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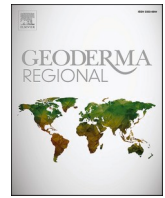
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# Impacts of soil de-sealing practices on urban land-uses, soil functions and ecosystem services in French cities

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## ABSTRACT

Soil sealing has been recognised as one of the main causes of urban soil degradation in Europe. To tackle this issue, de-sealing measures have recently been promoted in cities to increase the sustainability of soil ecosystem services. To our knowledge, very few evaluations of de-sealing projects have as yet been done to assess the current framework of these urban planning practices. Therefore, we conducted an online survey to collect and analyse soil de-sealing projects throughout mainland France. A 60-question survey was run over a 4-month-period, and data about 57 projects were collected. The answers covered a diversity of projects, structures and stakeholders and included data such as the location / objectives / costs and benefits of the projects implemented in cities of various sizes. A typology of urban land-uses before and after de-sealing was defined. Among the diverse objectives of de-sealing, rainwater management, reducing urban heat, and greening were most frequent. More than half of the respondents (64%) indicated that ecosystem services were used to drive their de-sealing project. The methods usually required excavation of the sealing cover and road layers being replaced by newly imported fertile materials. Recent de-sealing projects have reused derelict materials from the site (soil-material inventory) and/or local urban waste for soil construction, which can help minimise both the economic and environmental costs of urban greening projects. The results of this study provide quite an exhaustive view of current French de-sealing practices and could provide guidelines for improving soil functions by applying soil engineering processes to construct sustainable fertile soils for urban greening.

## 1. Introduction

Urbanisation-related artificialisation alters natural ecosystems and especially their soil compartment. Artificialisation processes including soil sealing, excavation and storage, inputs of exogenous materials, mixing of different soil horizons and compaction, and dramatically impact soils. Soil sealing resulting in Ekranic Technosols (IUSS Working Group WRB, 2022) consists in covering the soil with buildings or impervious artificial materials (e.g., asphalt, concrete or pavers), so that exchanges between the soil and other environmental compartments are limited or prevented. This strongly modifies biochemical and

hydrological cycles locally. Moreover, soil sealing fragments the landscape and leads to an overall loss of biodiversity (loss of habitats and connectivity) and functioning soils (through modifications of the physical and chemical conditions of the soils) (European Commission, 2012; Prokop and Salata, 2017; Raciti et al., 2012). Imperviousness is considered to be the main cause of the reduced capacity of soils to provide expected ecosystem services in cities such as flood risk and stormwater runoff management, or the contribution to microclimate regulation and thermal comfort (Hanna et al., 2023). Yet, the surface area of sealed soil surfaces has been increasing in all European countries over recent decades, with an average annual increase of 429 km<sup>2</sup>

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between 2006 and 2015 in 39 European countries – 4 times the surface of Paris (EEA European Environment Agency, 2021). In 2018, France was the country with the highest sealed surface area in Europe: impervious surfaces represented 3.96% of the mainland French territory, with a 52% increase since 1982. Soils sealed for transport infrastructures (roads, car parks, tracks, railways) accounted for 37% of the artificialised soils (i.e. 2.2 million hectares), representing more than constructed areas (850,000 ha) (Agreste, 2021).

No binding documents are currently published by the European Commission to state common targets and guidelines for limiting, mitigating and compensating for soil sealing (European Commission, 2012; Prokop and Salata, 2017). Still, the growing awareness of citizens and lawmakers of the need to adapt cities to climate change (in particular to high-intensity rainfalls and heat waves), together with a general expectation of an improved life quality in cities have recently fostered the need for de-sealing measures and soil renaturation (European Commission, 2012). This has been specifically implemented in recent French legislation, in particular with the 2021 Climate-Resilience Law, which aims to halve the rate of artificialisation between 2021 and 2031 compared to the previous ten years and to achieve the objective of ‘zero net artificialisation’ by 2050 (Desrousseaux, 2018). All these objectives must be translated into planning and urban development documents at the regional level and implemented at the inter-municipal and communal levels. One of the ways of achieving the ‘no net land take’ target is to de-seal soils (European Commission, 2016). De-sealing can enable the soil to regain certain functions altered by sealing. This is why the EU strategy proposes a target of zero net loss of urban green space by 2030, and a total increase in urban green space coverage by 2040 and 2050 (European Commission, 2020). However, there is no single definition of de-sealing, as this is a rather new concept. De-sealing procedures commonly consist in removing the impermeable covering layer, decompacting and replacing the underlying materials or restructuring the soil profile in order to re-establish an effective connection with the subsoil and develop a new soil use or to replace it by a more permeable cover (European Commission, 2012; Tobias et al., 2018; Maienza et al., 2021). However, reusing or recycling materials from a de-sealing project is in accordance with the 2015 French law “Energy transition for green growth” that sets the State and local authorities the objective of recovering at least 70% of the materials and waste produced on construction sites when they are the contracting authority.

Scientific literature about the effects of de-sealing on soil functioning and on the nature of the soils underneath the sealed surfaces is scarce, and information about de-sealing projects is scattered in the so-called ‘grey literature’. As a result, many regional and local de-sealing initiatives have been implemented in response to varied objectives like favouring water infiltration to reduce the risk of flooding, reducing heat islands, promoting biodiversity, and making the landscape more aesthetically pleasing. However, information on de-sealing projects is often very vague and does not provide an assessment of the benefits actually obtained in terms of ecosystem services and soil functioning. No real guidelines or recommendations are currently available for optimising de-sealing projects, or providing tools to enhance ecosystem services provided by de-sealed soils while minimising resource use. The research project named DESSERT (De-sealing of soils, ecosystem services and territory resilience – 2020-2024) supported by the French Agency for Ecological Transition (ADEME) aims to inventory soil de-sealing practices. The main objective is to acquire scientific knowledge about de-sealed soils to provide tools for urban stakeholders and design and implement soil de-sealing practices aimed at improving soil functions and ecosystem services. Within this project, the present work aims to provide an overview of de-sealing projects in French cities. The study should improve our knowledge to assess the objectives and techniques of de-sealing projects as well as the land-use changes induced in urban environments. To do so, information on soil de-sealing projects was collected using an online survey and through direct interactions with urban operators. Quantitative and qualitative data were gathered

in a database and analysed to draw an initial picture of soil de-sealing practices and propose future lines of research.

## 2. Materials and methods

Given the scarce sufficiently detailed data in the scientific and grey literature, two complementary strategies were implemented to compile a database on French de-sealing projects: i) a survey was developed using the LimeSurvey web application, and ii) two partners of the DESSERT project (an engineering office and a landscaping company) provided detailed information – based on the questionnaire – on soil de-sealing projects in which they were involved as urban operators to complete the database.

### 2.1. Structure of the survey

The introduction of the survey stated that the targeted projects were considered to be de-sealing projects if the impervious surface material was removed or the impervious surface was replaced by a pervious one. Projects involving above-ground structures such as green roofs, urban gardens in containers or modular green walls were ignored. The survey consisted of approximately sixty independent mostly semi-open questions (multiple choice with single or multiple answers) and no questions were mandatory. The questions were divided into seven thematic groups supporting a same idea (Table 1; the complete questionnaire is detailed at <https://doi.org/10.57745/VTMYP0>). The questions from the “Objectives and specific notions” group helped to classify the ecosystem services targeted by developers during the de-sealing projects. The questions from the “Soil characteristics before and after de-sealing” and “Characterization carried out before and after the de-sealing project” groups were aimed at assessing how soil functions were taken into account by developers. These answers formed a basis for the development of a guide to assist in the design of de-sealing favourable to renaturation.

