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Territorial Context, Road Environment and Potential Exposure of Urban Agriculture Sites to Atmospheric Particulate Matter

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Abstract

Urban agriculture sites may be exposed to atmospheric particulate matter because of their location in densely urbanised environments. This study characterised the territorial, road and atmospheric contexts of 758 urban agriculture sites identified in France and compared them with 172,455 organic agricultural parcels and 304 town halls used as urban reference locations. Each location was assigned to one of seven environmental profiles previously defined at the municipality level according to urbanisation, landscape and agricultural characteristics. Profiles 1–5 represent predominantly rural, agricultural or peri-urban contexts, whereas profile 6 corresponds to peripheral urban municipalities and profile 7 to dense urban centres. Of the urban agriculture sites surveyed, 651 (85.9%) belonged to profiles 6–7. Compared with the 107 urban agriculture sites in profiles 1–5, these sites had higher PM_{10} and $PM_{2.5}$ concentrations and a more developed surrounding road network. Comparisons with organic agricultural parcels were conducted within the same grouped environmental contexts. In profiles 6–7, urban agriculture sites had higher particulate concentrations and greater surrounding road lengths than organic parcels, whereas contrasts were smaller in profiles 1–5. Town halls were used only for road indicators because the 1 km resolution of the atmospheric model did not permit a meaningful local comparison of particulate concentrations. In within-municipality analyses, class 1 road length was 329 m greater around urban agriculture sites than around their reference town halls, and 71.6% of sites were closer to a national road or motorway than the corresponding town hall. These results show that the potential exposure of urban agriculture sites depends on both the broader environmental context and their position within municipalities, and they identify settings in which local air, deposition and crop measurements should be prioritised.

2. Introduction

Urban agriculture (UA) encompasses agricultural practices located in urban and peri-urban areas that maintain close functional links with the city (Moustier, 1999; Nahmias and Le Caro, 2012). Although historically present in urban areas, it has attracted renewed interest in recent decades because of its economic, social and environmental functions (De Bon et al., 2010; Aubry, 2013). In countries of the Global North, its development serves several purposes, including local food production, the use of available urban land, the development of short food supply chains and stronger social ties. These projects may also contribute to urban greening and to residents' health and well-being by providing access to cultivated spaces and fresh produce (Aubry, 2013; Taguchi and Santini, 2019; Giacchè et al., 2022). Urban agriculture encompasses a wide range of forms, including community or shared gardens, professional urban farms, microfarms, rooftop cultivation and cultivation in interstitial spaces. Their locations, objectives and relationships with the urban environment vary among projects.

Although urban agriculture is generally associated with social, environmental and health benefits, it develops in environments that may contain specific sources of contamination. Soil, water and air quality may affect the sanitary quality of plant produce and, consequently, consumer exposure. The transfer of contaminants from soil to plants has been widely studied because contaminants may accumulate in

plant tissues intended for human consumption (Nabulo et al., 2012; Antisari et al., 2015; Dala-Paula et al., 2018; Dumat et al., 2019). In France, the R.E.F.U.G.E. methodological guide provides a structured approach for assessing and managing risks associated with soil contamination in urban agriculture projects (Barbillon et al., 2019). Contamination associated with air quality and atmospheric deposition is less frequently included in preliminary site assessments, although it represents another potential route of crop exposure.

In urban areas, air pollution is a major environmental and public-health concern (WHO, 2021). Particulate matter is of particular concern because of its multiple sources, dispersion through the urban environment and health effects. Road traffic contributes to particulate emissions through fuel combustion and through non-exhaust mechanisms, including wear of brakes, tyres and road surfaces and the resuspension of dust deposited on roads (Harrison et al., 2021; Fussell et al., 2022). Airborne particles are generally classified according to their aerodynamic diameter. PM_{10} comprises particles with a diameter of 10 µm or less, whereas $PM_{2.5}$ is the fine fraction with a diameter of 2.5 µm or less. Their small size enables them to enter the respiratory tract, and $PM_{2.5}$ can reach the alveolar region of the lungs. Ultrafine particles, with a diameter of 0.1 µm or less, have specific properties related to their number, surface area and ability to penetrate the body; however, their monitoring is less standardised than that of PM_{10} and $PM_{2.5}$ (Schraufnagel, 2020). Exposure to particulate matter is associated with respiratory and cardiovascular effects and increased mortality, including at low exposure levels (WHO, 2021; Rorat et al., 2021). Because particulate concentrations are generally higher in densely urbanised areas and near roads, urban agriculture sites may be affected by pollution associated with their location (Putaud et al., 2010; Huszar et al., 2024).

After being emitted and transported through the atmosphere, particulate matter may be deposited on soils and plant surfaces. Particles may settle on and adhere to the surfaces of edible plant parts. Some contaminants associated with these particles may also enter plant tissues through the stomata or cuticle; this transfer depends particularly on particle size and composition and on plant characteristics (Schreck et al., 2014; Izquierdo-Díaz et al., 2023). Deposits reaching the soil may also contribute to root uptake. Consumer exposure therefore depends on several mechanisms, among which direct deposition on edible parts is especially important for leafy vegetables. Particulate matter deposited on plant surfaces may persist after washing and contribute to their trace-metal content (Augustsson et al., 2023a, 2023b). Despite the growing importance of urban food production (Orsini et al., 2013; Provent and Raton, 2022), the respective contributions of surface deposition, foliar absorption and root uptake remain insufficiently documented. Characterising the atmospheric environment of sites is therefore a first step towards identifying situations in which direct measurements of crops would be particularly relevant.

Because the environmental context of urban agriculture varies considerably across France, the sites were interpreted using the municipality-level typology developed by Paumelle et al. (2023). This typology distinguishes seven environmental profiles according to urbanisation, landscape and agricultural characteristics. Profile 1 comprises predominantly forested rural municipalities; profile 2, predominantly agricultural rural municipalities; profile 3, diversified rural municipalities; profile 4, predominantly

agricultural peri-urban municipalities; and profile 5, intensive agricultural municipalities under urban influence. Profile 6 corresponds to peripheral urban municipalities and profile 7 to dense urban centres. For the comparative analyses, profiles 1–5 were grouped as the less urbanised reference contexts, whereas profiles 6–7 represented the most urbanised contexts.

In this context, the primary objective was to determine whether urban agriculture sites located in the most urbanised environmental contextswere potentially more exposed to airborne particulate matter than the other sites. Secondary analyses compared urban agriculture sites with organic agricultural parcels belonging to the same grouped environmental contexts and assessed whether their road environments differed from those of town halls located in the same municipalities. Potential exposure was characterised using modelled annual PM_{10} and $PM_{2.5}$ concentrations, road-network length within 500 m buffers and distance to the nearest national road or motorway. Organic agricultural parcels were used as agricultural reference locations, whereas town halls provided urban references for the road indicators.

3. Materials and methods

3.1. Data sources

Several spatial databases were used in this study. The first, referred to as the ‘urban farms’ database, contains 758 urban agriculture sites with primarily social or productive purposes throughout France. The database was compiled manually from information published by the French Association for Professional Urban Agriculture (AFAUP). The geographical coordinates of each site were then identified and added to the database (Fig. 1).

