that Cu significantly reduced chlorophyll content in Rhytidiadelphus squarrosus, whereas Pb and Zn had no significant effect. Other studies have reported reductions in chlorophyll content or photosynthetic performance in response to Pb, Zn, Cd, and other metals, but the responses varied among species and exposure levels (Shakya et al. 2008, Tuba et al. 2010, Kaur et al. 2010, Świsłowski et al. 2022). In a recent laboratory study, Phaenark et al. (2023) found that chlorophyll-a concentrations decreased with increasing Cd, Pb, and Zn exposure in three acrocarpous moss species, with metal toxicity following the order Cd > Pb > Zn.

However, relationships demonstrated under controlled experimental conditions may not be directly transferable to naturally growing mosses. Experimental metal concentrations are often higher than those occurring in the field, whereas moss pigment concentrations and photosynthetic performance under natural conditions may simultaneously respond to seasonal and microclimatic variation, moisture and nutrient availability, and interactions among environmental stressors (Tremper et al. 2004, Salemaa et al. 2008). Nitrogen deposition may be particularly relevant because high nitrogen availability can inhibit bryophyte growth, whereas at low to moderate levels, growth may exhibit a unimodal response, with the precise relationship varying among species (Salemaa et al. 2008). It therefore remains uncertain whether metal-related changes in moss pigments are sufficiently strong and specific to be distinguished from natural environmental variation at environmentally occurring concentrations under heterogeneous urban field conditions. The combined analysis of elemental concentrations and photosynthetic pigments was consequently evaluated to determine whether physiological responses provide information complementary to metal accumulation and thereby improve the preliminary assessment of urban environmental quality.

The present study focused on *Syntrichia ruralis* (Figure 1), a moss commonly found in urban environments and considered one of the most suitable bioindicators for assessing urban pollution in Estonia (Rajandu et al. 2024) and in other urban areas (Sfetsas et al. 2024). Owing to its tolerance of environmental stressors, including heavy-metal contamination, *S. ruralis* has been identified as a particularly suitable indicator of heavy-metal pollution (Naszradi et al. 2007). It is relatively easy to identify in the field and occurs on a wide range of substrates, including soil, concrete, and asphalt. The species tolerates diverse soil and moisture conditions and typically thrives in well-lit habitats. It was also among the eight moss species identified by Mallen-Cooper et al. (2023) as both abundant and functionally important across temperate and Arctic ecosystems. The growth phenology of *S. ruralis*, reported under its former name *Tortula ruralis*, has been described in detail by Mishler and Oliver (1991). Restricting chemical analyses to the living apical parts of the shoots can consequently help distinguish active growth from older moss tissue and make the samples more relevant to the assessment of relatively recent local environmental conditions.

Although mosses have been widely used as bioindicators of atmospheric metal deposition, previous studies have generally focused on one or a limited number of components, such as elemental accumulation, physiological responses under controlled exposure, spatial patterns of atmospheric deposition, or relationships with individual environmental variables. Their application as an early screening tool for existing and potential urban garden sites remains less well established. The distinctive feature of the present study is the combined field analysis of six heavy metals and photosynthetic pigments in naturally growing *S. ruralis*, together with modelled PM_{10} and NO_x concentrations, available soil-metal data, and local habitat variables, including light availability and growth substrate. This integrated design enabled us to assess whether pigment responses provide information complementary to metal accumulation and whether relationships observed under controlled exposure remain detectable under heterogeneous urban field conditions.

Therefore, this study evaluated the potential of *S. ruralis* to provide preliminary information on environmental contamination in the vicinity of existing and potential community and educational gardens across Tallinn. Specifically, we examined (1) whether heavy-metal concentrations in the living parts of moss reflected spatial variation in local pollution conditions and were related to modelled PM_{10} and NO_x concentrations and available soil-metal data, and (2) whether chlorophyll and carotenoid concentrations were consistently associated with accumulated metals after accounting for variation in light availability, season, and growth substrate. Direct metal analysis was used to assess contaminant accumulation in moss, whereas pigment analysis was evaluated as a potentially simpler and less expensive preliminary screening method for identifying sites where further chemical analyses may be warranted.

Figure 1. *Moss Species Syntrichia ruralis*

Source: Elle Rajandu photo.