### 2.2. Data collection strategy

The respondents and structures targeted by the survey were French contracting authorities or project managers of development projects (local authorities in particular), private developers in charge of the management of green spaces or urban infrastructures, engineering offices, landscape architects-designers, and building and civil engineering companies. The questionnaire was sent out through Plante & Cité’s network members composed of various public and private structures (> 600 structures mostly based in France but also in Switzerland, Belgium, Spain and Canada), and categorised as follows: 199 local authorities, 103 landscape architects-designers, 147 engineering offices, 16 private developers in charge of the management of green spaces or urban infrastructures, 79 educational and research institutions, 44 consulting and support organisations for local government professionals, 30 supply companies or horticultural companies or professional federations, 8 social landlords, and 3 non-profit organisations. The questionnaire was made available from June 7th to September 17th, 2021. It was sent by e-mail, automatically or manually, with a link to the online questionnaire. Reminders were sent to the organisations that had not completed the questionnaire while the survey was still accessible.

### 2.3. Data processing

All the collected information was stored in Excel format in a database available at <https://doi.org/10.57745/VTMYP0> (only the data related to citizen participation or details about implemented vegetation are not presented). Each de-sealing project corresponded to a line in the database. Each question corresponded to a variable presented in columns. The term ‘answer’ corresponded to each respondent’s record for each question, and the term ‘data’ was the information provided by each answer. The data was unlinked because each question was independent

**Table 1**  
Structure of the survey, type of information and typology of answers collected about de-sealing projects.

Thematic group	Type of information	Typology of answers	Propositions
Information about the respondent	Structure identity	One choice	'Engineering offices', 'local authorities', 'non-profit organisations', 'construction company', 'other company', 'research institute or school', 'landscape companies and designers'
	Function	One choice	'Project owner assistance', 'contracting authority', 'project manager', 'project setup', 'diagnostic', 'design', 'technical studies and characterisations', 'preparatory work', 'implementation work', 'management/maintenance', 'other'
General description of the project	Experience	One choice	Yes/no/no information
	Expertise	One choice	'I have little experience' / 'experience'
	City localisation	Open text	
	City population	One choice	'small' <20,000 inhabitants, 'intermediate' 20,000 to 400,000 inhabitants, 'large' > 400,000 inhabitants
	Start date	Open text	
	Total cost (euros m <sup>-2</sup> , taxes included)	One choice	'0-30', '30-60', '60-100', '100-200', '200-300', '>300'
	Funding	Open text	
Objectives and specific notions	Site, de-sealed surface (m <sup>2</sup> )	Open text	
	Land-uses before and after de-sealing	Multiple choices	'Public service building', 'public industrial building', 'private service building', 'private industrial building', 'collective block', 'area around the 5 types of building', 'cemetery', 'green space', 'sport and recreation area', 'schoolyard', 'sidewalk part', 'roadway part', 'parking lot', 'square', 'railroad', 'area around a road', 'brownfield', 'agricultural area', 'natural area', 'stormwater management structure', 'other', 'no info'
	Objectives ranked in order of importance	Multiple choices	'Reduction of urban heat', 'noise reduction', 'improving ecological corridors', 'sustainable mode of transport', 'greening', 'carbon storage', response to a regulatory framework', 'reclaiming agricultural areas', 'restoring urban waterway', 'rainwater management', 'coastal protection', 'urban

**Table 1 (continued)**

Thematic group	Type of information	Typology of answers	Propositions
Soil characteristics before and after de-sealing	4 specific notions	Comment for each one	agriculture', 'recovering natural areas', 'other', 'no info', 'Ecosystem service', 'circular economy', 'avoid-mitigate-compensate', 'zero-net artificialisation'
	Causes of sealing	Multiple choices	'Building', 'soil compaction', 'impervious cover', 'no information'
	Sealing material	Multiple choices	'Asphalt', 'stabilised', 'concrete', 'pavers', 'other', 'no information'
	Seal cover management	One choice	'Removed and disposed of as final waste', 'on-site reuse for the construction of a new soil', 'removed and recycled in a treatment centre', 'on-site conservation (original state)', 'other', 'no information'
	Layers under sealing material	Multiple choices	'Road base layer', 'foundation layer', 'road subbase layer', 'fill', 'presence of buildings or foundations', 'no information'
	Layer composition	Multiple choices	'Asphalt gravel', 'concrete gravel', 'untreated gravel', 'heterogeneous backfill', 'homogeneous backfill', 'concrete', 'topsoil', 'soil-stone mix', 'sand', 'no layer', 'no information'
	Layer management after de-sealing	Multiple choices	'Removed and disposed of as final waste', 'on-site reuse for the construction of a new soil', 'removed and recycled in a treatment centre', 'on-site conservation (original state)', 'other', 'no information'
	De-sealing method	Multiple choices	'Pavement fracturing', 'pavement cutting', 'pavement removal', 'excavation', 'other method', 'no information'
	Water management	Multiple choices	'Infiltration basin', 'rain garden', 'vegetated ditches', 'vegetated trenches', 'permeable road', 'none', 'other type', 'no information'
	Type of pervious layer	Multiple choices	'No permeable pavement', 'pervious concrete', 'cover made of unbound organic materials, e.g., wood chips', 'cover made of unbound mineral materials, e.g., gravel', 'concrete grid pavers with grass', 'porous asphalt', 'permeable paving blocks', 'wood

(continued on next page)

Table 1 (continued)

Thematic group	Type of information	Typology of answers	Propositions
Characterisation before and after the de-sealing project	Type of soil or substrate materials used after de-sealing	Multiple choices	decking', 'no information' 'Green waste compost', 'non-composted green waste', 'chemical fertilisers', 'organic fertilisers', 'untreated roadbed aggregate', 'organic waste from the site or not', 'mineral waste from the site or not', 'structural soil', 'topsoil', 'others', 'no information'
	Soil studies before	Multiple choices	'Geotechnical', 'agronomic', 'biological', 'contaminated'
	Geotechnical indicators before	Multiple choices	'Infiltrometry', 'compaction', 'penetration resistance', 'slope', 'percolation', 'permeability', 'plasticity', 'water table', 'bearing capacity', 'soil water sensitivity', 'no information'
	Agronomic indicators before	Multiple choices	'Profile description', 'carbonates', 'cation exchange capacity', 'hydraulic conductivity', 'vegetation cover', 'bulk density', 'solid density', 'pH', 'porosity', 'soil water content', 'nutrient content', 'texture', 'structure', 'no information'
	Contaminant indicators before	Multiple choices and open text	'Trace metals and metalloids', 'hydrocarbon components', 'pathogens', 'other', 'no information'
Greening of the de-sealed site	Type of monitoring after	Multiple choices and open text	'Contaminant assessment', 'agronomic properties', 'biological activities', 'vegetation aspects', 'hydrological measures', 'others', 'no information'
	Vegetating method	Multiple choices and open text	'No vegetation planted', 'planting or sowing', 'spontaneous vegetation', 'no information'
	Type of vegetation	Multiple choices	'List of species', 'musical (mosses, lichens, dwarf cover crops) (0–5 cm)', 'herbaceous (5–80 cm)', 'shrubs (1–7 m)', 'trees (> 7 m)', 'no information'
	Criteria of vegetation choice	Multiple choices	'Adaptation to climate change', 'promotion of local species (possibly with a label)', 'spontaneous species', 'aesthetical value of the vegetation (e.g., flowering, foliage, shape)', 'low

Table 1 (continued)

Thematic group	Type of information	Typology of answers	Propositions
Respondent's answers about the project (benefits, difficulties)	Vegetation monitoring	Open text	maintenance costs', 'no information'
	Opinion	Open text	
	Limitations encountered	Multiple choices	'Purchase and/or delivery of materials', 'climatic hazards', 'evacuation and treatment of construction waste', 'cost management', 'site governance management', 'team management'
	Citizen participation	Multiple choices	'Information and raise of awareness', 'consultation', 'concertation', 'co-production', 'initiative entirely carried out by citizens (collective/group, association)', 'citizens not involved in the project', 'other', 'no information'
	Additional information	Open text	

of the others. The links between questions (and therefore between answers) were established for each de-sealing project. The data acquired on the various projects was studied as the survey was completed. Where responses were incomplete, we extracted information from the files attached by the respondents to complete their answers, or we interviewed them by phone or e-mail to help them finalise their answers. Various corrections were made when necessary, using a detection-analysis-decision method for each line. Corrections were made when an answer seemed inconsistent with the overall description of the de-sealing project described by the respondent, and when 2 or more answers seemed inconsistent with each other. These corrections were made on the basis of the overall understanding of the project. Where possible, the correct qualitative and quantitative values were estimated by a plausible value; otherwise, when uncertainty was too great, the answers were not taken into account in the analysis of the project. This work resulted in a more robust dataset. However, it was not possible to complete 100% of the data because some information was not available or the person in charge of the projects had moved.