The second database contains organically managed parcels recorded in the French Land Parcel Identification System (Registre parcellaire graphique, RPG). The RPG is a geographical database describing the agricultural blocks and parcels declared annually by farmers under the Common Agricultural Policy. Organic parcels within 50 km of urban agriculture sites were selected to form an agricultural reference group. The same parcel could be selected from the search areas of several urban agriculture sites. However, it was identified as a single entity on the basis of its geographical characteristics for parcel-level analyses. The final database therefore contained 172,455 distinct organic agricultural parcels.

A third database contained the geographical coordinates of town halls in municipalities with at least one urban agriculture site. These coordinates were obtained from the Contours administratifs dataset distributed through data.gouv.fr, which is based primarily on the French National Geographic Institute’s Admin Express product. Because every municipality has a town hall, these locations were used as urban reference points. They were used to determine whether the characteristics observed around urban agriculture sites were specific to those sites or reflected the wider road environment of the municipality in which they were located.

The typology developed by Paumelle et al. (2023) was used to characterise the territorial context of the sites. It classifies French municipalities into seven environmental profiles according to their degree of urbanisation, landscape characteristics and agricultural context (Table 1). Profile 1 corresponds to predominantly forested rural municipalities; profile 2 to predominantly agricultural rural municipalities; profile 3 to diversified rural municipalities; profile 4 to predominantly agricultural peri-urban municipalities; profile 5 to intensive agricultural municipalities under urban influence; profile 6 to peripheral urban municipalities; and profile 7 to dense urban centres. Each urban agriculture site, town hall and organic agricultural parcel was assigned the profile of its municipality, without merging the three databases.

Table 1
Description of the environmental profiles defined by Paumelle et al. (2023)

Profile	Designation	Main characteristics
1	Municipalities dominated by natural areas	High degree of naturalness, low atmospheric and agricultural pollution, and extensive surface-water areas.
2	Municipalities dominated by livestock farming and extensive natural areas	High proportion of grassland and biodiversity reservoirs; high ammonia emissions.
3	Municipalities with extensive and diversified agriculture	Extensive agriculture with substantial livestock farming, low $PM_{2.5}$ concentrations and low urban pressure.
4	Municipalities with intensive agriculture outside urban influence	Intensive agriculture, high pesticide pressure, limited artificial land cover and distance from urban centres.
5	Municipalities with intensive agriculture under urban influence	Intensive specialised agriculture, high pesticide pressure and urban influence.
6	Peripheral urban municipalities	Municipalities on the outskirts of major metropolitan areas, with lower contamination levels than dense urban centres.
7	Dense urban centres	High proportion of artificial land cover, high $PM_{2.5}$ concentrations and a high density of contaminated sites.

The road network was extracted from BD TOPO®, the large-scale vector topographic database of the French National Geographic Institute (IGN). Roads were divided into four classes according to their importance: class 1 comprised national roads and motorways, class 2 departmental roads, class 3 municipal roads and class 4 local roads and tracks.

Finally, mean annual PM_{10} and $PM_{2.5}$ concentrations, expressed in µg/m³, were obtained for urban agriculture sites and organic agricultural parcels. These estimates were derived from a 1 km spatial grid produced by the deterministic CHIMERE chemistry-transport model and made available as public data. Values were assigned to the entities studied according to their geographical location.

3.2. Spatial analysis

All spatial analyses were conducted in QGIS. Two complementary indicators were used to characterise the road environment: road-network length in the immediate surroundings (RNL) and distance to the nearest national road or motorway (DNR).

To analyse local road-network density, a circular buffer with a 500 m radius was created around each urban agriculture site, town hall and organic agricultural parcel. Road segments intersecting each buffer were selected and their cumulative length was calculated. Lengths were determined separately for the four road classes defined above and for the entire road network. The absence of a given road class within a buffer was recorded as a length of zero. Missing values generated by the spatial intersection in this situation were therefore replaced by 0 m before statistical analysis.

To analyse proximity to major roads, only class 1 roads, corresponding to national roads and motorways, were selected. The minimum distance between each entity and the nearest class 1 segment was calculated using the QGIS Join attributes by nearest algorithm. This procedure was applied to urban agriculture sites, town halls and organic agricultural parcels. The resulting distance, expressed in metres, indicates proximity to road infrastructure likely to carry substantial traffic.

Mean annual PM_{10} and $PM_{2.5}$ concentrations were assigned to urban agriculture sites and organic agricultural parcels by spatially joining them to the CHIMERE model grid. Each entity was assigned the value of the 1 km grid cell in which it was located.

At this resolution, the available atmospheric data could not reliably distinguish an urban agriculture site from a town hall located in the same municipality or nearby urban context. Town halls were therefore excluded from PM_{10} and $PM_{2.5}$ comparisons. Atmospheric comparisons involved urban agriculture sites and organic agricultural parcels, whereas town halls were retained as urban reference locations for road-network and road-distance analyses calculated precisely around each location.

3.3. Statistical analysis

Statistical analyses were conducted in R, version 4.5.1. Descriptive analyses were first performed for each variable: road length by class within the buffers, total road-network length, distance to the nearest class 1 road, and PM_{10} and $PM_{2.5}$ concentrations. Counts, means, medians, standard deviations, interquartile ranges, minima and maxima were calculated. Because the distributions were highly skewed, many road-length values were zero and extreme values were present, non-parametric tests were used. These tests were selected on the basis of the characteristics of the data rather than solely on the result of a preliminary normality test.

Urban agriculture sites, town halls and organic agricultural parcels were first compared using Kruskal–Wallis tests. When an overall difference was detected, pairwise comparisons were performed using Dunn’s post hoc test with Bonferroni correction. These analyses were applied separately to the four road classes, total road-network length and distance to the nearest class 1 road.

The distribution of all urban agriculture sites and organic agricultural parcels among the seven environmental profiles was first described using counts and proportions. For urban agriculture sites, PM_{10} and $PM_{2·5}$ concentrations and road indicators were summarised separately for profiles 1–7 to describe the full territorial gradient. Because profiles 1–5 contained relatively few urban agriculture sites, inferential analyses used a prespecified grouped comparison between profiles 6–7 and profiles 1–5, while profile-specific values were retained for descriptive interpretation.

Annual mean PM_{10} and $PM_{2·5}$ concentrations were compared in two complementary steps. First, urban agriculture sites in profiles 6–7 were compared with urban agriculture sites in profiles 1–5. Second, urban agriculture sites were compared with organic agricultural parcels within the same grouped environmental context: profiles 6–7 and profiles 1–5. This grouping separated the most urbanised contexts from the remaining profiles while avoiding multiple profile-specific comparisons based on small numbers of urban agriculture sites.

All two-group particulate comparisons used Wilcoxon–Mann–Whitney tests. P values within each comparison family were adjusted using the Holm method, and rank-biserial correlations were calculated to estimate the magnitude and direction of the effects. Because CHIMERE values may be shared by several sites in the same municipality or grid cell, the resulting contrasts describe differences in modelled environmental context rather than independent individual exposure measurements.

For road indicators, profiles 1–7 were first described separately. Urban agriculture sites in profiles 6–7 were then compared with the 107 urban agriculture sites in profiles 1–5. Comparisons with organic agricultural parcels were performed within the same grouped environmental contexts: profiles 6–7 and profiles 1–5. Wilcoxon–Mann–Whitney tests and rank-biserial correlations were calculated for the four road classes and total road length; the five p values within each comparison family were adjusted using the Holm method.

Associations between particulate concentrations and road indicators were assessed among the 651 urban agriculture sites in profiles 6–7 considered as a single group. The four road classes and total road length were analysed separately for PM_{10} and $PM_{2·5}$ using Spearman correlations. The ten p values were adjusted using the Holm method.