Materials and Methods

Sampling Sites and Sample Collection

Thirty study sites were investigated, including 13 community gardens or potential community garden sites, 9 educational gardens at schools and kindergartens, 6 reference sites within Tallinn, and 2 control sites located outside Tallinn in Jäneda (Figure 2). Two reference sites were located near (up to 5 m) heavy traffic streets (multiple lanes in one direction) and/or crossings, and four reference sites were located away from heavy traffic streets (at least 100 m). At each sampling site, measurements of light availability were taken, canopy cover was estimated, the moss substrate was identified, and the growth surface was classified as either horizontal or vertical. Concentrations of Zn (zinc), Cu (copper), Ni (nickel), Cd (cadmium), Pb (lead), and Hg (mercury), as well as chlorophyll a, chlorophyll b, and carotenoids, were measured in the moss *Syntrichia ruralis* in autumn 2019. Mercury concentrations could not be determined at two sites because insufficient moss material was available. Pigment analyses were generally conducted using three replicates per study site. For six reference sites, moss pigment data from a previous survey conducted in spring 2018 were also available, allowing seasonal and interannual comparisons. Soil heavy metal data for Zn, Cu, Cd, and Pb were available from eleven of the studied gardens, with complete soil data for all investigated metals available from eight gardens. Soil heavy-metal data were collected from eight gardens in 2019 and three in 2023.

Figure 2. *(A) Location of Estonia in Europe. (B) Study Area Tallinn and Control Site in a Rural Area Jäneda. (C) Sampling Sites (dots) in Tallinn (At each site, samples were collected from three different locations)*

Heavy Metal Measurements

Living parts of moss were washed with ultrapure water, air-dried and lyophilised. All samples were stored at room temperature. Concentrations of Zn, Cu, Ni, Cd, and Pb were measured using flame and graphite furnace atomic absorption spectroscopy (AAS), and Hg was measured using cold-vapour AAS.

Chemicals and Reagents

All reagents used were of high purity, and all solutions were prepared in ultrapure water (Millipore, USA). The Zn, Cu, Ni, Cd, Pb and Hg 1000 mg/L single metal AAS standard solutions were obtained from Honeywell Fluka™. The reducing solution for cold-vapour AAS measurements was prepared by dissolving $SnCl_2 \cdot 2H_2O$ (Merck, Germany) at 25% (m/v) in 20% HCl (v/v) (Merck, Germany). Nitric acid Suprapur, 68% (Merck) and 35% H_2O_2 (Fluka) were employed for the digestion of the samples. The applicability of the method to real samples was demonstrated by the analysis of the CRM testing material LGC6187 (LGC standards).

AAS Analysis

AAS metal analysis was carried out according to the overall procedure described in ISO standard EN 14084:2003: Foodstuffs - Determination of trace elements - Determination of lead, cadmium, zinc, copper and iron by atomic absorption spectrometry (AAS) after microwave digestion. Samples were microwave-digested using Microwave GO (SN: 81801381) equipment according to ISO EN 13805:2002 and EN 13804:2002. Concentrations of Zn, Cu, Ni, Cd, and Pb were determined using flame and graphite furnace atomic absorption spectrometry (AAS; SpectrAA 220F and SpectrAA 220Z, Varian). Argon 4.0 was used in the AASG, and an air-acetylene flame was used for the AASF method. For each sample, two replicate measurements were made, and the results given in this work are the average concentrations.

Hg determination was performed using a CV-AAS system SpectraAA 220F (Varian). Samples of 0.2–0.3 g were digested in a water bath with 5 mL of nitric acid (24 h) and 1 mL of hydrogen peroxide (24 h) in a disposable test tube. After digestion, the samples were diluted with water to 25 mL. The test solution was transferred to the reaction vessel of the Hg analysis unit, and the mercury content was measured using continuous-flow cold-vapour-atomic absorption spectrometry.

Chlorophyll and Carotenoid Analyses

For pigment analyses, moss samples were collected from three sampling points within each study site. Samples were kept in dark and cool conditions during transport, cleaned with distilled water within 24 h of collection, and stored at −15°C until analysis. The apical 0.5 cm segments of the moss shoots were used for all measurements.

Chlorophyll-a (Chl-a), chlorophyll-b (Chl-b), total chlorophyll (Chl-a+b), and carotenoid concentrations were determined using an 80% acetone extraction method modified from Porra et al. (1989). Prior to extraction, samples were divided into two subsamples. One subsample was oven-dried at 60°C for at least 24 h to determine dry mass, while the second subsample was used for pigment extraction.

Frozen moss tissue was homogenised in a phosphate buffer solution (2.5 mM sodium phosphate, pH 7.8) and extracted with an 80% acetone–20% buffer solution under dim light conditions. The extracts were centrifuged at 3000 rpm for 10 min and analysed spectrophotometrically (Shimadzu UV-1800, Japan). Absorbance was measured at 470, 645, 663 and 750 nm using an acetone-buffer solution as a blank.

Concentrations of chlorophyll-a, chlorophyll-b, total chlorophyll, and carotenoids were calculated from absorbance values and expressed on a dry-mass basis (mg g^{-1}

DW). Water content was determined from the difference between fresh and dry sample mass.

