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CIREd corresponding author: mathilde.salin.pro@gmail.com

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Centre international de recherche sur l'environnement et le développement
Unité mixte de recherche CNRS - Ecole nationale des ponts et chaussées - Cirad - EHESS - AgroParisTech
Site web: www.centre-cired.fr Twitter: @cired8568
Jardin Tropical de Paris – 45bis, avenue de la Belle Gabrielle 94736 Nogent-sur-Marne Cedex

Digging into the Costs of Urban Soil Restoration

Mathilde Salin^{*1,2}, Charles Claron^{1,3}, Elodie Nguyen-Rabot¹, Nicolas Mondolfo¹, and Harold Levrel¹

¹UMR Cired, Université Paris-Saclay, AgroParisTech, Ecole des Ponts ParisTech, CNRS, CIRAD, EHESS, 94130, Nogent-sur-Marne, France

²Banque de France^{**}

^{**}This paper reflects the opinions of the authors and does not necessarily express the views of the Banque de France.

³LATTS, École des Ponts, Université Gustave Eiffel, CNRS, Marne-la-Vallée, France

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Abstract

Urbanisation leads to soil compaction, pollution and sealing, degrading soils' ecological functions and ecosystem services essential for urban resilience, such as flood mitigation and climate regulation. Ecological restoration of urban soils is thus critical for sustainable and climate-adapted cities. However, the economic dimensions of urban soil restoration, particularly its costs, remain unexplored. This study estimates that median urban soil restoration costs range from 50 to 320€/m² for compacted, sealed, or built-up soils, escalating to over 800€/m² for polluted soils. Urban soil restoration involves a sequence of up to ten steps, combining several techniques, with significant cost variation. Preliminary analysis is the least expensive, while building deconstruction and pollution remediation are the most costly. These new cost estimates will facilitate the prioritization of restoration areas and the development of economic incentives for ecological restoration in cities. These finding also highlight the need for healthy soil preservation, alongside restoration efforts.

*mathilde.salin.pro@gmail.com

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Urban land covers around 3% of the global land surface (IPBES, 2019), against 10% in France (Bocquet, 2023). The conversion of agricultural and natural land into urban areas – a process referred to as ‘land take’ (Commission, Commission) – is still ongoing: city areas worldwide doubled over 1992-2015 (IPBES, 2019), and in France, land take currently amounts to 21,000 ha/year (Bocquet, 2023). Urbanisation degrades soils in multiple ways (Pavao-Zuckerman, 2008; Byrne, 2021): they are compacted, constructed, polluted by human activities, and sealed with impervious surfaces – the most intense form of land degradation (Tobias et al., 2018; O’Riordan et al., 2021). These processes affect soils’ functions, inducing a decline in the multiple ecosystem services provided by soils to city dwellers, like flood mitigation, climate regulation, carbon storage or food provision (Dominati et al., 2010; Adhikari and Hartemink, 2016; Greiner et al., 2017). Many of these ecosystem services are crucial to the habitability of cities, in a context of rising climate change impacts, including heatwaves and heavy rains.

Soil restoration is a key strategy to recover ecosystem services (IPBES, 2018; Keesstra et al., 2018; Lal, 2015) and a crucial element of sustainable transition plans. It is included in Target 2 of the Kunming-Montreal Global Biodiversity Framework and in the United Nations’ Sustainable development goal 15.3. For urban soils more specifically, the recent European Union Nature Restoration Law includes a section on increasing urban green spaces. In France, the ‘Climate-Resilience’ law (2021)¹ establishes a ‘No *net* land take’ objective, and allows for compensating the remaining land take in 2050 thanks to soil restoration.²

However, scientific analysis on how to restore degraded urban soils remains embryonic (Byrne, 2021). Indeed, restoration ecologists have only recently considered soils and, *a fortiori*, urban soils, as part of their research (Heneghan et al., 2008; Harris, 2009; Kardol and Wardle, 2010; Farrell et al., 2020). A particular challenge lies in the impossibility of defining a reference state for the ecosystem and the significance of cultural factors in the selection of restoration pathways (Klaus and Kiehl, 2021; Pavao-Zuckerman, 2008). Therefore, departing from canonical definitions of ecological restoration (Society for Ecological Restoration International Science & Policy Working Group, 2004), Byrne (2021) proposes to define urban soil restoration as ‘*the science and practice of managing urban soils to achieve integrated social-ecological goals for improving the sustainability of urban cultural landscapes and well-being of urban citizens and desired biodiversity.*’ Therefore, for urban soils the notion of ‘restoration’ comes close to that of ecosystem ‘rehabilitation’ or ‘refunctionalisation’. As opposed to traditional ecosystem restorations (e.g., ‘grassland restoration’), ‘*urban soil* restoration’ refers to the initial rather than the final state of the restored ecosystem – which can take various forms (forest, urban park, etc.).

In parallel to the development of scientific knowledge on urban soil restoration, understanding its costs and their structure is crucial to assess the efforts required to reach the aforementioned political objectives. While we find studies on the restoration costs of several ecosystems (De Groot et al., 2013), no analysis focuses explicitly on urban soils. Some papers have explored costs associated with specific aspects of urban soil restoration (like Carrera and Robertiello (1993) for decontamination), without a comprehensive overview of restoration processes. In France, Fosse et al. (2019) is the primary reference for the renaturation costs for urban soils. It distinguishes between four steps involved in an urban soil restoration process (deconstruction, depollution, desealing and soil construction) and presents associated cost ranges. However, it provides very few sources and no explanation of the method.

The present article proposes a first-of-its-kind database providing a comprehensive and detailed overview of urban soil restoration costs in France. This is a fundamental contribution to estimate the total investment needs associated with land degradation neutrality targets. It will also contribute to the design of economic policies to reach those targets. Indeed, the sort of ‘urban land abatement costs’ we assess can help prioritising the urban areas to restore (Claron et al., 2022) and calibrating policy tools providing economic incentives for restoration.

¹LOI n° 2021-1104 du 22 août 2021 portant lutte contre le dérèglement climatique et renforcement de la résilience face à ses effets (1)

²This law uses the terms ‘renaturation’ and ‘de-artificialisation’ (*désartificialisation*). However, because defining and reinstating a ‘natural’ state is impossible, we prefer the term ‘restoration’ – with a meaning close to the ones of ‘refunctionalisation’ and ‘rehabilitation’ (Deboeuf de Los Ríos et al., 2022).