The comparison between urban agriculture sites and town halls was supplemented by a within-municipality analysis. Each urban agriculture site was paired with the town hall in its municipality using the municipal INSEE code. For each road indicator, the difference between the value at the site and that at the corresponding town hall was calculated. A positive value indicated a greater road length around the urban agriculture site; for distance, the indicator was oriented so that a positive value indicated that the site was closer to a class 1 road than the town hall in the same municipality. The main analysis assigned equal weight to each site while accounting for the clustering of sites within municipalities. A sensitivity analysis based on mean differences by municipality was also performed so that each municipality contributed equally, irrespective of the number of sites it contained.

To limit the risk of error associated with multiple testing, p values belonging to the same family of indicators were adjusted using the Holm method. Bonferroni correction was retained for post hoc comparisons following Kruskal–Wallis tests. Statistical significance was set at 0.05. The number of observations available was reported for each analysis, and missing values were not imputed, except for road lengths, for which the absence of a road segment within a buffer explicitly corresponded to a value of 0 m.

4. Results

4.1. Environmental profiles of urban agriculture sites and organic agricultural parcels

The distribution of urban agriculture sites and organic agricultural parcels across the seven environmental profiles differed markedly between the two groups (Fig. 2).

Among the 758 urban agriculture sites surveyed, 526 were located in profile 7, corresponding to dense urban centres, and accounted for 69.4% of the sites. Profile 6, comprising peripheral urban municipalities, contained 125 sites (16.5%). Together, profiles 6 and 7 contained 651 urban agriculture sites, representing 85.9% of the database. Profile 2 contained 48 sites (6.3%), whereas profiles 1, 3, 4 and 5 each accounted for between 1.6% and 2.4% of the sites. The presence of 48 urban agriculture sites in profile 2 may appear unexpected because this profile corresponds to predominantly agricultural rural municipalities with extensive natural areas. This finding can be partly explained by the fact that classification as urban agriculture was based on the characteristics and functions of the identified projects, whereas the environmental profile was assigned to the municipality as a whole. Some projects may therefore be located in small municipalities or in territories with predominantly rural characteristics.

The distribution of organic agricultural parcels was different. Of the 172,455 distinct parcels, 162,390 could be assigned an environmental profile. The remaining 10,065 parcels intersected several municipalities with different profiles and were excluded from this analysis to avoid arbitrary assignment. Profile 2 was the most common, with 60,900 parcels (37.5%). It was followed by profile 4, with 36,971 parcels (22.8%), and profile 6, with 32,084 parcels (19.8%). Profiles 3 and 1 accounted for 9.7% and 7.9% of the parcels, respectively. Profiles 5 and 7 were the least common, accounting for 1.3% and 1.1% of organic agricultural parcels, respectively.

4.2. Exposure to atmospheric particulate matter

4.2.1. Particulate concentrations at urban agriculture sites

Across the seven profiles, median PM_{10} concentrations at urban agriculture sites were 17.09, 17.77, 17.94, 18.18, 21.76, 18.75 and 22.56 µg/m³ for profiles 1–7, respectively. The corresponding $PM_{2.5}$ medians were 11.53, 11.75, 12.19, 12.04, 14.88, 12.35 and 15.13 µg/m³. These descriptive values show

an overall increase towards the most urbanised contexts, although profiles 1, 3, 4 and 5 contained only 12–18 sites each and were therefore not interpreted through separate pairwise tests.

4.2.2. Comparison of profiles 6–7 with profiles 1–5

Atmospheric particulate concentrations at urban agriculture sites in profiles 6 and 7 were also compared with those at the 107 sites in profiles 1–5. Median PM_{10} concentrations were 22.27 µg/m³ [19.50–22.77] and 18.09 µg/m³ [17.62–18.97], respectively; corresponding $PM_{2.5}$ medians were 14.56 µg/m³ [12.91–15.13] and 11.87 µg/m³ [11.59–12.59]. Concentrations were higher in profiles 6–7 for both PM_{10} and $PM_{2.5}$ (adjusted $p < 0.001$; rank-biserial correlations = 0.66 and 0.64).

4.2.3. Comparison with organic agricultural parcels in the same grouped environmental contexts

In profiles 6–7, urban agriculture sites had greater road lengths than organic agricultural parcels for all four road classes and for the total network. Mean total road length within 500 m was 4,754 m around urban agriculture sites and 1,545 m around organic parcels; medians were 4,800 and 1,220 m, respectively. The difference was large (adjusted $p < 0.001$; rank-biserial correlation = 0.66). In profiles 1–5, mean total road length was 1,580 m around urban agriculture sites and 1,046 m around organic parcels; medians were 1,482 and 1,032 m. Differences were detected for class 2 (adjusted $p = 0.013$), class 4 (adjusted $p < 0.001$) and total road length (adjusted $p < 0.001$), whereas classes 1 and 3 did not differ after Holm correction.

Among profiles 1–5, the 107 urban agriculture sites also had higher concentrations than the 134,251 organic agricultural parcels, although the differences were much smaller. PM_{10} medians were 18.09 and 17.84 µg/m³, respectively (adjusted $p = 0.018$; rank-biserial correlation = 0.13), and $PM_{2.5}$ medians were 11.87 and 11.68 µg/m³ (adjusted $p < 0.001$; rank-biserial correlation = 0.23). These effect sizes were small.

Town halls were not included in the particulate-matter comparisons. At the 1 km resolution of the CHIMERE model, a town hall and an urban agriculture site located in the same municipality or nearby urban area may share the same modelled concentration. Such a comparison would therefore not provide an independent local atmospheric reference.

4.3. Road environment

4.3.1. Road environment of urban agriculture sites

The descriptive analysis of all seven profiles also showed a territorial gradient in road-network development. Median total road length within 500 m was 1,555, 1,116, 1,214, 1,115, 1,834, 1,702 and 5,501 m for profiles 1–7, respectively. Profiles 1–5 each contained few urban agriculture sites, so these profile-specific values describe context rather than supporting multiple pairwise inferences.

4.3.2. Comparison of profiles 6–7 with profiles 1–5

Road lengths at sites in profiles 6 and 7 were also compared with those at the 107 sites in profiles 1–5. Mean total road length was 4,754 m in profiles 6–7 and 1,580 m in profiles 1–5; medians were 4,800 and 1,482 m. Lengths were higher in profiles 6–7 for all four road classes and for the total network (adjusted $p < 0.001$).

4.3.3. Comparison with organic agricultural parcels in the same grouped environmental contexts

Within the same environmental profile, urban agriculture sites also had a more developed road network than organic parcels. In profile 6, mean total road length was 2,144 m around urban agriculture sites and 1,489 m around organic parcels; differences involved classes 3 and 4. In profile 7, mean total road length was 5,374 and 2,574 m, respectively, and all four road classes were longer around urban agriculture sites.

4.3.4. Road-network comparison with town halls

To place the road environment of urban agriculture sites in an urban reference context, road lengths within the 500 m buffers were compared among the 651 urban agriculture sites in profiles 6–7, the corresponding town halls and the organic agricultural parcels. Lengths differed among the three groups for all four road classes and for the total network (Kruskal–Wallis tests, adjusted $p < 0.001$ for each of the five indicators; Fig. 3).