Modelled PM_{10} and NO_x

The long-term average concentrations of the air pollutants particulate matter (PM_{10}) and nitrogen oxides (NO_x) in Tallinn were estimated using the AEROPOL 5.3 dispersion model (Kaasik et al. 2017), based on meteorological observations collected at the Tallinn-Harku Meteorological Station between 2015 and 2018. Traffic-related emissions were derived from urban traffic flow modelling conducted by AS Stratum for the reference year 2017. Emissions from domestic heating were also included; however, model results indicated that their contribution to local air pollution levels was relatively minor. This was likely due to the predominance of district heating in the study area and the location of most sampling sites near major roads rather than residential areas relying on wood or coal heating.

Within Tallinn, pollutant concentrations were modelled on a spatial grid with a resolution of 50 m, while a finer 10 m resolution was applied in the city centre. Model outputs were validated against measurements from three urban air quality monitoring stations, and regression-based corrections were used to reduce systematic deviations.

For sites located outside Tallinn, annual average concentrations of NO_x and PM_{10} were estimated using rural background levels measured at the nearest rural air quality monitoring station in Lahemaa, combined with the contribution of emissions dispersed from nearby major roads. Rural background concentrations in Estonia show relatively little spatial variation, ranging from 1.8 to 2.1 $\mu g/m^3$ for NO_x and from 3.9 to 4.5 $\mu g/m^3$ for PM_{10}.

Data Processing

Differences between groups were evaluated using one-way ANOVA. Homogeneity of variances was tested with Bartlett's test, and Welch's ANOVA was applied when heteroscedasticity was detected. Multiple comparisons were performed using the Games–Howell post hoc test. Relationships between variables were assessed using Spearman's rank correlation coefficient (McDonald 2014). To investigate associations between moss pigments, heavy metals, and environmental variables, Canonical Correspondence Analysis (CCA) and General Linear Models (GLM) were performed using CANOCO 5 software (ter Braak and Šmilauer 2012).

Results

The calculated annual average NO_x concentrations exceeded 20 $\mu g/m^3$ at reference sites located adjacent to major roads, including areas near the intersection of Sõpruse and Mustamäe road and along Liivalaia road (Table 1). Elevated NO_x levels were also found near educational and community gardens located relatively close to heavily trafficked roads, including the study sites near Tallinn Co-education Gymnasium (TYG), Tallinn University (TLU), and the Rõõmutareke kindergarten. These sites also exhibited relatively high modelled PM_{10} concentrations. Heavy metal concentrations exceeded the average across the 30 study sites for all six metals at the Liivalaia sampling site, where the lead concentration was more than five times higher than the average, reaching 79.7 µg/g. Other heavily polluted sites with respect to heavy metals were located near the Põhjala, Telliskivi, and Ameerika community gardens. At the first two of these locations, concentrations of more than half of the analysed metals were 2–3 times higher than the average values across all study sites. The Põhjala site had the lowest modelled PM_{10} and NO_x concentrations among the Tallinn sites.

Heavy metal concentrations in soil varied considerably among the study sites (Table 2). Zinc was the most abundant metal, followed by Cu and Pb, whereas Cd and Hg occurred at substantially lower concentrations. Among the individual sites, the highest Zn (232.0 µg/g), Cu (38.0 µg/g) and Ni (6.6 µg/g) concentrations were measured near Rõõmutareke educational garden. The highest Pb concentration was recorded near Mõmmik educational garden (29.2 µg/g), while the highest Cd concentration occurred at Ameerika community garden (0.29 µg/g). Hg concentrations ranged from 0.06 to 0.10 µg/g in samples in which it was detected. Ni and Hg were below the detection limit at several educational garden sites.

Table 1. *Heavy Metal Concentrations in Moss S. ruralis and the Modelled Concentration of Nitrogen Oxides (NO_x) and Particles (PM_{10}) (CG – community garden or potential community garden, EG – educational garden at schools or kindergarten, RSa – reference site in Tallinn, near (up to 5 m) heavy traffic streets (multiple lanes in one direction) and/or crossings, RSb – reference site in Tallinn, located away from heavy traffic streets (at least 100 m), and CS – control site located outside Tallinn in Jäneda. ND – not determined, SD – Standard Deviation, SE – Standard Error)*