Before processing the data, we adjusted the terms of the questions requiring a free answer according to our expertise in urban soil and road infrastructures. For example, concerning the different layers under a sealing cover, some respondents grouped the different layers together under the term "fill". A phone call was made to clarify their response and obtain the expected data with accurate precision. For an indicator like surface, when one de-sealing project corresponded to several patches in different locations at the scale of a municipality, the surfaces of the different locations were cumulated.

The way the data was structured did not lend itself to complex statistical analysis. The results were processed to express trends in the way de-sealing projects have been carried out in France over the last 15 years. Whenever possible, we used very simple data processing with and we processed some of the data using boxplots. The R (4.0.2) and RStudio (1.3.1093) software programs were used for data processing and statistical analyses (4.1.2; R Core Team and contributors worldwide). Only the link between the variables of surface area de-sealing and the average cost of each de-sealing project was evaluated using a Kruskal test (4.1.2; R Core Team and contributors worldwide).

### 3. Results

#### 3.1. Respondents' representativeness

Forty-seven de-sealing projects were collected through the online survey, and ten projects through the two partners of the DESSERT project. The percentages of the respondent types were fairly representative of the urban actors targeted in the survey: most of the respondents were representatives of local authorities (24 out of 57 projects, i.e. 42%), landscape designers (23%) and engineering offices (19.7%) (the other respondents represented less than 7% each). These three types of structures acted as project managers for the setup, design, technical study and characterisation phases of the project, as well as for its implementation and management. They played a strong role in the decision-making process, particularly in relation to the sustainability of the project. Nineteen respondents (out of 57) had already carried out more than one de-sealing project, and 7 felt they had significant experience. The project was the first de-sealing experience of 18 respondents, who all felt they had little experience. The quality and quantity of the data is specified each time in the rest of the Results section.

#### 3.2. General description of the projects

Information on the general description of the projects was complete for city localisation & population and start date. The total de-sealed surface (48 responses - 84%), the total cost of the de-sealing project (47–82%) and the funding source (46–80%) were quite well documented. Information about land-uses before and after de-sealing was also well documented.

##### 3.2.1. Timeframe, location and surface of the de-sealing projects

The de-sealing projects registered in our database started between 2009 and 2021 (Fig. 1). However, these practices increased significantly over the last few years: 70% of the projects were conducted over the 2017–2021 period, and some of them are still ongoing or have been recently completed. Moreover, many respondents indicated that 45 other de-sealing projects altogether were planned within the same city or by the same urban operator in the years to come.

The de-sealing projects were located all over the French mainland territory, in cities of various sizes (Fig. 2). Eleven projects were located in metropolitan areas (> 400,000 inhabitants). Thirty-three projects were carried out in cities of an intermediate population size (20,000 to 400,000 inhabitants). Thirteen were carried out in small cities (< 20,000 inhabitants).

The surface areas of the de-sealed surfaces were rather heterogeneous: the median area *per* project was about 1150 m<sup>2</sup>, and the average

area was 4595 m<sup>2</sup>. The de-sealed surfaces were less than 4754 m<sup>2</sup> in 75% of the projects, and 39% of the total projects had de-sealed surfaces of less than 500 m<sup>2</sup> (19 out of 48 answers) (Fig. 3). Large de-sealed areas were not frequent: only six projects had a de-sealed surface of more than 8000 m<sup>2</sup>, and only four included a de-sealing area of more than 24,000 m<sup>2</sup>. Whatever the type of land-use, the projects covered a wide range of categories, which made it impossible to distinguish any trend. The 10 projects around buildings were between less than 500 m<sup>2</sup> to more than 24,000 m<sup>2</sup>. The 13 developments of spaces linked to educational activities were generally less than 4000 m<sup>2</sup> (7 were less than 1000 m<sup>2</sup>), except one town that combined all schoolyard de-sealing projects for a total of 42,000 m<sup>2</sup>. The 30 transport infrastructure projects were present in all categories, but 33% covered an area of less than 500 m<sup>2</sup>.

##### 3.2.2. Land-use changes before and after de-sealing

The questionnaire allowed the respondents to select one or more land-uses for each project, chosen from 26 types of use. To make it easier to process the data and express the results, the land-uses were grouped by major land-use types that can be used to describe the entire urban fabric (Table 2). Associating one or more land-uses to each land-use type was possible. A code was assigned to each class of defined land-use. Land-use type linked to educational activities were split in 'sports and recreational activities' (U5) and 'school yards' (U6) because the available areas and the intended purposes were different. Similarly, the land-use type linked to transport infrastructures were split in 'vehicle and pedestrian traffic zones' (U7) and 'vehicle and parking zones' (U8).

First of all, the overall changes in the urban fabric were described by looking at variations of land-use types before and after de-sealing (Fig. 4). The process reduced the number of land-use type in the surroundings of public and private buildings from 9 to 6, and those in the surroundings of transport infrastructures from 52 to 42. All 4 brownfield areas were converted into other types of land-use. The land-use type in the surroundings of residential areas and educational and leisure infrastructures slightly increased from 2 to 4 and 13 to 17, respectively. De-sealing also led to a great increase of the number of 'green spaces' from 3 to 22. A new type of land-use was developed, linked to the introduction of alternative methods to manage urban rainwater (Fig. 4).

It appeared appropriate to examine each project and list the land-uses before and after de-sealing. The sites were classified according to the number of land-uses present on the site before de-sealing: 40 sites with 1 use, 10 sites with 2 uses, 5 sites with 3 uses and 2 sites with 4 uses. Each site was likely to include one or more uses after de-sealing. The land-use names before and after de-sealing were defined according to the list in Table 2. The post-de-sealing land-use modifications were analysed for the sites with a single use (U2 to U9) before de-sealing (Fig. 5): 17 sites out of 40 retained their original use and the de-

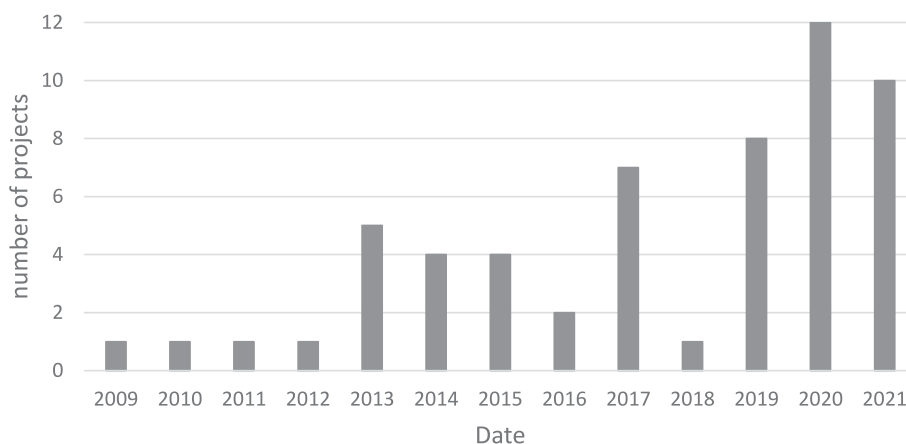


Fig. 1. Number of de-sealing projects *per* year between 2009 and 2021 ( $n = 57$ , number of projects recorded in the survey). Date, starting year of the project; the starting year of the overall project was used for projects consisting of several continuous de-sealing interventions over time.



Fig. 2. Localisation of the 57 projects across the French mainland territory and distribution in metropolitan areas (> 400,000 inhabitants), intermediate-sized cities (20,000 to 400,000 inhabitants) and small cities (< 20,000 inhabitants).