For class 1 roads, comprising national roads and motorways, mean road length was 403 ± 845 m around urban agriculture sites, 80 ± 416 m around organic agricultural parcels and 71 ± 371 m around town halls. The median was zero in all three groups because these roads were absent from most buffers. Nevertheless, a class 1 road was present around 22.4% of urban agriculture sites, compared with 4.3% of organic parcels and 5.3% of town halls. Road lengths were greater around urban agriculture sites than around both reference groups (adjusted $p < 0.001$), whereas no difference was detected between organic parcels and town halls (adjusted $p = 0.484$).

For class 2 roads, mean length was 676 ± 1,210 m around urban agriculture sites, 429 ± 816 m around town halls, and 156 ± 483 m around organic parcels. The class occurred in 34.3%, 28.3%, and 12.7% of buffers, respectively. Lengths were greater around urban agriculture sites than around organic parcels (adjusted $p < 0.001$) and town halls (adjusted $p = 0.014$).

Mean class 3 road length was 1,449 ± 1,459 m around urban agriculture sites, 1,107 ± 1,147 m around town halls and 276 ± 544 m around organic agricultural parcels. Road lengths were greater around urban agriculture sites and town halls than around organic parcels (adjusted $p < 0.001$ in both cases). After correction across the full family of comparisons, the difference between urban agriculture sites and town halls did not reach statistical significance (adjusted $p = 0.056$).

For class 4 roads, mean lengths were 2,226 ± 1,707 m around urban agriculture sites, 1,936 ± 1,191 m around town halls and 638 ± 756 m around organic agricultural parcels. Road lengths were lower around

organic parcels than around the two urban groups (adjusted $p < 0.001$), whereas no difference was detected between urban agriculture sites and town halls (adjusted $p = 0.247$).

Across all classes, mean total road-network length was 4,754 ± 2,870 m around urban agriculture sites and 3,543 ± 1,842 m around town halls, compared with 1,150 ± 1,117 m around organic parcels. Medians were 4,800, 3,179 and 1,063 m, respectively. Organic parcels differed from both urban groups (adjusted $p < 0.001$), whereas urban agriculture sites and town halls did not differ (adjusted $p = 0.772$).

Table 2
Pairwise comparisons of road lengths within 500 m buffers. P values were adjusted using the Holm method across all road comparisons

Indicator	UA vs organic	UA vs town hall	Organic vs town hall
Class 1	< 0.001 (***)	< 0.001 (***)	0.772 (ns)
Class 2	< 0.001 (***)	0.014 (*)	< 0.001 (***)
Class 3	< 0.001 (***)	0.056 (ns)	< 0.001 (***)
Class 4	< 0.001 (***)	0.370 (ns)	< 0.001 (***)
All classes	< 0.001 (***)	0.772 (ns)	< 0.001 (***)

Distance to the nearest class 1 road

Urban agriculture sites were closer to national roads and motorways than town halls and organic agricultural parcels (Fig. 4). Distance to the nearest class 1 road differed among the three groups (Kruskal–Wallis test, $p < 0.001$).

For the 651 urban agriculture sites in profiles 6 and 7, mean distance to the nearest class 1 road was 2,301 ± 3,520 m and the median was 1,493 m; half of the observations ranged from 690 to 2,682 m.

Town halls occupied an intermediate position, with a mean distance of 4,624 ± 6,046 m and a median of 2,400 m for the 304 locations studied. The interquartile range extended from 1,354 to 5,781 m.

Among the 172,455 distinct organic agricultural parcels, distance data were available for 117,999. These parcels were furthest from class 1 roads, with a mean distance of 8,645 ± 8,265 m and a median of 6,075 m. Half of the distances ranged from 2,727 to 11,557 m.

Post hoc comparisons indicated that all three groups differed pairwise: urban agriculture sites were closer to class 1 roads than town halls and organic agricultural parcels, whereas town halls were closer than organic parcels (adjusted $p < 0.001$ for all three comparisons).

Within-municipality road comparison with town halls

The within-municipality comparison included all 651 urban agriculture sites in profiles 6 and 7. These sites were distributed across 210 municipalities, and all had a reference town hall and complete data for

the indicators studied (Fig. 5).

When each urban agriculture site received equal weight, class 1 road length was 329 m greater around sites than around their municipal town hall (95% CI: 254 to 404 m; adjusted $p < 0.001$), whereas class 3 road length was 601 m shorter (95% CI: −822 to − 379 m; adjusted $p < 0.001$). Differences were not significant for class 2 (+ 264 m; adjusted $p = 0.375$), class 4, or total road length.

A sensitivity analysis giving equal weight to each of the 210 municipalities confirmed greater class 1 and shorter class 3 road lengths around urban agriculture sites, with no difference for class 2. Class 4 and total road lengths were also shorter around the sites. Distance to a class 1 road was 229 m shorter than for town halls (95% CI: −381 to − 77 m; adjusted $p = 0.003$).

Urban agriculture sites were, on average, 989 m closer to a class 1 road than the town hall in the same municipality. However, the confidence interval included zero by a small margin (95% CI: −1,995 to 17 m), and the result was at the threshold of statistical significance after correction for multiple comparisons (adjusted $p = 0.054$). At the individual level, 466 of the 651 sites (71.6%) were closer to a class 1 road than their reference town hall.

When each municipality was given equal weight, urban agriculture sites were, on average, 229 m closer to the nearest class 1 road than town halls (95% CI: −381 to − 77 m; adjusted $p = 0.003$).

Differences between weighting strategies for some variables show that class 4 and total road-length results partly depended on the number of sites recorded per municipality. Both analyses nevertheless supported a robust finding: within the same municipality, urban agriculture sites had greater class 1 and shorter class 3 road lengths than town halls, with no within-municipality difference for class 2.

4.4. Associations between road environment and particulate concentrations

Among urban agriculture sites in profiles 6–7, PM_{10} and $PM_{2.5}$ were positively correlated with class 3 road length ($\rho = 0.30$ and 0.37), class 4 road length ($\rho = 0.41$ and 0.44), and total road length ($\rho = 0.47$ and 0.51; adjusted $p < 0.001$). No association was detected for classes 1 or 2.

5. Discussion

5.1. Environmental context and particulate exposure of urban agriculture sites

The urban agriculture sites identified in France were mainly located in the most urbanised environments. Of the 758 sites surveyed, 651 (85.9%) belonged to profiles 6 and 7 defined by Paumelle et al. (2023), corresponding to peripheral urban municipalities and dense urban centres, respectively. Profile 7 alone contained 69.4% of the sites. This distribution confirms the predominantly metropolitan setting of urban

agriculture described in the literature, where its development is associated with population concentration, demand for local produce, citizen initiatives and urban greening policies (Fleury and Donadieu, 1997; Orsini et al., 2013; Nahmias and Le Caro, 2012; Provent and Raton, 2022).

This preferential location clearly distinguished urban agriculture sites from organic agricultural parcels. The latter were distributed across a wider range of territorial profiles, particularly profiles 2, 4 and 6, and therefore represented more diverse rural, peri-urban and urban contexts. The comparison thus concerned structurally different production environments: sites integrated into the urban fabric and agricultural parcels located mainly in less densely urbanised areas.

The grouped comparison showed that urban agriculture sites in profiles 6–7 had substantially higher PM_{10} and $PM_{2.5}$ concentrations than urban agriculture sites in profiles 1–5. Comparisons with organic agricultural parcels clarified this gradient. In profiles 6–7, the differences between the two site types remained pronounced, whereas in profiles 1–5 they were statistically detectable but small. The environmental context was therefore the dominant source of contrast, although site type and precise location may contribute additional variation within a given grouped context.