		Heavy metals in moss *S. ruralis* (µg/g)						**Modelled parameter (µg/m³)**	
Site	**Type**	**Zn**	**Cu**	**Pb**	**Ni**	**Cd**	**Hg**	**NO_x**	**PM_{10}**
Aafrika	CG	124.2	14.3	6.3	3.5	0.21	0.24	22.7	11.6
Ameerika	CG	115.2	48.4	14.4	11.2	0.28	0.20	19.7	11.7
Balti jaam	CG	88.8	24.8	12.8	3.3	0.17	0.04	14.9	11.2
Kollane	CG	119.6	30.5	15.1	4.0	0.30	0.17	18.9	12.6
Laagna	CG	41.0	21.8	6.1	3.6	0.14	<0.01	14.7	10.5
Mustamäe	CG	65.2	21.8	9.9	3.5	0.19	0.11	12.9	10.3
Möldre	CG	146.1	9.0	1.9	2.3	0.09	<0.01	12.4	10.4
Pae	CG	46.1	30.6	14.3	7.7	0.20	0.15	14.7	11.1
Pelgulinn	CG	372.8	26.0	8.0	4.3	0.21	0.08	10.0	10.0
Priisle	CG	60.1	13.2	2.0	2.7	0.11	0.04	11.5	10.1
Põhjala	CG	83.4	114.5	38.4	22.5	0.73	0.16	7.9	9.8
Telliskivi	CG	265.5	91.8	35.9	7.5	0.26	0.30	15.4	11.4
TLU	CG	157.2	36.1	30.2	4.1	0.22	<0.01	22.1	16.5
Kullerkupu	EG	165.8	26.4	6.0	5.2	0.22	<0.01	17.1	11.5
Lepatriinu	EG	176.1	57.7	6.4	6.4	0.37	0.04	13.4	10.5
Liivalossi	EG	33.2	25.5	5.3	2.8	0.35	0.13	21.5	11.6
Lille	EG	240.8	37.9	8.4	4.4	0.18	0.15	17.4	11.7
Mutionu	EG	126.4	39.7	6.8	4.6	0.23	0.11	18.3	11.9
Mõmmik	EG	198.7	25.4	24.7	9.5	0.28	<0.01	12.8	10.6
Pääsküla	EG	20.2	11.3	10.0	2.8	0.14	ND	13.6	10.5
Rõõmutareke	EG	64.4	45.0	6.2	3.4	0.20	0.26	20.9	12.7

TYG	EG	116.1	48.2	11.8	9.2	0.17	<0.01	26.9	16.7
Liivalaia	RSa	142.8	52.9	79.7	5.6	0.33	ND	24.9	14.4
Sõpruse	RSa	159.1	101.7	10.1	4.2	0.14	<0.01	24.0	17.3
Merivälja	RSb	17.4	7.8	1.4	0.9	0.11	0.02	9.6	10.1
Õie 1	RSb	105.0	21.2	10.2	3.7	0.21	<0.01	18.5	12.3
Õie 2	RSb	33.4	9.7	5.2	3.3	0.23	0.05	18.0	12.0
Õismäe	RSb	43.4	13.9	11.6	2.4	0.14	0.66	11.5	10.1
Jäneda 1	CS	95.2	7.1	11.6	4.8	0.21	0.07	2.2	5.9
Jäneda 2	CS	160.4	8.3	6.8	2.3	0.22	0.07	2.2	5.9
Mean		119.5	34.1	13.9	5.2	0.23	0.11	15.7	11.4
Median		115.6	25.7	9.9	4.0	0.21	0.07	15.1	11.3
SD		79.4	27.4	15.5	4.0	0.12	0.14	6.0	2.5
SE		14.5	5.0	2.8	0.7	0.02	0.03	1.1	0.5
Minimum		17.4	7.1	1.4	0.9	0.09	0.01	2.2	5.9
Maximum		372.8	114.5	79.7	22.5	0.73	0.66	26.9	17.3

Table 2. *Measured Heavy Metal Concentrations in Soil Samples (µg/g) (Abbreviations as in Table 1)*

Site	**Type**	**Heavy metals from soil (µg/g)**					
		Zn	**Cu**	**Pb**	**Ni**	**Cd**	**Hg**
Ameerika	CG	220.0	32.0	28.0	5.7	0.29	0.10
Laagna	CG	160.0	20.5	18.5	5.8	0.18	0.08
Mustamäe	CG	187.0	28.0	22.6	6.0	0.25	0.08
Pae	CG	180.0	27.5	22.5	4.9	0.24	0.08
Põhjala	CG	200.0	27.5	24.8	5.4	0.26	0.08
Kullerkupu	EG	48.9	7.0	12.6	ND	0.08	ND
Lepatriinu	EG	157.0	23.5	23.9	5.2	0.22	0.07
Liivalossi	EG	10.9	9.9	3.1	ND	0.13	ND
Mutionu	EG	172.0	18.5	15.5	5.7	0.19	0.06
Mõmmik	EG	147.5	23.1	29.2	ND	0.16	ND
Rõõmutareke	EG	232.0	38.0	25.8	6.6	0.28	0.10
Mean		155.9	23.2	20.6	5.7	0.21	0.08
Median		172.0	23.5	22.6	5.7	0.22	0.08
SD		68.0	9.1	7.7	0.5	0.06	0.01
SE		20.5	2.7	2.3	0.2	0.02	<0.01
Minimum		10.9	7.0	3.1	4.9	0.08	0.06
Maximum		232.0	38.0	29.2	6.6	0.29	0.10