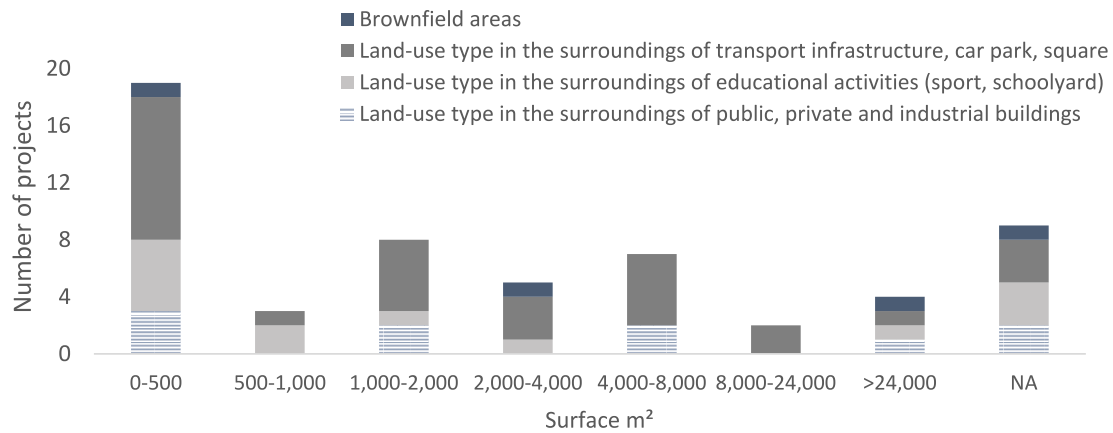


Fig. 3. Surface areas of the de-sealing projects as related with the land-use types before de-sealing (n = 48).

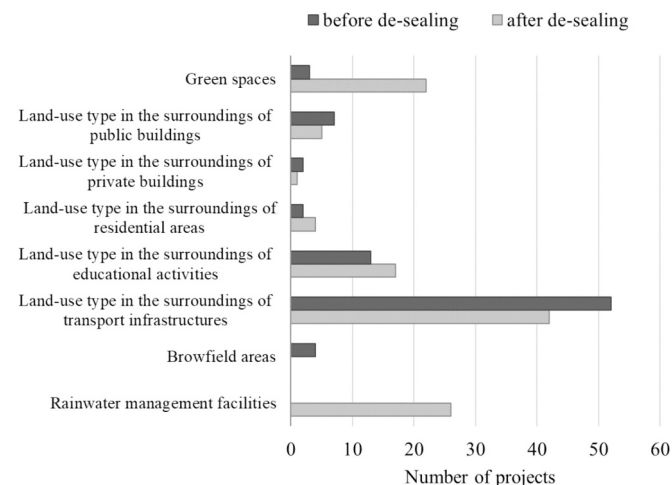
sealing project only consisted in reducing the impervious surface; 15 sites kept their initial use, but acquired a second one – generally the installation of rainwater management structures (U10 for 14 sites) or to a lesser extent, the creation of a park-like area (U1 for 2 sites); for 6 sites (1 U7, 3 U8 and 2 U9), the original use was completely replaced by a park or garden use (U1) after the impervious surface was removed. Two wasteland sites were completely transformed by the construction of a block of flats (U7) along with park-like and rainwater management structures, roads for both sites plus commercial buildings and parking lots for one site.

The same work was performed for the 10 sites with 2 uses before de-sealing (Fig. 6). Eight sites had a first use equivalent to ‘parking lot’ or ‘public square’ (U8) and a second use corresponding to ‘road-like’ (U7) or ‘residential area’ (U4) or ‘sports facility’ (U5) for 6, 1 and 1 sites,

respectively. Two sites had a first road-like use (U7) and a second use corresponding to a public building area (U2) or a residential area (U4). Half of the projects (5) consisted in creating rainwater management facilities (U10) or new green spaces (U1), and 3 combined both (U10+U1). Half of the projects still had ‘road-like’ use (U7) and/or a ‘parking lot’ or ‘public square’ use (U8) after de-sealing, but the initially occupied surface had been reduced to leave space for new land-uses. U8 was completely removed in 5 sites out of 8, and both U8 and U7 were completely removed when they were combined in 2 sites transformed into green (and blue) infrastructures (U1 and U1 + U10). For 2 U8 sites, one was transformed into a green space (U1), and one was transformed into area around building (U2). U7 was left in 7 out of 8 initial sites, and it was newly built up in only one site. The number of uses after de-sealing ranged from 4 to 5 for only 3 sites, all of which had a

**Table 2**  
Classification of the land-use types and associated land-use specifications.

Land-use types	Land-use specifications	Code
Green spaces	Urban parks, peri-urban parks, gardens, squares, maintained natural areas, ...	U1
Surroundings of an administrative building or equipment	Public service and industrial buildings, e.g., town hall, museums, hospitals and areas around these buildings	U2
Surroundings of private buildings or industrial plants	Private commercial, service or industrial buildings, and facilities around these buildings	U3
Residential areas	Block of flats or individual housing, allotments, cemetery	U4
Surroundings of educational and leisure infrastructures	Sports and recreational activities, leisure	U5
	School yards, university yards	U6
Surroundings of transport infrastructures	Roadway sections, streets, sidewalks, roundabouts, railroads, and areas around these structures	U7
	Parking lots, public squares	U8
Brownfield areas	Urban or industrial wasteland	U9
Rainwater management facilities	Rainwater basins, trenches, ditches, rain gardens, ...	U10



**Fig. 4.** Land-use types of the 57 projects before and after de-sealing.

‘rainwater management’ use (U10) and a new green space (U1).

### 3.2.3. Costs of de-sealing projects

In general, 10% of the total cost selected by the respondents corresponded to the study and design phase and 90% to the work phase. The global cost was given by 42 respondents: 12 indicated a cost of less than 100 euros per m<sup>2</sup>, 16 a cost ranging between 100 and 300 euros per m<sup>2</sup>, and 14 a cost of above 300 euros per m<sup>2</sup> (Fig. 7). With 37 surface-cost pairs, no statistical difference was established between the de-sealed surfaces and the different classes of de-sealing cost. Similarly, the cost was not really linked to the land-use type before de-sealing. Projects linked to transport infrastructures had prices ranging from less than €30 to more than €300 per m<sup>2</sup>. For developments around public or private buildings, the cost was above €100 per m<sup>2</sup>.

Fifty-one respondents indicated their source of funding for the de-sealing project. Funding came from at least two or more different sources for 31 of them. Projects were funded primarily by local authorities (31 respondents). Funding also came from higher territorial authority levels in 19 projects (Conurbation, Department, Region, and more rarely the State or the European Union). Twenty-eight projects were also financed by public subsidies: this was most frequently in the context of calls for research projects by the French Water Agencies (which funded up to 70% of the costs). Public subsidies also came from the French Agency for Ecological Transition or other public structures,

or in the context of calls for territorial experiments.

### 3.3. Objectives of the de-sealing projects

All the respondents gave one or several answers among the de-sealing objectives to be ranked (Fig. 8). ‘Rainwater management’ was ranked among the top three choices by 40 respondents (70%), ‘reduction of urban heat’ by 32 respondents, ‘greening’ and ‘sustainable mode of transport’ by 25 and 24 respondents, respectively. De-sealing was part of plans aimed at increasing ecological corridors and carbon storage in only 8 answers. The other objectives were given less priority. ‘Others’ included social aspects or aestheticism and attractivity, among others.

Thirty-seven respondents (64%) answered ‘yes’ to the question about including the notion of ecosystem services in the first steps of the de-sealing project (setup, design), 24 (42%) answered ‘yes’ to the one about integrating it in a circular economy (reuse or recycling of materials), and 20 answered ‘yes’ to both questions. ‘Avoid-mitigate-compensate’ policy or ‘zero net artificialisation’ were selected by only 5 and 4 respondents, respectively.

The objectives of de-sealing crossed with the specific urban land-uses were used as criteria to propose a four-level typology of de-sealing actions.

The first type was *roadway requalification aiming at rainwater management*, which mainly included the two land-uses of transport infrastructures (U7 and U8).