1 Results

1.1 Steps and techniques for urban soil restoration

Our research suggests that a restoration process can be described as an ‘operating chain’³ possibly implying ten main steps, each involving different fields of expertise (more detail in Annex 4.3). First, (-1) Planning consists in determining the most appropriate site for soil restoration, using tools like soil or biodiversity maps, and consulting and co-constructing the project with local residents. Following (0) Land control, (1) Preliminary analyses evaluate the soil’s biological, chemical and physical quality. If the soil is built on, (2) Building demolition is required, while (3) Desealing is necessary if the soil is covered with impervious paving preventing its colonisation with plants and organisms and water infiltration. As urban soils are often polluted (e.g., with oil or heavy metals), a (4) Soil remediation, including pollution treatment or containment, will be needed. More generally, a (5) Soil improvement can be envisaged: soil can be partially replaced with more fertile topsoil; simply decompacted and amended; or its horizons can be fully reconstructed using pedological engineering techniques. (6) Management of waste and excavated soil may follow steps (2) to (5), often implying storage in landfills. Finally, the soils’ surface can be vegetated – although natural colonisation is also possible – involving a (7) Planting step. Often in urban settings, restoration will be concluded with a (8) Management and monitoring step, possibly running over several years.

Within each step, several techniques can be involved, listed in Table 1 (see Annex 4.3 for definitions). Techniques can be more or less disaggregated: for example, the ‘soil construction’ technique is itself an assemblage of decompaction, the addition of various materials (rubble, etc.), compost and biostimulation techniques.

1.2 Costs of techniques

We then analyse the costs (in €/m²)⁴ associated with each step and technique. We exclude Planning and Land control from this analysis, because Planning was added *a posteriori* following experts’ suggestions, and because the costs of Land control are well-studied. The latter vary substantially with location (land prices are around 10,000€/m² in Paris, against 40€/m² for urban wasteland in the North département). Experts interviewed also stressed that the initial state of the soil could play a role. In particular, polluted sites can sell at a very low price.

We find significant variations in the costs’ orders of magnitude depending on the restoration step (as shown by the axes of each quadrant in Figures 2 and 1, or Figure A11). Preliminary studies appear cheaper (with average costs of each technique between 1-13€/m²), followed by Management and monitoring (1-29), Desealing (7-101), Soil improvement (2-114), Building demolition (15-225), Management of excavated soil and waste (26-484) and Soil remediation (35-559).

There are also important variations among the costs of techniques within each step. This is because techniques can be complementary or the sum of each other. However, sometimes techniques that are substitutes can have very different costs – for example, decontamination via thermal desorption appears more costly than via chemical oxydation. An interesting result is that techniques in the Preliminary studies step cost below 10€/m², which is low relative to other steps, going against the idea that limiting technical studies can strongly reduce restoration costs. Conversely, many experts we interviewed explained that poorly-made studies can *increase* the costs of the downstream restoration process due to the discovery of unanticipated soil contaminant, protected species, etc.

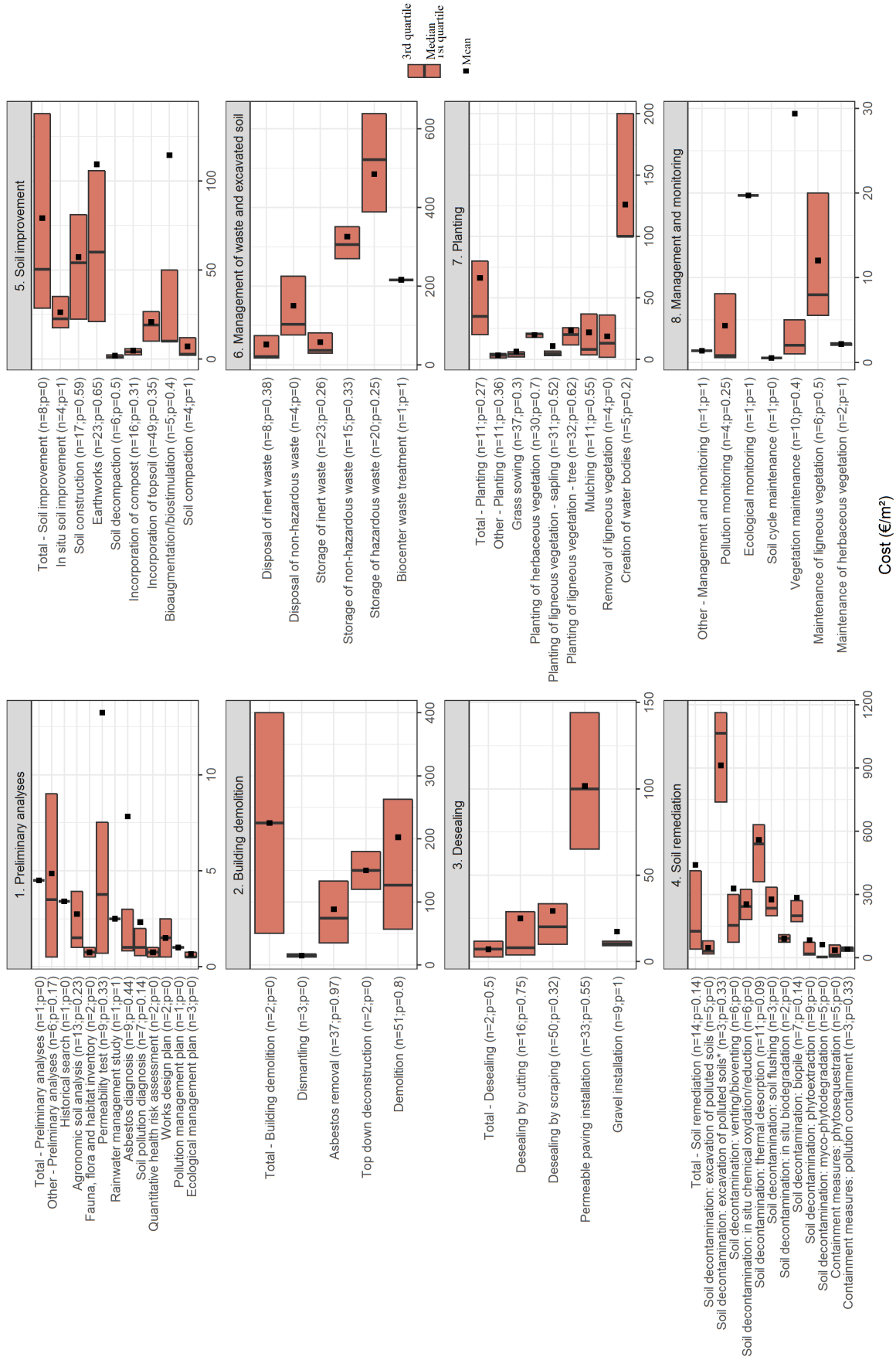
³In the anthropology of techniques, the concept of ‘operating chain’ or *chaîne opératoire* is a descriptive and analytical tool aimed at representing a technical process as a sequence of operations (see e.g., [Coupaye \(2022\)](#)).