Correlation analyses between modelled PM_{10} concentrations and heavy metal contents revealed no statistically significant relationship for most metals, with the exception of copper, which showed a significant positive correlation (Table 3, Figure 3). The lowest heavy metal concentrations were found in Merivälja and near the school gardens of Laagna, Priisle, and Pääsküla, where concentrations of all analysed metals were substantially below the overall study-site averages. Concentrations of Cu, Cd, Ni, and Pb in *S. ruralis* were strongly correlated with each other. Among the 11 sites for which soil data were available, higher concentrations of Hg, Cd and Cu in soil were associated with greater Hg concentrations in moss (Figure 4). The modelled PM_{10} concentrations in air correspond to usual levels measured in urban monitoring stations, except one, which is in rural background range.

Table 3. *Correlation Matrix with Spearman's Correlation Coefficients (Statistically significant correlations are marked in bold (p<0.05). Zn, Cu, Ni, Cd, Pb, and Hg – measured heavy metal concentrations in moss S. ruralis (µg/g), NO_x – the modelled concentration of nitrogen oxides (µg/m³) and PM_{10} – the modelled concentration of particles (µg/m³))*

	Zn	Cu	Ni	Cd	Pb	Hg	NO_x	PM_{10}
Zn	1							
Cu	**0.42**	1						
Ni	**0.46**	**0.73**	1					
Cd	0.33	**0.49**	**0.56**	1				
Pb	0.27	**0.52**	**0.65**	**0.40**	1			
Hg	-0.13	0.19	0.04	0.28	0.23	1		
NO_x	0.09	**0.50**	0.23	0.19	0.18	-0.01	1	
PM_{10}	0.16	**0.52**	0.25	0.17	0.21	-0.11	**0.95**	1

Figure 3. *Correlation between Particles PM_{10} and Cu in Moss S. ruralis (Spearman's rho 0.5, ($p < 0.05$)*

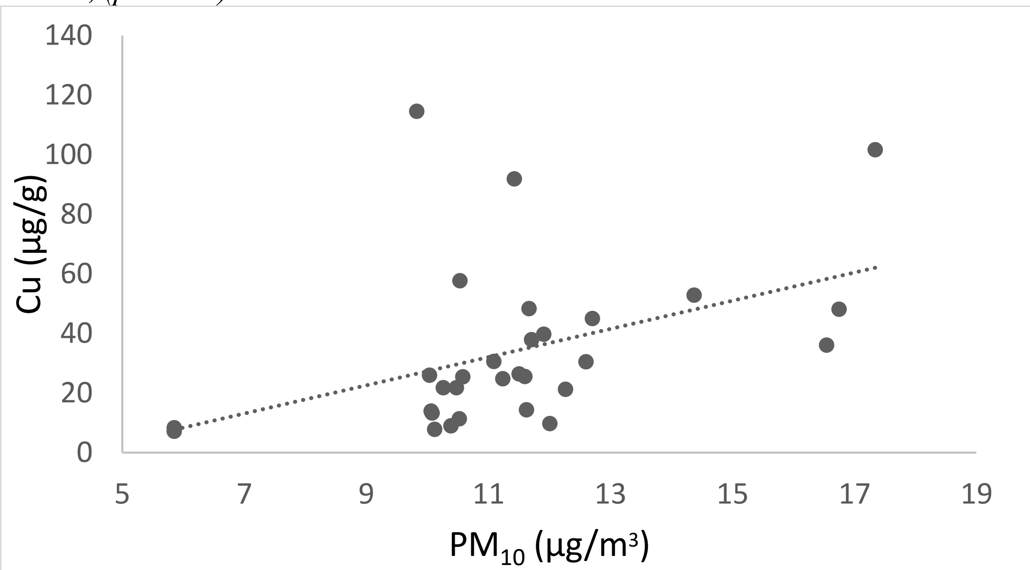
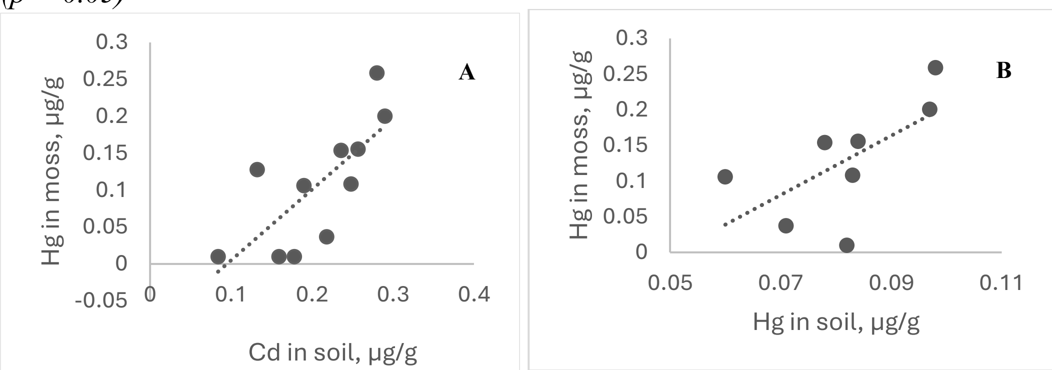