The second type concerned *de-sealing of pavement areas managed by citizens* and *de-sealing for the redevelopment of sport and leisure areas* (U7 and U5) and the very few projects on *roadway requalification that did not aim at rainwater management*. Its main objectives were to tackle the urban heat island phenomenon and increase vegetation. In particular, *greening initiatives of pavement areas by citizens* (6 projects) also aimed to improve aestheticism, involve city dwellers (citizens were involved in planting and maintaining the plants in agreement with the technical services of cities) and also reduce ecological fragmentation. One advantage of these projects lay in the tiny but multiple de-sealed and vegetated surfaces, which ranged from less than 1 m<sup>2</sup> to 10 m<sup>2</sup> at the base of trees, buildings and walls, and were distributed within the city.

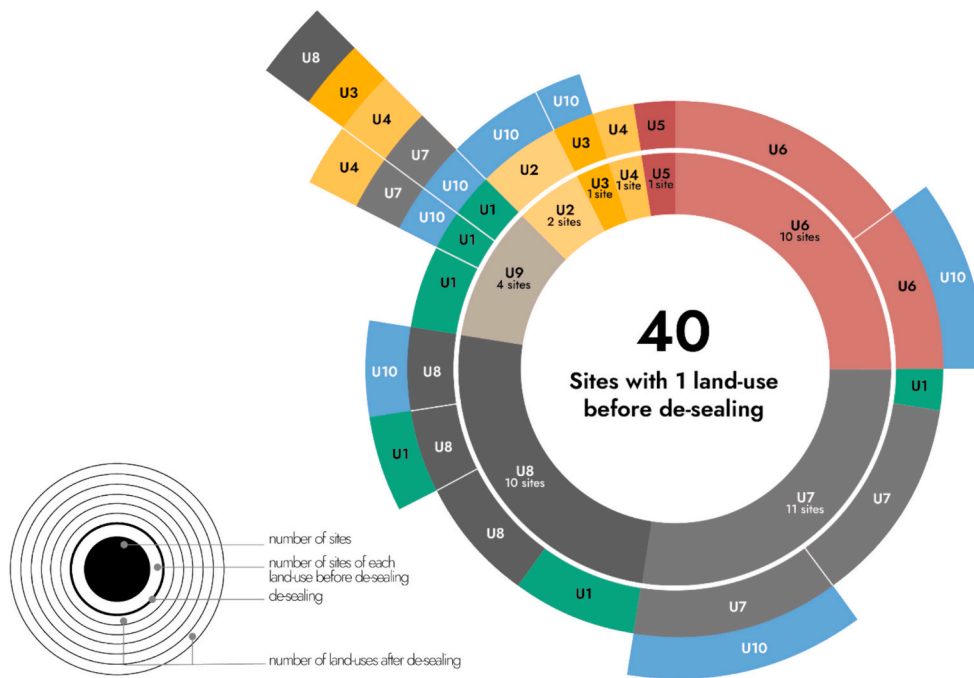
The third type – *schoolyard de-sealing* (10 projects) – included one land-use (U6) and aimed to i) improve the urban microclimate and vegetation implementation, and ii) store carbon, reduce ecological fragmentation and meet regulatory constraints (e.g., in terms of rainwater management). These projects also sought aestheticism, social and educational purposes with composting devices, vegetable gardens or playground equipment. De-sealing of schoolyards systematically replaced only part of the impermeable cover, and several types of permeable materials and vegetation were implemented afterwards. The de-sealed surfaces generally covered 200 m<sup>2</sup> to 300 m<sup>2</sup>.

The fourth type – *ecological restoration projects* – included only one use type (U9–4 projects) and consisted in constructing green spaces by reopening covered waterways, removing buildings, or redeveloping brownfield platforms. The de-sealing actions aimed at i) improving vegetation and biodiversity and reducing ecological fragmentation, and ii) meeting regulatory constraints and developing sustainable transport facilities. These kinds of projects potentially concerned heterogeneous surfaces and represented opportunities for enlarging green spaces at the scale of parcels, especially in shrinking cities (Kabisch and Haase, 2013; Tobias et al., 2018). They were less common and more technical than the others because of the frequently encountered changes of land-uses and contamination constraints.

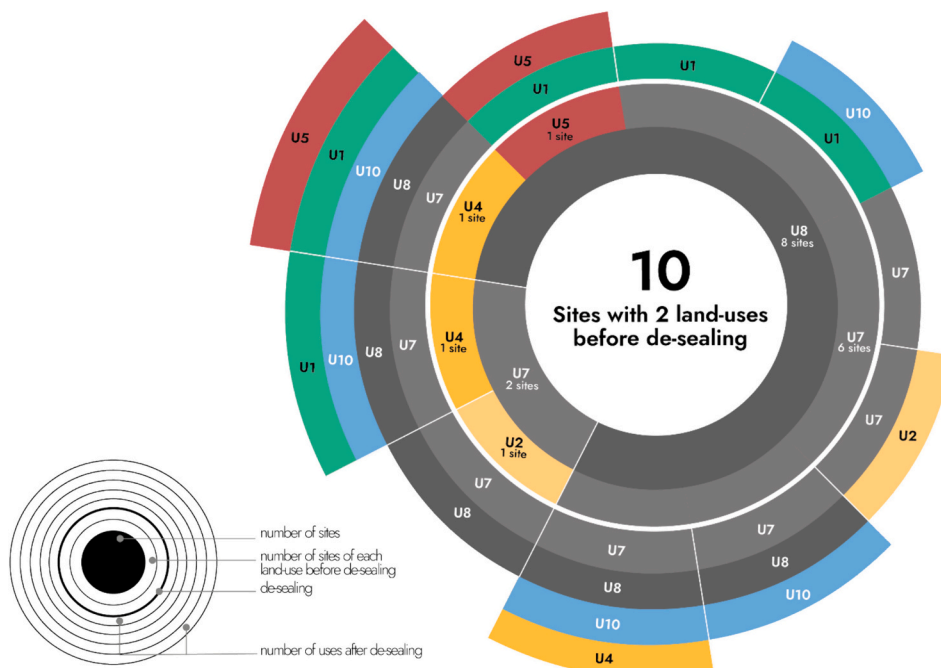
### 3.4. Material and soil characteristics before and after de-sealing

Information on technical aspects was least precise and least complete because one in two respondents did not manage and maintain the project on site. However, the results did give a trend for the types of cover, their management after de-sealing and the treatment of the layers





**Fig. 5.** Land-uses after de-sealing for the 40 sites with one land-use before de-sealing. U1, park-like use (urban parks, peri-urban parks, gardens, squares, maintained natural areas); U2, administrative building or equipment, e.g., town hall, museum, hospitals, etc.; U3, commercial or service buildings and industrial facilities; U4, collective or individual housing, allotments, cemetery; U5, sports and recreational activities, leisure; U6, school yards, university yards; U7, road-like use (road networks, railways, streets); U8, parking lots, public squares; U9, urban or industrial wasteland, waterways; U10, rainwater management structures, e.g., rainwater basins, trenches, ditches, rain gardens.



**Fig. 6.** Land-uses after de-sealing for the 10 sites with two land-uses before de-sealing. U1, park-like use (urban parks, peri-urban parks, gardens, squares, maintained natural areas); U2, administrative building or equipment, e.g., town hall, museum, hospitals, etc.; U3, commercial or service buildings and industrial facilities; U4, collective or individual housing, allotments, cemetery; U5, sports and recreational activities, leisure; U6, school yards, university yards; U7, road-like use (road networks, railways, streets); U8, parking lots, public squares; U9, urban or industrial wasteland, waterways; U10, rainwater management structures, e.g., rainwater basins, trenches, ditches, rain gardens.

uncovered beneath the impermeable covering.