⁴Costs in this paper are all excluding VAT.

Table 1: Steps and techniques of urban soil restoration

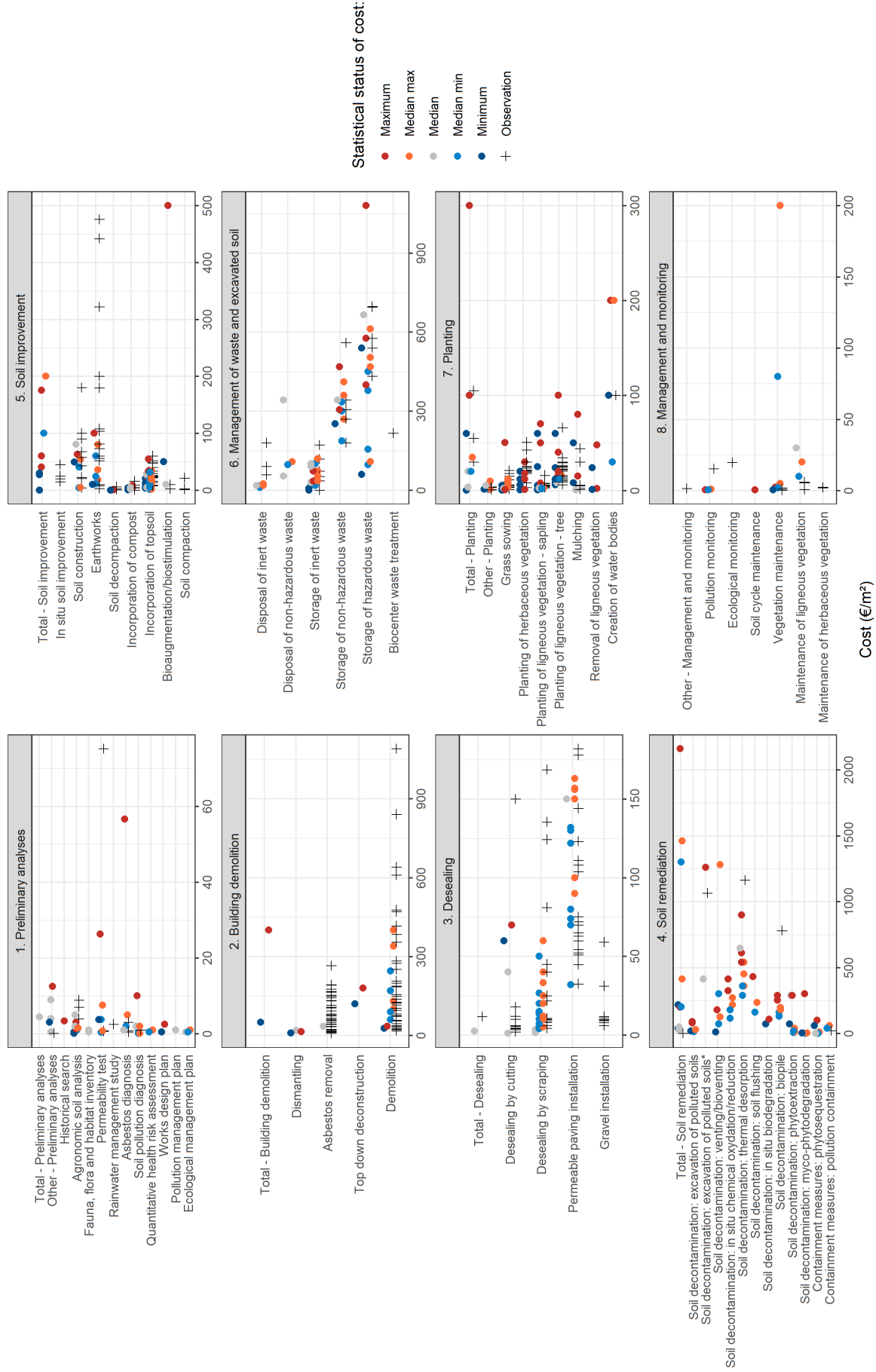
Step	Technique
-1. Planning	Total - Planning
0. Land control	Total - Land control Other - Land control
1. Preliminary analyses	Total - Preliminary analyses Other - Preliminary analyses Historical search Agronomic soil analysis Fauna, flora and habitat inventory Permeability test Rainwater management study Asbestos diagnosis Soil pollution diagnosis Quantitative health risk assessment Products, equipments, materials and waste diagnosis Work design plan Pollution management plan Ecological management plan
2. Building demolition	Total - Building demolition Other - Building demolition Dismantling Asbestos removal Lead removal Top down deconstruction Demolition
3. Desealing	Total - Desealing Other - Desealing Desealing by cutting Desealing by scraping Permeable paving installation Gravel installation
4. Soil remediation	Total - Soil remediation Other - Soil remediation Soil decontamination: excavation of polluted soils Soil decontamination: venting/bioventing Soil decontamination: <i>in situ</i> chemical oxydation/reduction Soil decontamination: thermal desorption Soil decontamination: soil flushing Soil decontamination: <i>in situ</i> biodegradation Soil decontamination: biopile Soil decontamination: phytoextraction Soil decontamination: myco-phytodegradation Containment measures: phytosequestration Containment measures: pollution containment Groundwater decontamination: pump and treat Groundwater decontamination: sparging
5. Soil improvement	Total - Soil improvement Other - Soil improvement <i>in situ</i> soil improvement Soil construction Soil reconstitution Earthworks Soil decompaction Incorporation of compost Incorporation of topsoil Bioaugmentation/biostimulation Soil compaction
6. Management of waste and excavated soil	Total - Management of waste and excavated soil Other - Management of waste and excavated soil Disposal of inert waste Disposal of non-hazardous waste Disposal of hazardous waste Storage of inert waste Storage of non-hazardous waste Storage of hazardous waste Biocenter waste treatment Crushing of inert waste
7. Planting	Total - Planting Other - Planting Grass sowing Planting of herbaceous vegetation Planting of ligneous vegetation - sapling Planting of ligneous vegetation - tree Mulching Removal of ligneous vegetation Creation of water bodies
8. Management and monitoring	Total - Management and monitoring Other - Management and monitoring Pollution monitoring Surveillance of access and use Management of invasive alien species Ecological monitoring Soil cycle maintenance Vegetation maintenance Maintenance of ligneous vegetation Maintenance of herbaceous vegetation Green waste recycling Green waste disposal Irrigation

Figure 1: Costs of techniques (in €/m²) - Distribution



Note: *n* indicates the number of costs used to build the distribution, *p* indicates the share of those costs which are of the type 'observation' as opposed to statistics.
 *Here, excavation costs also including earthworks, transportation and storage.