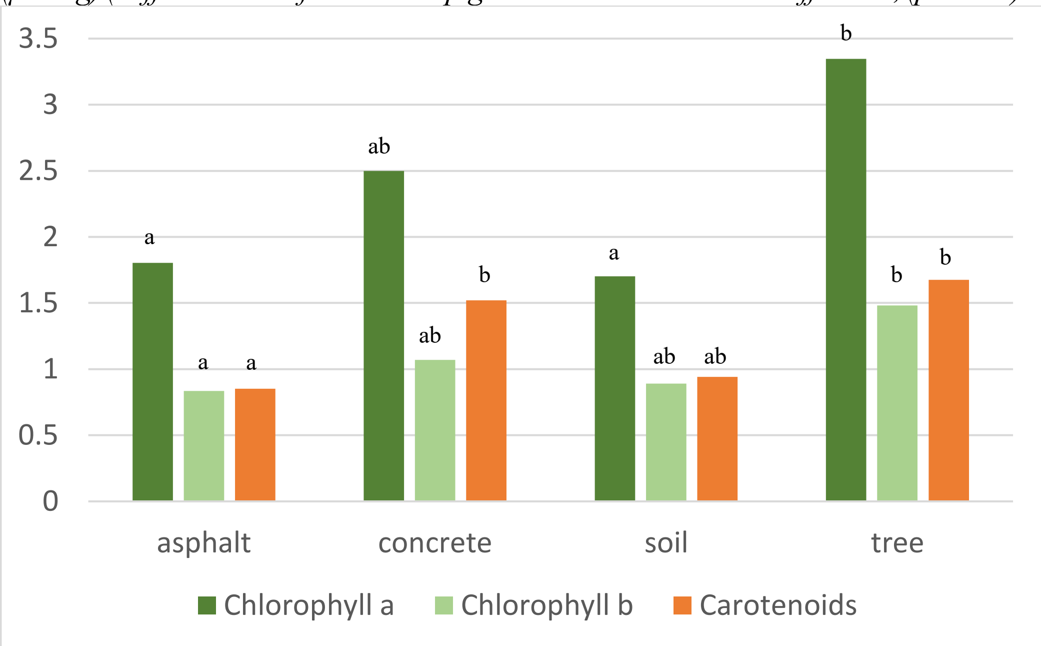
Figure 4. *(A) Correlation between Cd in Soil and Hg in Moss (Spearman's rho 0.7, ($p < 0.05$). (B) Correlation between Hg in soil and Hg in moss, Spearman's rho 0.7 ($p < 0.05$)*



Various statistical analyses (GLM, ordination analysis, and correlation analysis) did not reveal strong relationships between pigment concentrations and heavy metal levels. However, light availability was significantly correlated with all pigment concentrations. Ordination analysis likewise showed that light explained the largest proportion of variation in moss pigment content.

Pigment concentrations differed significantly among growth substrates (ANOVA, $p < 0.05$), with the highest values recorded on trees and the lowest on soil and asphalt (Figure 5). Comparisons of pigment concentrations measured at reference sites across different seasons and years revealed significant differences (Welch ANOVA, $p < 0.05$): values collected in spring 2018 were, on average, approximately twice as high as those collected in autumn 2019.