5.2. Road environment and comparisons with agricultural and municipal references

Road-network indicators supported the same interpretation. Urban agriculture sites in profiles 6–7 had a more developed surrounding road network than urban agriculture sites in profiles 1–5. When urban agriculture sites were compared with organic parcels within the same grouped environmental contexts, road lengths remained greater around urban agriculture sites in profiles 6–7. In profiles 1–5, the contrast was more limited: differences remained for class 2, class 4 and total road length, whereas classes 1 and 3 did not differ after correction. These results distinguish the contribution of the broader territorial context from differences associated with the local position of the sites.

Road proximity and network density in the immediate surroundings of urban agriculture sites indicate potential exposure to traffic-related emissions. Road transport contributes to particulate emissions through exhaust gases and through brake, tyre and road-surface wear and the resuspension of deposited particles (Harrison et al., 2021; Fussell et al., 2022). Road density alone cannot quantify these emissions because it provides no direct information on traffic intensity, vehicle-fleet composition, meteorological conditions or the built environment, all of which influence pollutant dispersion. The indicators used should therefore be regarded as markers of the traffic-related exposure context. Despite these limitations, road-network density and proximity are useful spatial indicators for identifying, at a large scale, urban agriculture sites that may require more detailed local characterisation.

Using town halls as a reference group distinguishes the general urban context from the specific location of urban agriculture sites. Located in the same municipalities and embedded in the urban fabric, town halls provide a more relevant benchmark than rural locations for this question. Sites and town halls did not differ in class 3, class 4, or total road length, but sites had greater class 1 and class 2 lengths.

The within-municipality comparison further reduced contextual differences among municipalities. Urban agriculture sites had greater national-road and motorway lengths than town halls, and 71.6% were closer to a class 1 road than their reference town hall. Potential exposure therefore depends not only on being located in a city but also on the site's position within the urban fabric. These indicators do not, however, demonstrate crop contamination or increased health risk.

Differences in the other road classes should be interpreted in relation to urban-network structure. Class 3 road length was shorter around urban agriculture sites than around town halls, whereas class 2 did not differ. Scientifically, this finding shows that total road length alone is insufficient to characterise potential exposure: network composition and road function must also be considered.

Together, these findings refine the results of the comparison with organic agricultural parcels. The greater potential road-related exposure of urban agriculture sites largely reflected their location in densely urbanised areas, but the within-municipality comparison showed that their position within these areas could also bring them closer to major road infrastructure. The observed pattern therefore depended both on the broader urban context and on the position of sites within municipalities. The importance of location within the urban fabric is consistent with local observations in several cities. In Berlin, Säumel et al. (2012) showed that traffic load, distance from roads and physical barriers were associated with trace-element concentrations measured in urban crops. In São Paulo, Amato-Lourenço et al. (2016) also observed a relationship between traffic intensity and the accumulation of metallic elements in leafy vegetables. These studies indicate that crop exposure depends on the precise location of sites relative to road sources as well as on the urban character of the wider area. The present study extends this finding to the national scale by showing that urban agriculture sites may occupy different positions within a municipality from an urban reference location.

5.3. Relationship between road indicators and particulate concentrations

Among urban agriculture sites in profiles 6–7, PM_{10} and $PM_{2.5}$ concentrations increased with class 3 and class 4 road lengths and with total road-network length, whereas no association was observed for classes 1 or 2. This pattern suggests that annual modelled concentrations reflected the overall intensity of the urban road fabric more strongly than the local presence of a major road alone. It is consistent with studies linking road-network characteristics, traffic intensity and proximity to roads with spatial variability in urban particulate matter (Lee et al., 2015; Suleiman et al., 2016). The absence of an association with classes 1 and 2 does not exclude a local influence because these roads were absent from many buffers and the kilometre-scale CHIMERE grid cannot represent near-road gradients. Road lengths also provide no direct information on traffic intensity, and the correlations do not demonstrate causality.

5.4. Study scope and limitations

The statistical significance of the concentration differences does not, by itself, establish whether they produce a measurable increase in particle deposition on plants, crop contamination or health risks to

consumers. The large difference in sample size between groups increases statistical power, but the large effect sizes indicate that the result was not attributable solely to the high number of organic agricultural parcels. Mean differences nevertheless remained within a few micrograms per cubic metre and should be interpreted in light of the spatial and temporal resolution of the data.

PM_{10} and $PM_{2.5}$ concentrations were based on annual estimates from the CHIMERE model. They describe the general atmospheric context of the sites but do not directly measure concentrations at crop level. In particular, kilometre-scale resolution cannot accurately capture variations in the immediate vicinity of a road, within a street canyon or inside a vegetated area. This limitation has also been described in urban modelling studies using CHIMERE, which show that model resolution, the accuracy of emission data and the representation of meteorological conditions affect the reproduction of local concentrations (Markakis et al., 2015). Local concentrations also depend on meteorological conditions, urban morphology, traffic characteristics and the presence of physical or vegetative barriers. Despite these limitations, the modelled data permit a consistent comparison of the atmospheric context of many sites across France and help identify those for which local measurements should be prioritised.

5.5. From potential atmospheric exposure to crop contamination

Atmospheric exposure at a site must also be distinguished from actual contamination of its produce. Higher ambient concentrations do not directly demonstrate greater accumulation of particles or associated contaminants in edible plant parts. Deposition depends on particle size and composition, leaf morphology, exposure duration, cultivation practices and post-harvest operations such as washing. The results therefore characterise potential environmental exposure without, by themselves, demonstrating a health risk to consumers. Several studies nevertheless show that traffic-related atmospheric deposition can contribute to the accumulation of metallic elements on edible plant parts, particularly in leafy species. This contribution varies with traffic intensity, distance from roads, the presence of barriers, crop species and washing practices (Säumel et al., 2012; Amato-Lourenço et al., 2016; Xiong et al., 2016). Higher atmospheric concentrations therefore represent a plausible contamination pathway, although they cannot be used to infer the level of contamination of the produce studied.

Field studies have documented particle deposition and associated contaminants on crops grown in urban and roadside environments. In Berlin, trace-element concentrations in vegetables varied with traffic load, crop species, planting system and the presence of buildings that acted as barriers to deposition (Säumel et al., 2012). In São Paulo, standardised spinach and collard greens exposed for 30–90 days in urban gardens accumulated traffic-related elements in relation to traffic density, distance from major roads and the presence of physical barriers (Amato-Lourenço et al., 2016). In Sweden, washing roadside vegetables removed approximately 56% of Pb, 55% of Cr and 33% of Ni, but only 7% of Cd; adhering particles still accounted for 0.05–1.3% of dry mass after washing and contributed to Pb and Cr concentrations (Augustsson et al., 2023a, 2023b). These studies support the plausibility of foliar

deposition but also show that transfer depends on the contaminant, crop, site configuration and post-harvest practices.

5.6. Practical implications and perspectives

This distinction does not reduce the practical value of the results. Identifying sites located in more highly exposed atmospheric contexts can help target situations that require more detailed local characterisation. Direct measurements at the sites, combined with analyses of deposits on vegetation and contamination of edible parts, would establish the extent to which the spatial differences identified translate into differences in the exposure of crops and, potentially, consumers.