**3.4.1. Characterisation of the materials before de-sealing**

In 32 projects out of 47, soil characterisation such as contamination risk, geotechnical characteristics, agronomic characteristics, or

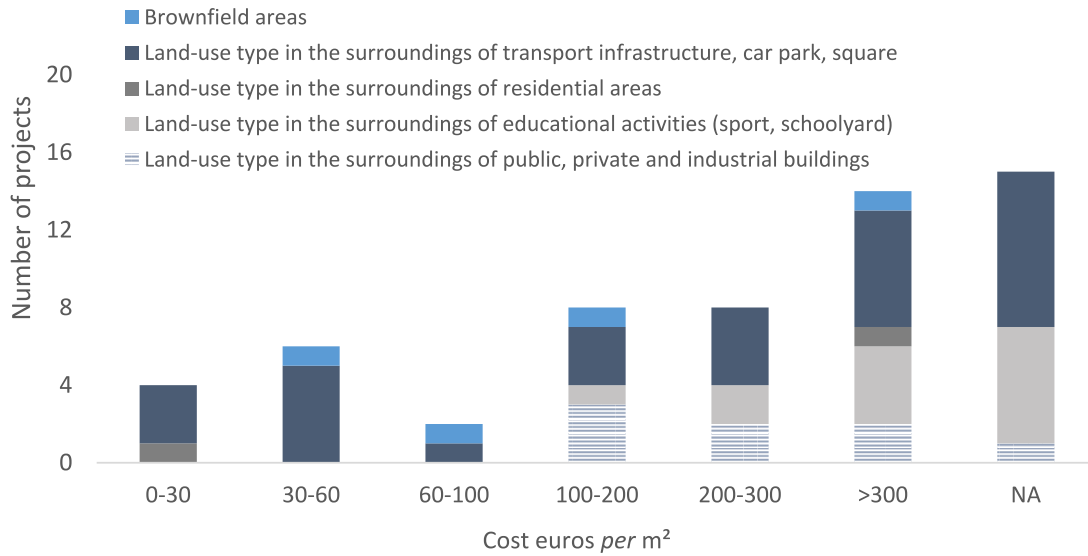


Fig. 7. Cost (in euros per m<sup>2</sup>) of de-sealing projects in link with the main land-use types (n = 42).

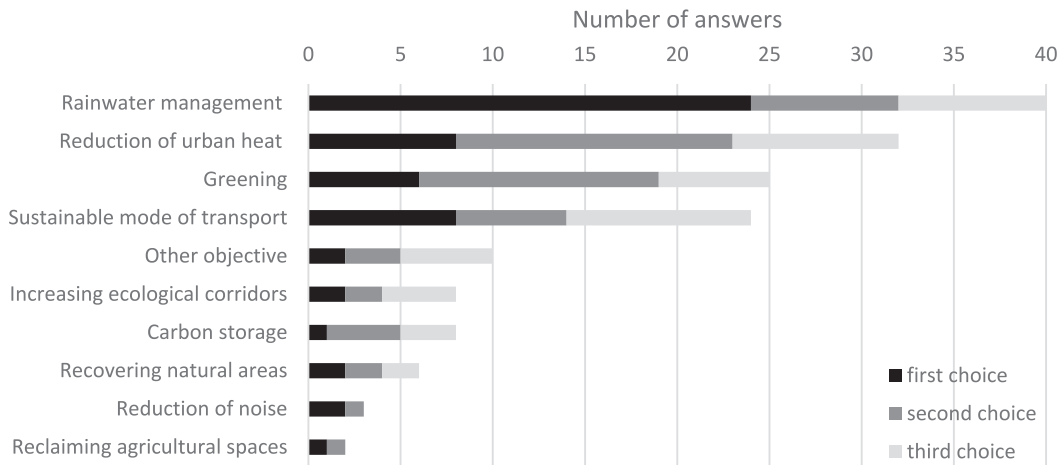


Fig. 8. Objectives of the de-sealing projects ranked in terms of importance among the top 3 choices (n = 57).

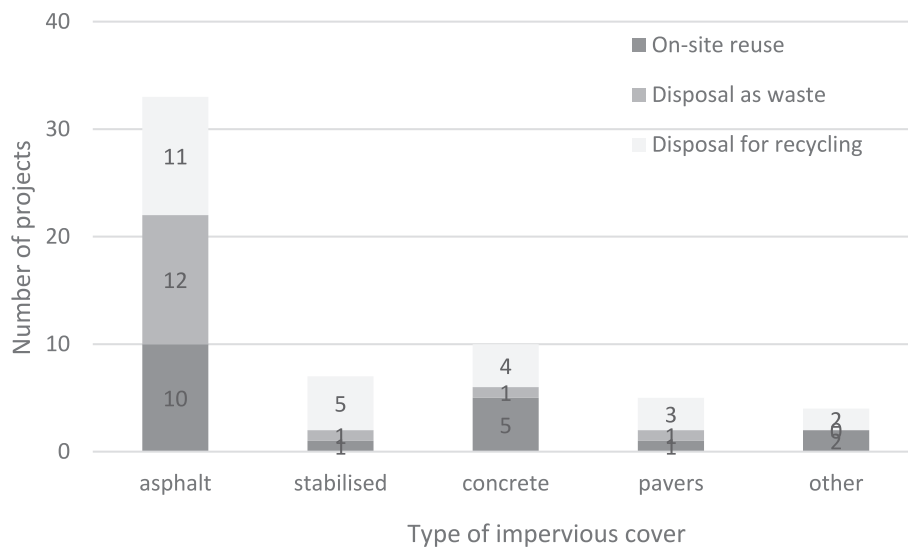


Fig. 9. Management of the impervious soil covers depending of the material: asphalt, stabilised soil, concrete, pavers, other (n = 38).

biological studies were carried out prior to de-sealing. Geotechnical studies were frequently carried out (in 25 projects out of 47), whereas agronomic and biological studies were rarely performed (in 8 and 3 projects, respectively). A dozen respondents indicated that no remediation treatment or any prior analysis or monitoring of contamination were done because the sites were not subject to pollution regulation. There was no obvious link between the reuse of subbase materials on-site and soil analyses (geotechnical and agronomic ones).

For 48 projects, soil sealing was caused by the presence of an impervious cover composed of a combination of one to 4 different materials: a hydrocarbon cover (bituminous mix or asphalt) was mentioned in 43 projects, a stabilised surface in 10, a concrete cover in 11, and a paving surface in 6. A synthetic resin was the cover material of 4 projects, and stabilised soil was the cover material of 10 projects. Each impervious cover was removed combining several techniques such as sawing, crushing with a jackhammer, and using a mechanical excavator. The de-sealed cover was treated in 3 main ways of equal importance in terms of use: i) on-site reuse to build a new soil profile (13 answers), ii) disposal of non-hazardous waste or hazardous waste as waste in landfill (12 answers) and iii) recycling in a treatment centre before being reused (12 answers) (Fig. 9). For asphalt covers, the 3 ways were identical in terms of the number of projects. The high number of landfills was linked to the detection or suspicion of polycyclic aromatic hydrocarbons at concentrations above  $500 \text{ mg kg}^{-1}$  coming from tar, which precluded the cover being recycled (Legifrance, 2010). Final disposal was the least used solution for the other covers.

The geotechnical layers under the impervious covers corresponded to road layer structures (top-down: base, sub-base), and subgrade below the road layer structure to reinforce the soil bearing capacity. The composition of the road layers was highly variable and depended on locally available materials (Fig. 10). Hydrocarbon binder was present in the base layer in 13 projects and then decreased strongly to 3 and 2 in the lower layers. Untreated gravel was very common in the base + sub-base and subgrade layers (15 and 10 projects, respectively) because it is cheapest. A base layer of cement-based gravel – a more expensive material than the previous two – was used in a few projects (3 to 5). In 5 to 7 projects, the type of material was not identified and was described as a heterogeneous mixture of materials. In 3 projects, the base layer was absent and the impermeable cover rested directly on the compacted soil. In 6 other projects, there was no sub-base or subgrade. Fifty percent of the road layers were reused on site in 15 projects, 8% were sent to landfill (2 projects) and 40% were disposed of for recycling (10 projects).