Figure 5. *The Pigment Content of Moss S. ruralis on Different Growing Surfaces (µmol/g) (Different letters for the same pigment indicate a statistical difference, (p < 0.05)*



Discussion

Heavy metal concentrations in *Syntrichia* mosses were generally lower in Tallinn than in Thessaloniki (Sfetsas et al. 2024, Table 4). However, the studies differed in their site-selection criteria. Sfetsas et al. (2024) selected 16 locations representing diverse urban activity zones, including motorway, industrial, city-centre, and airport environments, whereas the sites in the present study were selected primarily because they contained community or educational gardens. Therefore, the difference between the overall city means may reflect both actual differences in pollution levels and differences in the composition of the sampling sites. To improve comparability, the two Tallinn sites situated next to heavily trafficked roads, Sõpruse and Liivalaia, were also compared separately with the traffic-affected sites in Thessaloniki. The concentrations at the Tallinn roadside sites were generally comparable to those in Greece; only Ni has consistently higher levels in Greece, but for other metals it really depends on the specific area being studied. However, because the Tallinn roadside subgroup comprised only two sites, the comparison is descriptive and should not be interpreted as representative of all high-traffic locations in Tallinn.

Table 4. *Comparison of Heavy Metal Concentrations in Syntrichia Mosses in Estonia and Greece*

Statistics, Sample/Location	**Heavy metals from moss *Syntrichia* (µg/g)**				
	Zn	**Cu**	**Pb**	**Ni**	**Cd**
Tallinn (N=28, current study)					
Mean	118.9	36.0	14.3	5.3	0.23
Median	115.6	26.2	9.9	4.0	0.21
SD	81.8	27.4	15.9	4.1	0.12
SE	15.5	5.2	3.0	0.8	0.02
Minimum	17.4	7.8	1.4	0.9	0.09
Maximum	372.8	114.5	79.7	22.5	0.73
Tallinn, near heavy traffic streets and crossings (current study)					
Liivalaia	142.8	52.9	79.7	5.6	0.33
Sõpruse	159.1	101.7	10.1	4.2	0.14
Thessaloniki, Greece (N=16, Sfetsas et al. 2024)					
Mean	875.2	62.7	90.0	39.9	1.10
Median	529.6	57.2	70.4	36.4	0.50
SD	1152.6	41.3	77.8	23.4	1.50
SE	288.2	10.3	19.5	5.8	0.40
Minimum	40.3	9.7	3.4	7.9	0.06
Maximum	3927.0	146.7	274.0	114.3	5.78
Traffic-related air heavy metal contamination in Thessaloniki, Greece (Sfetsas et al. 2024)					
M01/L01	71.2	25.2	13.8	32.4	0.17
M02/L02	40.3	9.7	3.4	7.9	0.06
M03/L03	67.8	26.8	15.9	36.9	0.15
City centre, the overall urban background levels of heavy metals, Thessaloniki, Greece (Sfetsas et al. 2024)					
M04/L04	587.6	52.7	49.7	39.5	0.31
M05/L05	679.2	111.6	126.2	41.4	0.55
M06/L06	3927.4	89.8	176.9	35.3	5.78
M11/L12	1781.8	112	69.4	44.9	0.95
M14/L14	91.1	18.3	20.7	114.3	0.3

The highest heavy-metal concentrations in moss were generally measured near major roads, indicating an influence of traffic-related deposition. This agrees with Sfetsas et al. (2024), who reported elevated concentrations and strong positive correlations among several traffic-associated elements, including Cu, Cd, Pb, and Zn, in *Syntrichia* samples collected near major roads and in the city centre. These metals may originate from brake and tyre wear, exhaust emissions, and the resuspension of historically contaminated road dust. In the present study, concentrations of all six measured metals exceeded their respective study-site averages at the Liivalaia site, situated next to a major road, and its Pb concentration was more than five times the overall average. However, only Cu was significantly correlated with modelled PM_{10} concentrations, indicating that traffic-related particulate pollution was not the only factor affecting metal accumulation in moss.

A notable example was the Põhjala site, where relatively high metal concentrations in moss occurred despite the site having the lowest modelled PM_{10} and NO_x concentrations among the Tallinn sites. Two non-exclusive explanations should be considered. First, dispersion models inevitably involve spatial and emission-related uncertainty and may not capture highly localised pollution sources. Second, the modelled concentrations primarily represent emissions included in the contemporary emission inventory, whereas moss and especially soil may reflect local industrial emissions and contaminant accumulation from earlier periods. Põhjala is a former industrial area, and its soil concentrations of Zn, Cu, Cd, and Pb were above the respective means of the 8–11 sites for which soil data were available, while Hg and Ni concentrations were close to the corresponding subset means. Exploratory correlations between modelled PM_{10} and soil-metal concentrations ranged from very weak for Pb to moderate for Zn and Ni, but interpretation is limited by the small and incomplete soil dataset. Previous land use is known to influence metal concentrations in urban garden soils and their subsequent accumulation in plants (Kazantzoglou et al. 2016). The elevated moss concentrations at Põhjala may therefore reflect legacy or local industrial contamination not represented by the modelled traffic-related pollution, although local model uncertainty cannot be excluded.