Despite these limitations, this study provides an original national characterisation of the atmospheric exposure contexts of urban agriculture sites in France. It combines several complementary data sources: site locations, territorial profiles, road-network structure and modelled atmospheric concentrations. This approach moves beyond a simple comparison of urban and agricultural areas and examines variation among urban contexts and within the same municipality.

The results show that the potential exposure of urban agriculture sites should be assessed at several scales. At the national scale, these sites were mainly located in the most urbanised territorial profiles and had higher particulate concentrations than organic agricultural parcels. At the scale of urban environments, comparison with town halls showed that class 3 and class 4 road lengths and total road-network length were comparable around the two types of location. Finally, the within-municipality comparison showed a greater presence of national roads and motorways around urban agriculture sites, suggesting that their position within municipalities may also contribute to their potential exposure.

This multiscale interpretation is directly relevant to local authorities and site managers. Site creation or redevelopment should consider both territorial profile and the parcel's precise position relative to emission sources. Mapping road classes, distance to major roads and, where available, traffic data can identify sites requiring priority local assessment.

For existing sites near major roads, managers can document the distance between traffic lanes and cultivated areas, site configuration, barriers, crop species and edible organs, and washing practices. Depending on context, this information may guide cultivation towards areas furthest from roads, the selection of species less exposed to foliar deposition, suitable barriers, and targeted measurements in air, soil or plants. Spatial indicators identify potential exposure and investigation priorities; they are not a health-risk assessment.

Further work should now link the spatial indicators to field measurements. Air and atmospheric-deposition sampling campaigns at sites representative of profiles 6 and 7 would test the differences suggested by the modelled data. Simultaneous analysis of particles deposited on leaves, their composition and their persistence after washing would then help determine whether contrasts in environmental exposure translate into differences in the contamination of produce. Combining these

approaches could ultimately support recommendations tailored to site characteristics rather than uniform rules for all forms of urban agriculture.

6. Conclusion

This study investigated whether urban agriculture sites in France are located in environments with greater potential exposure to airborne particulate matter than organic agricultural parcels, and whether this pattern is explained mainly by their location in the urban fabric or also by their particular position within municipalities.

Urban agriculture sites were concentrated mainly in the most urbanised territories. Of the 758 sites surveyed, 651 (85.9%) belonged to profiles 6–7. Compared with the 107 urban agriculture sites in profiles 1–5, these sites had higher PM_{10} and $PM_{2.5}$ concentrations and a more developed surrounding road network. The grouped environmental context was therefore a major determinant of potential atmospheric exposure.

Comparisons with organic agricultural parcels refined this conclusion. Within profiles 6–7, urban agriculture sites had substantially higher particulate concentrations and greater surrounding road lengths than organic parcels. Within profiles 1–5, particulate differences were small and road differences were limited to class 2, class 4 and total road length. The contrast between urban agriculture and organic agriculture therefore varied with environmental context.

Comparison with town halls provided a more precise interpretation of this finding. Several road-network characteristics around urban agriculture sites were comparable to those of an urban reference environment. However, within-municipality analyses showed greater class 1 road length around urban agriculture sites and indicated that 71.6% of them were closer to these major roads than their reference town hall. The observed potential exposure therefore reflected both the location of sites in highly urbanised territories and, in many municipalities, their particular position relative to major road infrastructure.

These results do not directly demonstrate contamination of agricultural produce or a health risk to consumers. They nevertheless provide a consistent characterisation of the potential environmental exposure of the sites and identify situations in which local investigations would be especially relevant. Direct measurements in the air, on plant surfaces and in edible plant parts will be required to establish the relationship between territorial context, particle deposition and actual contamination of produce.

The approach developed here therefore provides a methodological basis for integrating atmospheric environmental quality into the assessment of urban agriculture projects. It highlights the value of jointly considering territorial profile, road-network structure and proximity to major roads when selecting or characterising sites. This approach could help guide monitoring campaigns and support recommendations adapted to local conditions while facilitating the development of forms of urban agriculture compatible with environmental-health objectives.

Declarations

Conflicts of interest:

The authors declare that they have no competing interests.

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Author Contribution

S.B. contributed to the conceptualization and methodology of the study, data collection and curation, formal analysis, investigation, visualization, and preparation of the original manuscript. M.P. provided the environmental-profile typology and contributed to the validation of the analyses. L.C. and A.D. contributed to the conceptualization, methodology, supervision, project administration, and validation of the study. S.B., L.C., and A.D. contributed to funding acquisition. All authors reviewed and edited the manuscript and approved the final version.

Data and code availability:

The datasets generated and analysed during the current study, as well as the analysis code, are not publicly available but may be obtained from the corresponding author upon reasonable request.