Figure 2: Costs of techniques (in €/m²) - By type of costs



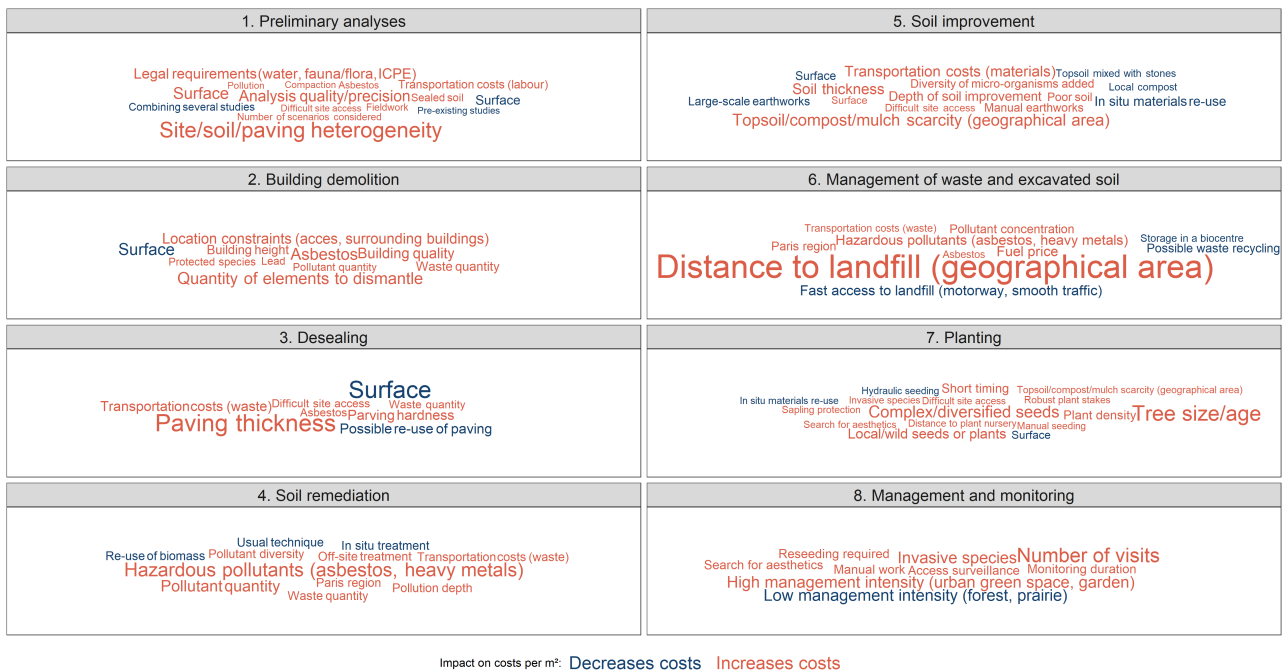
*Here, excavation costs also including earthworks, transportation and storage.

As the cost distributions in Figure 1 required making specific assumptions (see Section 3) to aggregate data with heterogeneous statistical status, Figure 2 also plots each cost estimate from our database. The apparent inconsistencies between expert declarations – e.g., with some estimations of ‘minimum’ costs being higher than estimations for ‘median’ or a ‘maximum’ costs – reflect that the different experts interviewed can be confronted with very different local situations – e.g., costs in the Paris area are often much higher than in other regions.

1.3 Costs drivers

We find that many steps can benefit from economies of scale: the ‘surface’ variable is often declared as pushing costs downwards (Figure 3) – in particular for the Desealing step, and to a lesser extent for Building demolition, Soil improvement, Planting and Preliminary studies. Conversely, according to our interviews, tight deadlines generally tend to push up the costs of the various steps.

Figure 3: Urban restoration cost drivers



Note: The size of words indicates the frequency with which they were mentioned by the experts interviewed and the documents reviewed. The drivers listed in this graph affect costs in €/m².

Most sources of cost variability strongly depend on the restoration step (Figure 3). For Preliminary studies, soil heterogeneity – a typical feature of urban soils, due to the long history of their uses (Morel et al., 2015) – pushes costs upwards as analyses will require more soil samples. Increased costs can also come from the presence of protected or invasive species, the difficulty of accessing the site or the transportation costs for technicians and engineers. For Building demolition, costs increase in particular if the building is close to other buildings or contains asbestos. Asbestos can also increase the cost of Desealing, along with the thickness and hardness of the paving. The costs of Soil decontamination increase with the depth, quantity and diversity of pollutants (making treatment more complex), and depending on where treatment occurs (off-site decontamination, which requires to transport the excavated soil, is quicker but more expansive than on-site). In the case of Soil improvement, the cost of topsoil is an important factor and can be much higher if the site is located in a region with a strong demand for this material, like in metropolitan areas, in particular near cities with ambitious plans to increase nature-based solutions. Likewise, re-using excavated soil (often less