### 3.4.2. Type of soil and vegetation implemented after de-sealing

Soil engineering processes after de-sealing depends on the intended uses, as described in Figs. 5 and 6. For squares and parks or to accompany building uses (U1, U2, U3, U4), the reconstituted soil must include a 30- to 40-cm growth horizon to ensure the intended soil functions (as a medium for plant growth and water infiltration, a habitat for soil organisms, a filter and an interface for nutrients and chemicals; Vidal-Beaudet et al., 2017). For street-tree use (U6, U7), it is necessary to build a structural soil-stone layer over one metre deep corresponding to a mixture of quarry aggregates, soil and organic matter. This structural layer must be highly resistant to mechanical stresses associated with traffic, but not necessarily with good fertility. A planting hole in the centre of this layer allows for a 60-cm deep growth horizon to ensure tree growth (Vidal-Beaudet et al., 2017). To build fertile soils, 47 respondents mainly reproduced growth layers and structural layers. To replace the impervious cover and the underlying layers by a growth layer, topsoil (0–30 cm depth) collected on another site or taken from an agricultural plot was the most frequently used material. It was generally mixed with compost or an organic substrate (15 projects) and used on its own (4 projects). A soil-stone structural matrix with new materials (topsoil and quarry aggregates) mixed on an off-site platform was provided for 11 projects. However, the structural horizon was mixed on site by reusing site aggregate mixed with added topsoil and organic material for 15 projects. Only four projects reused site aggregates alone or mixed them with compost. No synthetic fertiliser or non-composted green waste was used. Organic mulching was used in 9 projects. No geotechnical monitoring or agronomic characterisation was carried out after the de-sealing projects.

When de-sealed soils were vegetated (45 projects), a herbaceous cover was usually planted (40 projects), often associated with a shrub stratum and a tree stratum (32 and 27 answers, respectively). In most cases, vegetation was installed to avoid leaving the soil bare. Many criteria were retained for choosing the type of vegetation: the characteristics of the new soil, the landscape attractiveness (e.g., in terms of flowering, colours, foliage), adaptation to climate change (resistance to water stress) and cost minimisation.

## 4. Discussion

### 4.1. Soil de-sealing improves soil functions and ecosystem services

This study shows that sustainable rainwater management facilities, which are under the responsibility of local services, is the primary

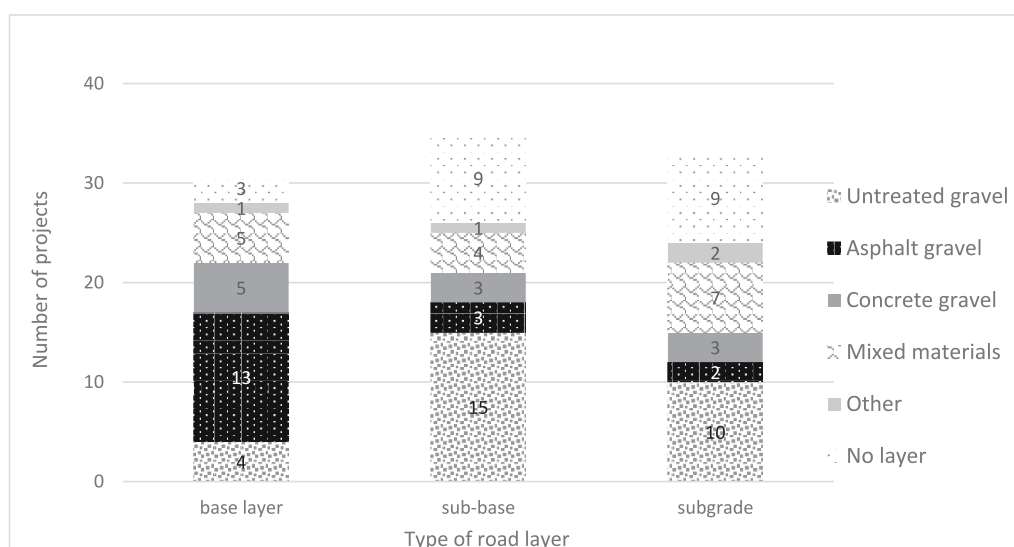


Fig. 10. Composition of the base, sub-base and subgrade of road structures: untreated gravel, asphalt gravel, concrete gravel, mixed materials, other ( $n = 31$ ).

objective of de-sealing (40 projects out of 57). Soil sealing increases anthropogenic pressure by altering the distribution of water resources in cities and increases the risk of flooding (Adobati and Garda, 2020). Urban flooding has become one of the most pressing issues because it causes intense overland flow and overstresses the urban drainage capacity (Rujner and Goedecke, 2016). It is no longer possible to install new underground rainwater collection networks in cities to improve rainwater management, except in new developments. Water infiltration at the soil surface should be encouraged to limit the risk of flooding due to heterogeneous and often intense rainfall. Reducing impervious surfaces should restore the natural infiltration function of soils (Hanna et al., 2023). However, areas of intense runoff in towns and cities are concentrated on road infrastructures. That is why the most frequent type of de-sealing project was public roadway requalification (31 projects; U7 and U8). These practices are widely documented beyond the context of de-sealing, and offer effective methods as standalone approaches or combined with traditional management approaches, also called “grey infrastructures” (Ahiablame et al., 2012). De-sealing even small surfaces should become a prominent part of urban planning and participate to the blue-green networks to improve environmental conditions and the health and quality of life of citizens (EEA, European Environment Agency, 2017). Patchy de-sealing projects lead to a “sponge-like city” that can improve water management. Regeneration of private and public spaces increases the permeability of the urban fabric (Adobati and Garda, 2020). The provided service by de-sealing projects is generally proportional to the surface area dedicated to the creation of a rainwater management facility. Our data indeed highlights the fact that the surface areas dedicated to rainwater management are generally greater than those dedicated to other uses. The median surface area of the de-sealing projects that included rainwater management was 3800 m<sup>2</sup> ( $n = 20$ ), whereas the median surface area of the projects that did not include rainwater management was only 334 m<sup>2</sup> ( $n = 27$ ).

Our results indicate that other ecosystem services than rainwater management were targeted by urban soil de-sealing (Fig. 8), i.e., tackling the urban heat island phenomenon, greening, redeveloping roadways with sustainable ways of transportation, and reducing ecological fragmentation. These additional ecosystem services can be provided because de-sealing the soil makes it multifunctional again. The contribution of urban soils, which can perform several functions, is still greatly underestimated (O’Riordan et al., 2021), even though it is increasingly clear that improving the quality of life in cities (Tardieu et al., 2021) depends on improving ecosystem services in anthropised areas by increasing green open space quantity (Adobati and Garda, 2020; Morel et al., 2023). Therefore, constructing fertile soils and loosening the sub-layer under the impermeable cover will promote other functions, i.e., i) organic matter storage, recycling and transformation that support global climate regulation, ii) physical support for vegetation that itself supports biomass provisioning and aestheticism, and iii) biodiversity support of the flora and fauna that regulate health and environmental risks.

Fig. 3 shows no direct proportional relationship between the de-sealed surface area and the land-use type after de-sealing. De-sealing projects often consist of rather small and punctual actions (like “urban acupuncture”) and do not need continuity of surface to be implemented. This makes them a suitable approach for the constrained urban matrix. Overall, the surface areas of the projects were highly variable (from 18 m<sup>2</sup> to more than 60,000 m<sup>2</sup>), but altogether rather small, with a median area of 1150 m<sup>2</sup> ( $n = 51$ ). These de-sealed surfaces are in line with the variability of public green space surfaces in Zurich (Vega and Küffer, 2021), i.e., many individual patches ranging from 1 m<sup>2</sup> to nearly 30,000 m<sup>2</sup>, but mostly small ones (< 20 m<sup>2</sup>) predominantly consisting of street tree discs (71% of all patches). Small de-sealed soil surfaces can significantly contribute to biodiversity support if they are numerous and close enough to each other. Vega and Küffer (2021) recommended between-patch-distances below 200 m. Within the land-sparing debate (Lin and Fuller, 2013), de-sealing small sites would be particularly relevant for dense urban-form areas, where buildings can be interspersed with small

tracts of semi-natural habitat patches. Additionally, de-sealing can be integrated at different territorial scales (parcel, street, neighbourhood, city) (as shown by our results) and sometimes launched at the regional and national scales (e.g., schoolyard de-sealing programs), so that small targeted actions can be efficient at a larger scale.