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Figures

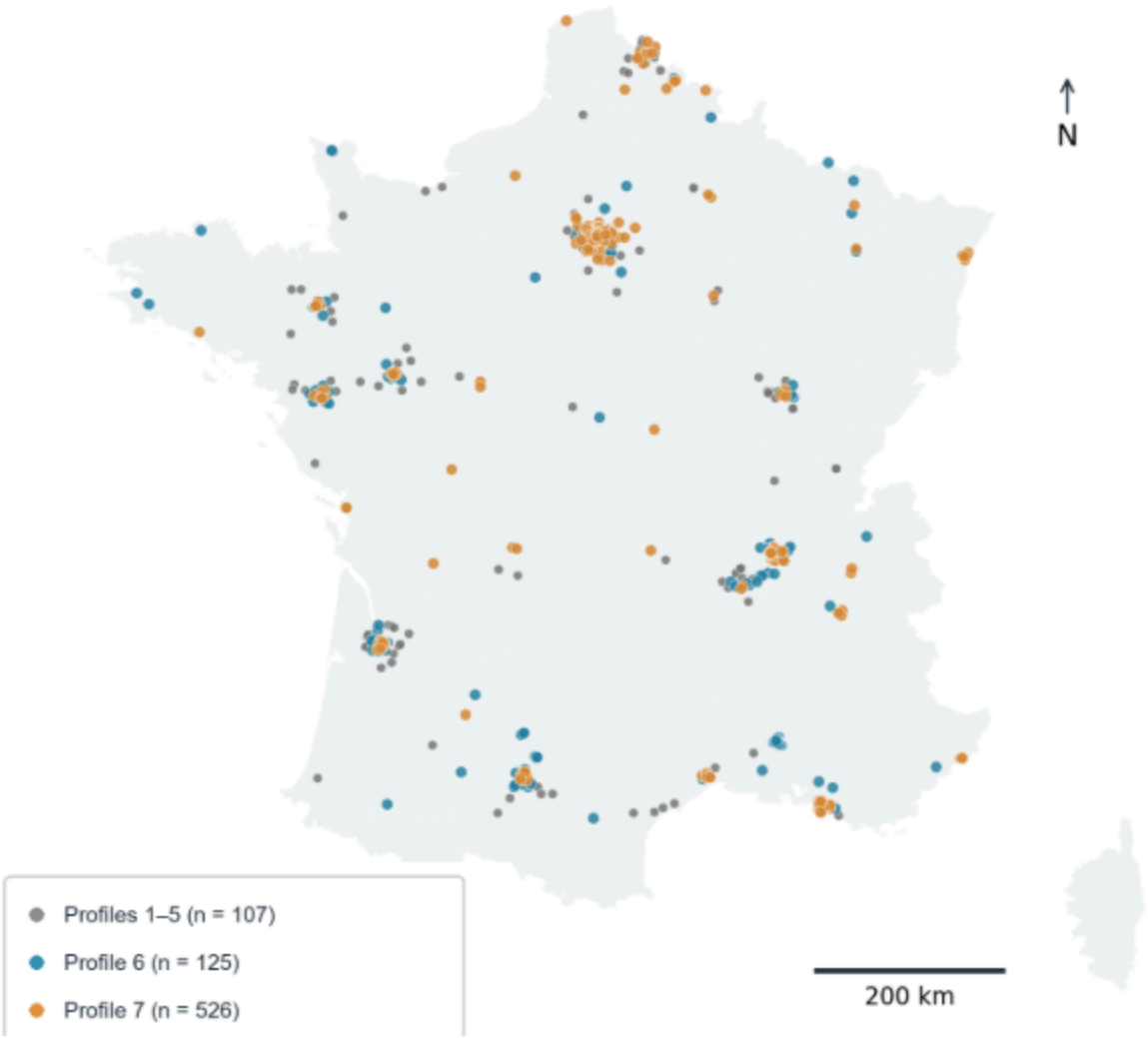


Figure 1

Locations of the 758 urban agriculture sites assigned an environmental profile. Symbols distinguish profiles 6 and 7 from profiles 1–5

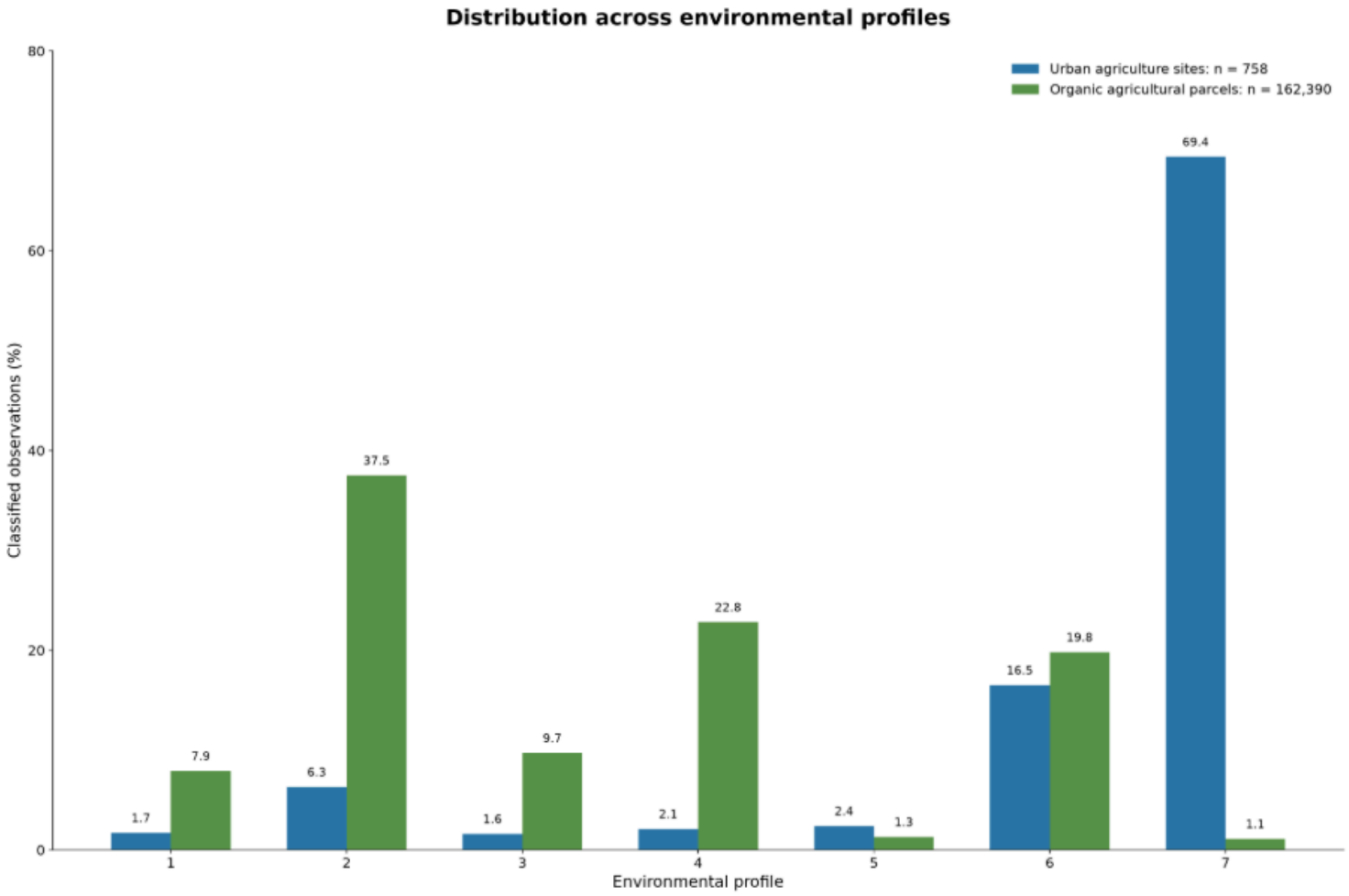


Figure 2

Distribution of urban agriculture sites and organic agricultural parcels among the seven environmental profiles defined by Paumelle et al. (2023). Percentages were calculated separately for each group from the entities that could be assigned a profile