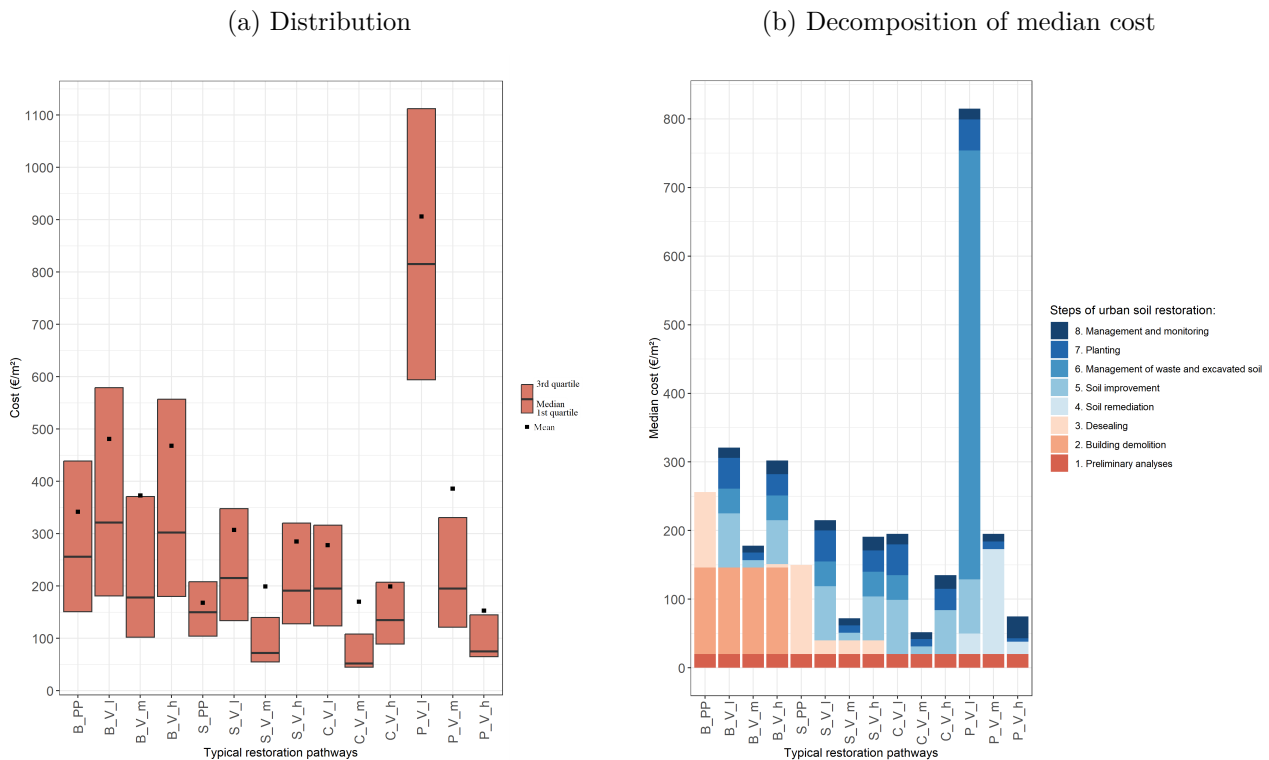
costly than topsoil) is difficult or impossible in dense cities with no available sites to store the soil. The cost of Managing waste and excavated soils will greatly depend on the accessibility to a nearby landfill, itself depending on the region, the presence of a nearby motorway and traffic congestion. Due to legal requirements (EU Directive 2008/98/EC on waste), higher fees must be paid for the disposal of polluted waste, in particular with heavy metals or asbestos. Finally, the costs of the Vegetation phase will increase when using diversified wild species of seeds, adapted to the local context, instead of standard grass. Overall, many experts explain that the research of (standard) aesthetic within a short timing increases costs, as it leads to favour high and more expansive trees, dense plantations and intensive plant management (lawn mowing, tree trimming) – although management and monitoring costs can also increase with unintended events, such as invasive species colonisation.

Finally, there are ways to decrease restoration costs. Pooling preliminary studies can make them cheaper. Using material found on-site or nearby, *in situ* pollution treatment or soil improvement techniques, can lower material and transportation costs. Re-using green waste and elements from demolished buildings or pavements can also decrease costs – although not systematically, because additional costs can be associated with the constraints imposed by re-using materials. For instance, deconstructing buildings so that elements like sinks, heaters or tiles can be re-used is more labour intensive than bare demolition. The money drawn from these elements’ sale may not be enough to compensate the additional costs.

1.4 Restoration pathways and associated costs

We combine steps and techniques into several restoration pathways, to move from a degraded soil to a ‘restored’ one. This allows obtaining typical costs for a comprehensive urban soil restoration process.

Figure 4: Cost of typical pathways (in €/m²)



Note: The name of each pathway have the following structure: *InitialState_FinalState_EcologicalEngineering*, where *Initial state* can be built-up (B), sealed with an impervious surface (S), compacted (C), or polluted (P); *Final State* can be porous paving (PP) or vegetation (V); *Ecological engineering* can be low (l), moderate (m) or high (h). Hypotheses for each pathway can be found in Annex 4.1.6.

Most of our scenarios display median costs between 50 and 320€/m², depending to a large extent on the initial state of soil degradation (Figure 4b). The restoration of compacted soils (*C_...*) yields median cost of around 50-200€/m²; followed by pathways with initially sealed soils (*S_...*) with median costs around 70-215€/m²; and initially built-up soils (*B_...*) with higher median costs (around 180-320€/m²), in particular due to demolition. By contrast, the median costs restoration pathways with an initially polluted soil (*P_...*) widely vary depending on the remediation technique used (from around 75€/m² for phytoremediation to more than 500€/m² for excavation). Although apparently cheap remediation techniques exist like phytodegradation, the latter remains at an R&D stage, cannot be used for all contaminants, require much more time, and must often be associated with other techniques, e.g., pollution containment. To a lesser extent, the final state of restoration also plays a role. Interestingly, installing porous paving – which is not proper ‘restoration’ as it only improves the soils’ water storage function – can be more expensive than soil’s greening.

However, costs can largely depart from the median (Figure 4a). Looking at the Q1-Q3 cost ranges, we find that restoring a polluted soil into a green area using soil excavation and disposal in landfill (*P_V_l*) can reach particularly high costs (Q3 is 1110€/m²), in particular because of the high cost of managing excavated soil. Exclude this particular pathway from the picture, we find parcel restoration costs ranging from 25€/m² (Q1 cost of a scenario with compacted soil restored into a vegetation area with low level of ecological engineering) to 465€/m² (Q3 cost of a scenario with a soil covered with a building, restored into a vegetation area with low level of ecological engineering). Figure A17a in Annex tests the sensitivity these our scenarios to alternative technical pathways, and shows for example that decontaminating using biopiles can be particularly expensive, and that asbestos can significantly increase the restoration costs of sealed soils.

Finally, costs do not increase linearly with the level of ecological engineering: for instance, greening with aesthetic objectives implies intensive management and planting mature trees and appears more expansive than restoring with a moderate involvement of ecological engineering (e.g., using seed mixes implying scarce mowing and planting younger trees). However, a higher reliance on ecological engineering techniques re-increases costs, as it implies creating habitats (e.g., a pond) and an important soil monitoring and maintenance to support the restoration process (cf. Figure 4b where costs associated with Management and monitoring are higher for pathways with high ecological engineering).

2 Discussion

2.1 Opening the black box of restoration costs

Our method of breaking down a restoration process into stages is innovative, and its transparency contrasts with other assessments of total restoration costs which do not document the steps and drivers explaining total costs (De Groot et al., 2013). It is particularly appropriate to the analysis of urban soil restoration processes, which can include a wide variety of situations (initial and final states) making global costs hard to understand.

Nevertheless, it faces some limitations. First, experts’ interpretations of what a given technique refers to can sometimes differ. For example, the cost of adding topsoil may be restricted to the topsoil’s cost for some, while other can also include the costs of groundwork and implementation.⁵ The decomposition in steps is also subject to overlaps. Some experts, for example, mention the distance to a landfill as a source of cost variability for the Desealing step, while it rather falls in the Management of waste and excavated soil step in our typology. Our method also misses the fact that, in reality, techniques can interact or be implemented simultaneously, which can impact costs. For example, remediation work can require the use of heavy machinery, with the unintended consequence that it will compact the soil and result in additional decompaction costs.