Estonian legislation defines target and limit values for heavy metal concentrations in soil (Riigi Teataja 2019). Soil data from the eleven studied sites did not indicate any exceedances of target or limit values, except for Zn concentrations in the Ameerika community garden and near the Rõõmutareke educational garden. These sites are also located relatively close to major roads. In such areas, it is advisable to use imported clean soil for cultivation and to thoroughly wash edible vegetables before consumption. For example, an analysis of lead concentrations in fruits from a community garden in Tallinn showed that washing reduced Pb levels by more than half on average; in several cases, Pb concentrations in unwashed fruits exceeded the threshold value above which plant material is considered contaminated (Vacht et al. 2022, Vacht et al. 2025). The present study did not distinguish between metals retained on the moss surface and metals incorporated into or strongly bound to moss tissues. Although moss samples were washed with ultrapure water before analysis, paired analyses of washed and unwashed material would be required to quantify the readily removable surface-associated fraction. Such an assessment represents an important topic for future work. Accordingly, the recommendation to wash produce from urban gardens should not be interpreted as being derived directly from the moss accumulation mechanism, but is supported by previous direct measurements showing substantial reductions in Pb concentrations in edible plant material after washing. The soil quality in the remaining nine gardens for which soil data were available can be considered good.

Hg concentrations in moss were the best indicator of heavy metal contamination in soil, showing significant associations with soil concentrations of Cd, Cu, and Hg. Contamination sources of different metals often overlap. Meyer et al. (2015) reported that heavy metal concentrations in mosses, including Hg, reflect atmospheric deposition relatively well and that, in some cases, metal accumulation can be predicted by population density. In one of our previous studies (Rajandu et al. 2025), which included five moss species (including *Syntrichia ruralis*), Hg concentrations in moss were most strongly correlated with Hg concentrations in soil, whereas relationships with other soil metals were not significant. At the same time, soil Hg concentrations were strongly correlated with concentrations of other metals, such as Fe and Cu, in moss. These findings suggest that Hg accumulation may serve as a useful proxy for broader patterns of heavy metal contamination.

Heavy metal concentrations measured in soil and *Syntrichia ruralis* were of the same order of magnitude. Although no comparable studies directly comparing heavy metal concentrations in *S. ruralis* and soil are known, previous research on *Pleurozium schreberi* and *Hylocomium splendens* has shown that these moss species accumulate heavy metals at levels reflecting environmental contamination (Kaasik and Liiv 2007). In our previous study (Rajandu et al. 2024), which compared heavy metal concentrations among five moss species, the Fe and Cd contents of *S. ruralis* were found to be significantly higher than those of *Sciuro-hypnum curtum*.

In the present study, concentrations of Cu, Cd, Ni, and Pb in *S. ruralis* were strongly correlated with each other. Similar patterns have been reported by Zhou et al. (2025), who found strong correlations among heavy metals accumulated in mosses, including Cu-Ni and Cu-Pb relationships.

Previous laboratory tests have demonstrated a reduction in chlorophyll content due to heavy metal-induced stress (Shakya et al. 2008, Tuba et al. 2010, Stanković 2018). We can conclude that the level of heavy metals in the selected moss species in Tallinn is not high enough to affect chlorophyll content, even under variable environmental conditions. Tremper et al. (2004) study in the field also did not give any measurable negative effect of heavy metals on the chlorophyll concentrations in moss species *Pleurozium schreberi* and *Rhytidiadelphus squarrosus*. Other factors, such as climatic factors, interaction with other pollutants or shelter, probably still had a stronger influence on the chlorophyll concentrations (Tremper et al. 2004). In another study (Tuba et al. 2010) where tested heavy metals effects in field and laboratory, the chlorophyll a fluorescence remained nearly constant in most of the studied bryophyte species (9) in field conditions and in laboratory at lower concentration (5 mM), revealing that the maximal photochemical capacity of the photosynthetic cells remains unchanged at lower Pb concentration, but two species were already affected by lower lead concentrations.

Conclusions

Heavy metal concentrations in *Syntrichia ruralis* revealed spatial variation among Tallinn's urban gardens, with Cu and Hg emerging as the most informative of the six metals analysed. In contrast, moss pigment concentrations were strongly affected by light, season and growth substrate and were not reliable indicators of metal contamination. Moss metal analysis may therefore serve as a supplementary screening tool for identifying sites where more detailed soil or produce analyses are warranted, including contamination not predictable from site location alone. Although edible plants were not analysed, thorough washing of urban-grown produce remains a reasonable precaution.

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