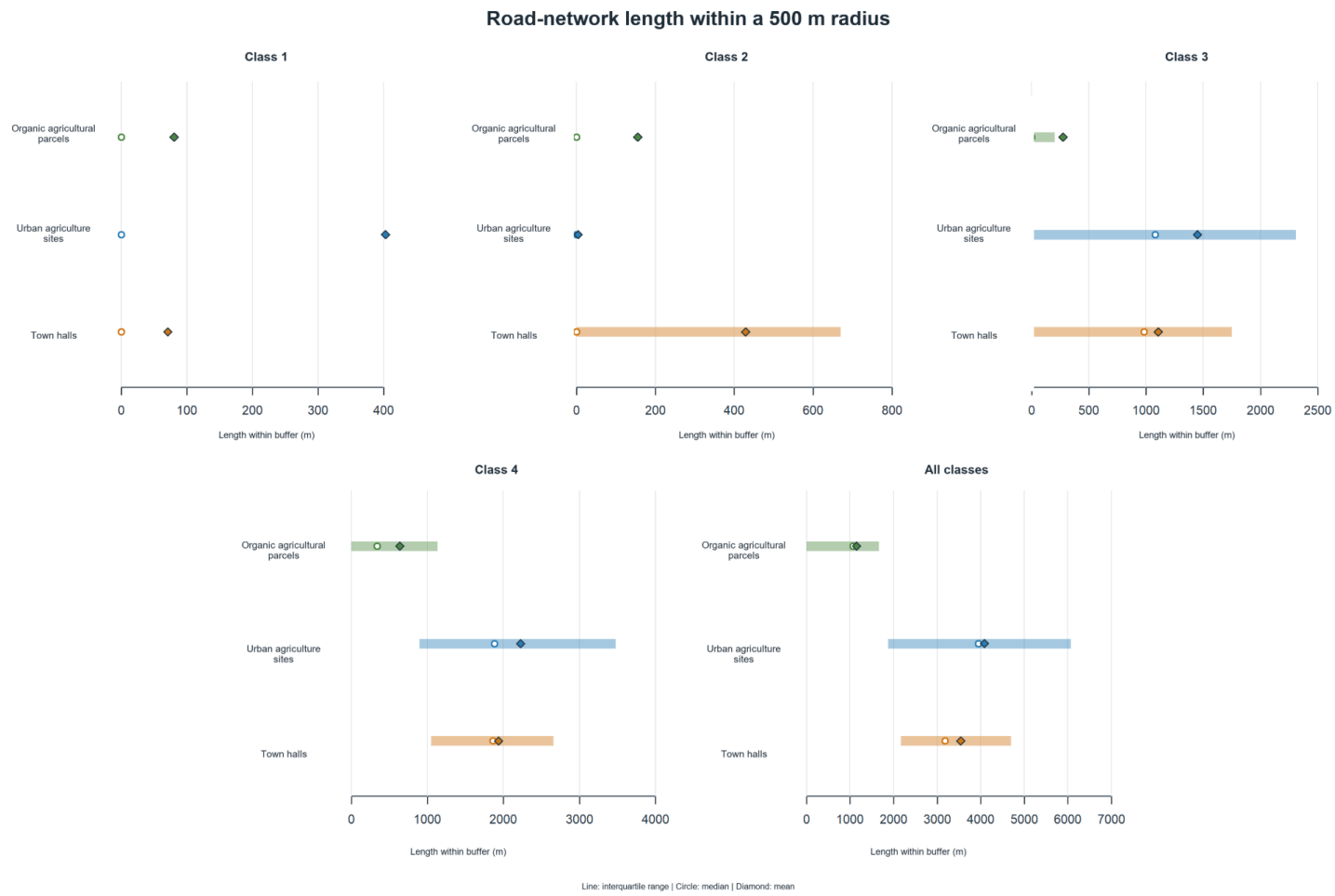


Figure 3

Distribution of road lengths within 500 m buffers around urban agriculture sites (n = 651), town halls (n = 304), and organic agricultural parcels (n = 172,455), by road class and for the entire network. Lines represent interquartile ranges, circles medians, and diamonds means. Zero values indicate absence of the relevant road class

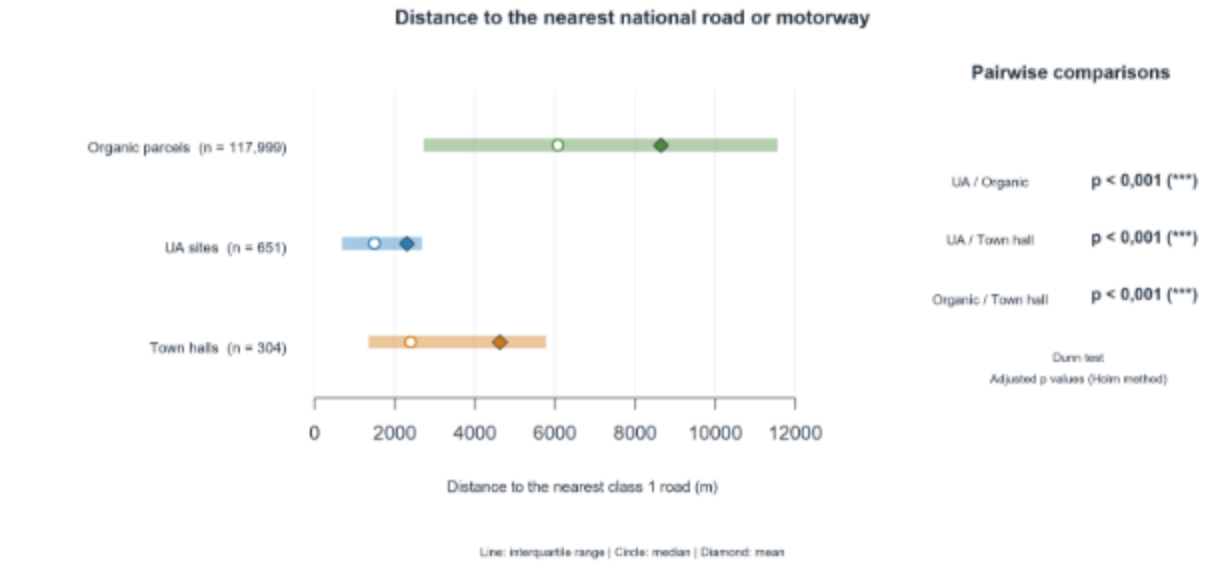


Figure 4

Distance to the nearest national road or motorway for urban agriculture sites in profiles 6 and 7, town halls, and organic agricultural parcels. Lines represent interquartile ranges, circles medians, and diamonds means. Pairwise Dunn tests were Holm-adjusted; ***, p < 0.001

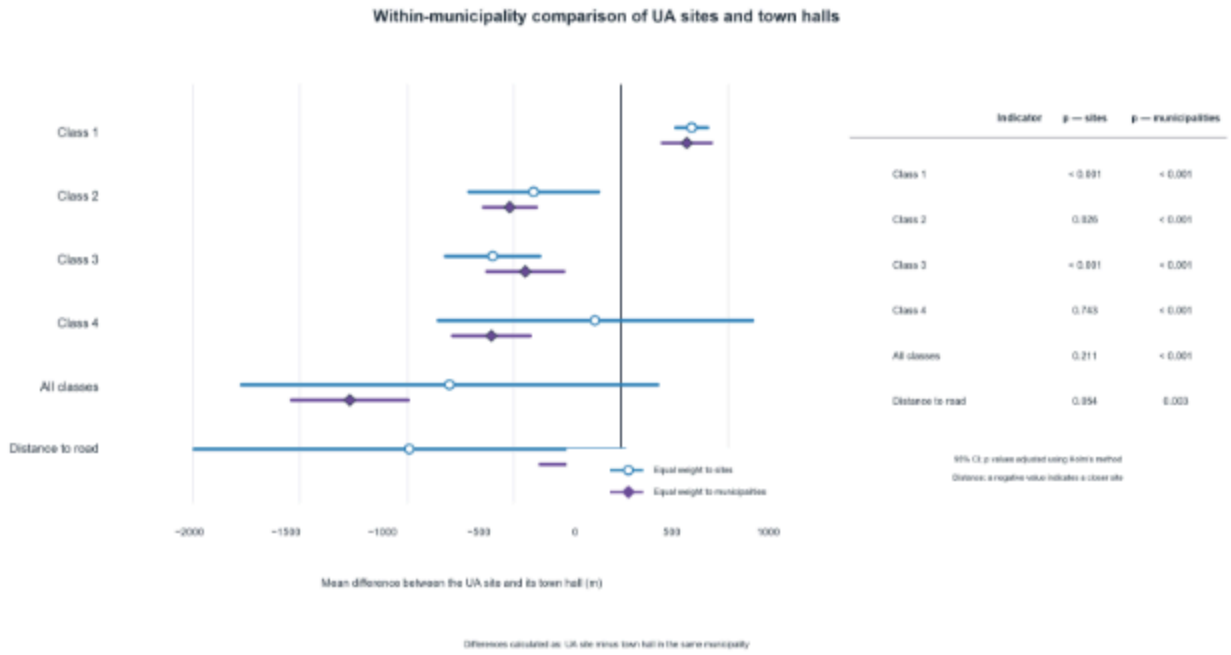


Figure 5

Within-municipality comparison of road characteristics around urban agriculture sites and town halls. Differences are the site value minus the town-hall value, in metres. Points represent mean differences and segments 95% confidence intervals. Positive road-length values indicate greater lengths around sites; a negative distance indicates that the site is closer to a class 1 road