In most cases, de-sealing projects enable the development of multi-use areas and make the soil multifunctional, which contributes to the sustainable development of the urban matrix. In our study, the typology of land-uses of the 40 single-use projects before de-sealing shifted from 8 to 16 combined uses after de-sealing and from 5 to 10 combined uses for the 10 “two uses before de-sealing” projects (Figs. 5 and 6). Changes in the urban fabric are made by converting and adding land-uses to the existing ones or through the implementation of new landscaped areas (green areas and alternative rainwater management facilities), which increase the number of soil functions and ecosystem services. Scenarios combining several types of nature-based solutions (including de-sealing for permeable parking and street trees) offer the best performances (Cortinovis et al., 2022). Increasing the number of land-uses on a same site – in particular creating green spaces – contributes to improving ecosystem services because soil performances are improved (Hanna et al., 2023).

#### 4.2. Sustainability of the de-sealing process

The impact of soil sealing on flood risk is well known, and specific environmental assessment tools have been developed to assess de-sealing effects (Ceci et al., 2023). In general, de-sealed soil improvement requires restructuring the soil profile, layer decompaction, and using imported materials to provide good agronomic properties adapted to plant growth (European Commission, 2012; Maienza et al., 2021; Prokop and Salata, 2017). Two main outcomes of the uncovered soil layers and the construction of fertile soils can be distinguished in our survey. The first one consists in using exogenous topsoil (0–30 cm) alone or mixed with organic materials (19 projects) or mineral materials (11 projects) to replace the impervious cover and the underlying aggregate layer and set up a growing medium. Such techniques have a significant environmental impact related to soil transportation by lorries into cities, as well as a loss of agricultural lands reducing the surfaces available for food production (European Commission, 2012). The second way consists in keeping and reusing the materials on site for soil construction (4 projects). This requires an on-site inventory of the soil-forming materials, which is rarely done according to our results and the literature (Bacholle et al., 2006). Two scientific research works involving on-site experimental trials demonstrated that a de-sealed soil can improve in fertility and biological functionality and support vegetation without adding topsoil (Maienza et al., 2021; Renella, 2020). The quality of the materials in place should be evaluated to adapt the de-sealing solutions to each situation and support a more sustainable urban design (Vrščaj et al., 2008). Several recent studies present methods, advantages and disadvantages of soil construction with mineral and organic waste (Deeb et al., 2019; Fabbri et al., 2021; Pruvost et al., 2020; Rokia et al., 2014; Séré et al., 2008; Vidal-Beaudet et al., 2017). These results, combined with pedological engineering, could be used to provide planners with sustainable solutions for managing on-site soils.

In our survey, urban soils de-sealing is rarely followed by an evaluation of the environmental (e.g., biodiversity, cooling) or social (e.g., visual appreciation, social bonding) benefits. There is no specific technical or scientific guidelines for monitoring de-sealing projects on a relevant scale, and for evaluating the benefits of de-sealing in terms of tackling urban heat island effects and promoting biodiversity or ecological continuities. The methods to evaluate the various benefits of such de-sealing projects in cities are well known, but would require additional funding, methods, and expertise after de-sealing.

#### 4.3. Contribution of the survey and prospects for further research

The objectives of this study were to provide a screenshot of existing de-sealing projects at a national scale in mainland France. The typology combining several answers helped to better perceive the different types of currently existing de-sealing projects and highlighted the similarities and differences between them. A limited number of similar approaches has been conducted from now. A summary of best de-sealing practices within the framework of the European project SOS4LIFE (Bazzocchi et al., 2019) identified a few de-sealing projects as case studies to help provide guidelines on resilience in urban regeneration. A recent French renaturation guide (Deboeuf De Los Rios et al., 2022) is aimed at identifying renaturation sites and different land-use types. Our results differ from these two works because a great number of de-sealing projects (57) are detailed, versus 19 from several countries (Belgium, Canada, Denmark, France, Germany, the USA) in Bazzocchi et al. (2019), and 17 from various countries as well (Belgium, France, Germany, Italy, South Korea, Switzerland, the USA) in Deboeuf De Los Rios et al. (2022). Our results were easier to compare because they were concentrated in the same area. There were also more exhaustive because they included several criteria such as the objectives and the land-uses, and took the project scale and the ease of implementation into account. The typology proposed by Bazzocchi et al. (2019) was based on one criterion – the de-sealing project scale (from “big urban projects”, “district projects”, to “small gardens” and “bottom-up projects”). Deboeuf De Los Rios et al. (2022) gave short examples of de-sealing projects based on their localisations in various countries to provide examples of existing renaturation projects. The project categories as defined by Deboeuf De Los Rios et al. (2022) are not exhaustive (as stated in their work) because their methodology did not include the smallest de-sealed surfaces (such as tree disks).

Potential de-sealing policies are currently based on hydraulic risk and heat island assessment (Ceci et al., 2023). Soil sealing is not related to multiple ecological and environmental aspects in the cities (Peroni et al., 2022). Based on our typology, estimating the potential recovery of soil functions after de-sealing could be a powerful indicator for choosing the best areas to be de-sealed as part of the renaturation of cities. However, it seems essential to also look at soil functions with a view to greening the city, to support all the services required for inhabitant well-being and health (Peroni et al., 2022). To be considered by urban planners, the ecosystem service to be reached should be defined before de-sealing, and the targeted soil functions should really be considered in the construction of a cognitive and analytical framework (Ceci et al., 2023). There are currently no indicators or tools to monitor soil-sealed areas to ecosystem services (Peroni et al., 2022). Mapping the quality of urban soils (physico-chemical and biological properties), with a good resolution (around 1 m), is essential to support public policy for protecting soil functions and services.

#### 4.4. Limitations of the study

Our survey collected data about 57 projects that we used to build a database, and it provided greatly varied information. However, some of it was difficult to obtain when the respondent had not been directly involved in monitoring the project. The accuracy of the responses to the 4th group of questions, which targeted more technical aspects (characterising the initially present anthroposols, implementation of de-sealing), was lower. Corrections improved the accuracy of some answers, but errors from the respondents may not have been detected, and errors of interpretation remain possible. The conclusions drawn from the results of this survey are mitigated by this incompleteness.

### 5. Conclusion and perspectives

This work shows that recent de-sealing projects have been implemented within cities of various sizes across the entire French mainland

territory, regardless of urban forms. In the survey, de-sealing increases the number of land-uses for a given site and renders space multifunctional by combining different types of technical solutions (rainwater management structures, permeable pavements, pavement greening). The primary objective of de-sealing soils was to regulate water run-off in the city. But the survey showed that a wider range of ecosystem services were sought, such as reducing the heat island effect through greening. De-sealing often consisted in small but multiple projects when greening was targeted, and resulted in vegetated patches that could significantly contribute to urban biodiversity if they were close enough to each other. To reinforce this initial trend in results, it would be useful to collect new information on practices in order to guide urban planning and select the most relevant areas to be de-sealed in relation to the land-use type targeted. This requires better knowledge of the quality of urban soils and a mapping of their physico-chemical characteristics.

In this study, the identified de-sealing methods usually implied replacing the sealing cover and subbase by newly imported materials, and hardly any soil characterisation or monitoring of the de-sealed sites has been performed. Urban planners could include in their specifications a requirement for materials to be recovered and recycled on site, rather than replacing them with agricultural topsoil for urban renaturation. The respondents explained that little is known about the properties of sealed and unsealed urban soils, and there is no specific guide for the design or monitoring of de-sealing projects. One recommendation for planners is that considering the pre-existing soil bases may help minimise the economic and environmental costs of urban greening projects. Consequently, the development of in-place tools and methods for evaluating the various benefits of de-sealing will be the subject of future work to determine the most sustainable solutions for improving the soil functions and the associated ecosystem services.

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#### Declaration of competing interest

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

#### Data availability

I have shared the link to the database

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