Despite those caveats, our results support this step-by-step approach. For instance, the costs of a restoration pathway implying the ‘soil construction’ aggregated technique (*B_V_h_soilconstruction*

⁵When experts make this decomposition explicit, we add this information in our database.

in Figure A17a) are similar to those of a soil construction process recomposed by summing the more granular techniques it involves (earthworks, adding stones and compost) (B_V_h). These tests overall validate our hypothesis that we can sum the costs of simpler techniques to obtain the costs of more complex ones.

2.2 ‘Typical’ urban soil restoration pathways

Our urban soil restoration pathways are archetypes and overlook several aspects. First, for simplicity, they exclude Land control and Planning – but as costs of the latter appear negligible compared with those of the works, they would only slightly increase total costs. Additional costs for project management (8% of the cost of works, according to experts) and taxes (VAT of $\approx 20\%$) should also be integrated to arrive at a complete estimate of total costs.

Second, we only focused on three parameters: the soil’s initial state, final state, and the ecological engineering involved. One could make soil’s initial and final condition more precise: in particular, location, surface, and type of sealing and pollutants are significant factors that could push costs upwards (e.g., in city centers) or downwards (e.g., economies of scales). In reality, technical pathways (final state and ecological engineering) are constrained by these initial characteristics, and costs can actually *determine* the chosen pathway rather than result from it. For example, decontaminating highly polluted sites can be extremely costly, so the soil’s final state and future use will be chosen to avoid complete decontamination – e.g., one will plant a forest with limited uses, rather than produce food. The chosen pathway can also be constrained by timing and political acceptability. For example, a mayor may prefer the planting of single species grass and mature trees to ambitious ecological engineering because the former may be more rewarding politically, as the outcome is quickly visible and follows the aesthetic standards of voters.

Finally, the way we defined levels of ‘ecological engineering’ in pathways, based on a set of grey and academic literature, can also be discussed. In particular, there can be trade-offs between the various environmental impacts of techniques: *in situ* soil improvement or remediation can negatively affect soil’s ecological functions. For example, *in situ* thermal desorption can reduce biological activity (ADEME et al., 2018), but has low CO₂ emissions because it doesn’t involve transporting excavated soil or soil construction material. Some specific restoration techniques are also debated – soil construction is for example criticized for focusing on emphasising soil’s productive properties at the expense of its intrinsic or cultural values (Meulemans, 2020). Some experts interviewed were also critical of building soils with construction waste that could be re-employed for other uses (e.g., pavement) and favoured ‘reconstituting’ soils with excavated ground. Finally, ‘ecological engineering’ in our typical pathways overlooks the site’s ecological connectivity – re-creating ‘green’ and ‘brown grids’ – while it is an important element of ambitious soil restorations (Deboeuf de Los Ríos et al., 2022).

Still, our pathways can be seen as representative of real-life urban soil restoration projects. For example, turning a sealed soil green (pathway $S_V_...$, with average costs between 199 and 307€/m²) typically represents restoration projects in schoolyards, parking lots or graveyards. The cost for real schoolyards restorations provided by some experts (around 200-300€/m² in Paris – excluding urban furniture – and 200€/m² in South-East cities) are consistent with our results.⁶ However, pathways with more complex initial states – e.g., simultaneously polluted, sealed and built-up – could better represent certain real-life situations – e.g., industrial wasteland. Finally, our pathways overlook some of the ‘surprises’ (Brunet, 2020) and uncertainties coming with remediation and ecological restoration that may imply unexpected additional costs.

2.3 Perspectives on restoration costs

We find median urban restoration costs between 50 and 320€/m², but up to 800€/m² for polluted soils. This order of magnitude is higher but overall consistent with Fosse et al. (2019) who find costs ranging from 33€/m² for a low-cost soil construction to 455€/m² for a restoration with costly demolition,

⁶Parisian costs are often in the top of cost distributions (Section 1.3).

desealing, remediation and soil construction. The costs we document are also much higher than for most ‘standard’ ecosystem restorations (with forests or grassland restoration below 1\$₂₀₀₇/m²), and are comparable to the costs of restoring coral reefs (De Groot et al., 2013) (see Annex 4.7). Urban soil restoration costs also appear particularly significant when compared to the purchase price of a building plot (92€/m² on average in France in 2022).⁷

High costs highlight the importance of *avoiding* soil degradation. During interviews, many experts were confused by our focus on restoration costs, rather than benefits, and feared it would provide arguments against urban soil restoration. Although we acknowledge that urban soil restoration has many benefits,⁸ assessing restoration costs can also *encourage* soil restoration, as it allows to value soil ecosystems,⁹ in line with a strong sustainability approach (Levrel et al., 2014). This is close to the concept of ‘ecological debt’ (Feger et al., 2023; Kervinio et al., 2023): if they don’t reach the ecological objectives defined by legal norms, organisations (e.g., firms, States) contract an ecological debt and should provision money for ecological restoration in order to pay it back. Using the restoration costs estimated by Fosse et al. (2019), Gonon et al. (2021) apply this conceptual framework to the French ‘no-net land take’ (NNLT) objective, and estimate that a business-as-usual scenario (i.e. inaction) would lead to accumulating an ecological liability of 154-632 EUR billion over 2020-2030.

Restoration costs can also help planning investments to improve urban ecosystems. As they largely depend on technical aspects, restoration costs have the advantage of being rather stable in time and space – at least compared with estimations of ecosystem benefits, varying with people’s preferences (e.g., between urban and rural dwellers, income groups, etc.). Making projections would involve characterizing the evolution of three important costs drivers: availability of topsoil, availability of sites to store excavated soil, and future costs of energy. Similarly, our estimates can be used in other geographical contexts than metropolitan France – although with caution, and accounting for the sources of variability we document.

Finally, the focus on *restoration*, instead of avoidance of degradation, may convey the idea that the loss of soil ecosystem is reversible, which it isn’t. Restoration takes time, has uncertain success (Maron et al., 2012), and may not fully replace the services provided by natural ecosystems. Existence, patrimonial and cultural values attached to soils are permanently affected by their degradation. Further research should therefore also explore the costs associated with investments to avoid and reduce the degradation of natural soils by urbanization.

⁷<https://www.statistiques.developpement-durable.gouv.fr/media/6902/download?inline>

⁸Joint Research Centre and European Environment Agency (2012) estimates the total costs of soil degradation in the form of erosion, organic matter decline, salinisation, landslides and contamination to EUR 38 billion annually for the EU-25 (see also Graves et al. (2015) for example). This points to the ‘benefits’ of restoring soils, in contrast with the restoration costs estimated in this paper.

⁹As part of the ‘cost-based estimation approaches’ for valuing ecosystems (Garrod and Willis, 1999). This method contrasts with approaches assessing ecosystem services based on people’s willingness to pay for the ecosystem’s restoration or preservation, which can result in low value for ecosystems if individuals do not perceive all the benefits ecosystems provide. This is particularly the case for invisible ecosystems (Dasgupta, 2021) like soils, which face the risk of remaining under-valued with this second type of method.

3 Method

3.1 Building a typology of steps and techniques for urban soil restoration

Following Fosse et al. (2019), we gather costs for various steps involved in a restoration process. There are several reasons for adopting such a modular approach. First, the restoration of urban soils involves multiple experts who may not all follow the restoration process from start to finish — an expert in landscaping may, for example, intervene to do the plantations without having been previously involved in the demolition of buildings or the decontamination of the soil. In addition, even if they have no experience in urban soil restoration *per se*, experts may have a good knowledge of the costs associated with techniques possibly intervening in a restoration process. For example, a company that decontaminates brownfields so that they can be re-built has valuable knowledge on depollution costs, even if it does not operate with the final objective of restoring soils. We also expected that experts would find it easier to give explicit costs for specific steps and techniques than to estimate the global cost of a comprehensive restoration process, as the latter can refer to very different situations and depend on multiple parameters.

We construct our typology of steps and techniques using two types of materials: interviews and grey literature. We conducted ten exploratory interviews with heads of scientific, technical or professional networks linked to ecological engineering, managers of restoration funding programmes (‘Fonds friches’ and ‘Nature 2050’) and scientific personalities with expertise in soil restoration. The objective of this first round of interviews was to understand the scientific and institutional background of urban soil restoration and to discuss the appropriate methodology for assessing soil restoration costs. Many experts were in line with the idea of processing via the definition of steps and helped us define the operations involved in urban soil restoration. In addition to providing advice on how to structure our data collection phase, they also helped us identify the categories of actors likely to have information on costs. In parallel, we reviewed several reports and documents describing detailed urban soil restoration processes (Deboeuf de Los Ríos et al., 2022; Castaing et al., 2022; Neaud, 2021; Limasset et al., 2021; Taugourdeau et al., 2020; Poudevigne et al., 2017; ADEME et al., 2018). This first phase enabled us to define a list of steps (or ‘operations’) that can intervene to restore urban soils that we disaggregate into a range of more specific substeps (or ‘techniques’).

3.2 Data collection and treatment

3.2.1 Data collection

The costs are collected based on an expert survey. We select the expert participating in the survey based on recommendations made during the first round of interviews, our own investigations, and then a ‘snowball sampling’ method (asking experts whether they knew other persons who could provide relevant answers to our questionnaire). Eventually, out of 169 experts contacted by email, 53 actively contributed to our research by agreeing to an interview or providing us with helpful information or documents via email or non-structured calls. We conducted structured interviews on the questionnaire with 46 experts. 61% of them came from private companies, 22% from public administrations, 13% from local municipalities, 2% from research and 2% from non-profit associations. More details about the interviewed experts can be found in the Annex. The interviews mainly took place by videoconference – except for two of them – and lasted 66 minutes on average.

Each interview consists of three main steps. (i) We go through our list of steps, define each of them and ask the expert to point to the ones she is most familiar with. We also ask her whether she will provide costs including or excluding VAT. (ii) For the restoration step selected by the expert, we present the different techniques it involves. For the overall step (e.g., ‘Planting’), and then for each technique possibly involved in the operation (e.g., ‘planting of herbaceous vegetation’, ‘mulching’, etc.), we ask the expert if she can give indicative costs, without putting any constraint on their unit (€/ton, €/m³, €/study, etc.) nor type (median, observation or range).¹⁰ We also ask for the parameters she

¹⁰It contrasts with more structured expert elicitation methods, where precise estimations of quantiles and distributions

believes are most likely to make these costs vary and, if possible, for the direction in which these drivers would play (upward or downward). (iii) We conclude the exploration of the restoration step by asking the expert if she sees essential techniques missing, and, if so, to provide associated costs.

Finally, after reviewing all the steps selected by the expert, we conclude the interview by asking if she could send us any document that would provide additional information regarding the costs of the steps and techniques we reviewed together.

3.2.2 Data treatment

Compilation of a cost database. We extract the costs from the interview transcripts and put them in a structured database (variable names are in Annex 4.1.4). Specifying the statistical status of the costs given orally can be a challenge. Indeed, when costs were explicitly mentioned by experts as being a minimum, a maximum, or a single observation (i.e. coming from a specific experience or quote), their statistical status is straightforward. However, some ambiguity emerges when experts said things like (i) ‘it usually costs around 3€/m²’, (ii) ‘it can range from 10€/m² to up to 300€/m²’ or (iii) ‘it is around 45-50€/t’. When, as in example (i), experts gave a unique point estimate coming from a broad range of experiences (as opposed to an observation reflecting a particular case), we classify the cost as being a ‘median’. For ranges, such as in examples (ii) and (iii), we differentiate between cases where the costs given are likely to be a minimum and a maximum, as in example (ii), and cases where it is probably a closer interval around the median (such as a Q1-Q3 interval), such as in example (iii). Costs of the case (ii) type are therefore labelled as ‘minimum’ and ‘maximum’, while we classify those similar to case (iii) as ‘median min’ and ‘median max’.

Similarly, we add to the database costs coming from the wide range of documents provided by the experts, which can be public reports, presentations and databases, as well as confidential or private quotes (‘devis’, ‘bordereaux de prix’), grant application files (‘dossier de demande de subvention’), and technical studies (Table A4).

Compilation of a drivers database. We build a second database focusing the cost drivers given by experts and documents. We standardize the drivers under short categories (e.g., if an expert says: ‘it is more expensive to use a large variety of seeds than to use standard grass’, the driver is labeled as ‘seed diversity’, with a positive impact on costs), while trying to maintain the specificity of each driver as much as possible (e.g., using ‘local seeds’ is not the same category as using ‘diversified seeds’). We also specify the direction in which the driver influences costs, based on the interviews and documents. When a driver was given without detail on its direction in one interview, we infer the direction based on the information from other interviews - if possible; otherwise, we label the direction as ‘undefined’. Finally, when using this database to build Figure 3, we apply a specific treatment to the ‘surface’ driver and keep only those which were provided as having a *negative* impact on costs. Indeed, this graph focuses on the drivers of costs in €/m², and there are good reasons to believe that people mentioning ‘surface’ as having a positive impact on costs were thinking about the *total* cost of the operation (e.g., of a preliminary analysis) rather than cost in €/m².

Additional treatments to obtain cost distributions in €/m². For our results to be comparable with other studies, we convert costs into €/m² (while they were initially collected in various units). Such conversion requires a set of hypotheses that we make based on the information collected during interviews. We present them in Table A5, along with sensitivity analysis (Figure A16). Nevertheless, some costs cannot be converted into €/m² – for example, when experts gave the total cost of a study without mentioning the site’s surface. Hence, while our initial database (all units included) contained 807 cost estimates, the database used in this paper – where costs were converted in €/m² – has 748 cost estimates. Figure A14 also provides results where we converted costs in the unit most used for each technique, rather than m² (alternative database, with 793 cost estimates).

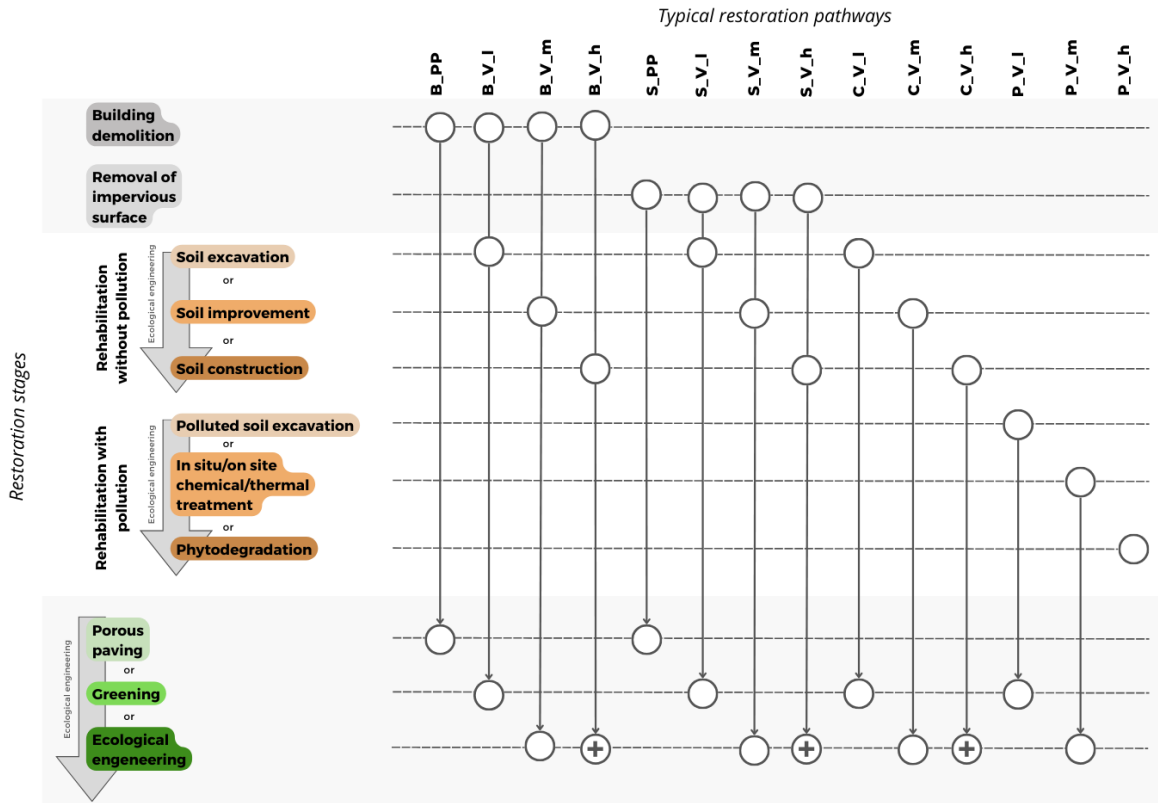
are asked (Verdolini et al., 2018). This is because the experts we interviewed are not necessarily familiar with providing standard costs, especially given the wide variety of contexts in which they intervene. Hence, they could find it very difficult to come up with detailed cost distributions for each technique.

Another challenge relates to the construction of cost distributions and statistics (e.g., medians or means) based on initial data with heterogeneous statistical status (medians, minima, maxima, observations, etc.). Therefore, we provide graphs that represent the different types of points given by experts, without any type of aggregation. Then, to build distributions and statistics, we choose to consider each point as an observation, whatever its initial statistical status. In particular, this leads to weighting the statistics stemming from the long-lasting experience of experts in the same way as single observations. Therefore, we provide sensitivity analysis where we give a weight of 50 to costs which have a status of ‘statistics’, against a weight of 1 for simple observations (Figure A15). This changes the results only marginally.

3.3 Building scenarios of typical restoration pathways

To provide orders of magnitude of the costs associated with a complete restoration process at a parcel level, we combine the costs of these different steps into ‘typical pathways’. In the vein of Phillips-Mao et al. (2015), these pathways depend on three main aspects, which are likely to condition the steps adopted during the restoration process: (i) the initial state of the soil, (ii) the final state one wants to reach via the restoration process, and (iii) the level of ecological engineering involved in the restoration. We focus on a theoretical parcel of 1m² and assume that costs of steps can be summed up to obtain the final cost of the restoration pathway.

Figure 5: Steps involved in each scenario

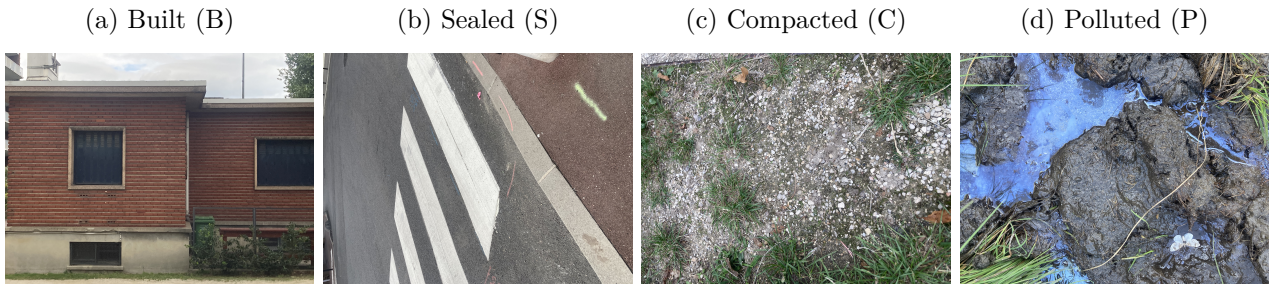


Note: The name of scenarios have the following structure: InitialState_FinalState_EcologicalEngineering, where Initial state can be built-up (B), sealed with an impervious surface (S), compacted (C), or polluted (P); Final State can be porous paving (PP) or vegetation (V); Ecological engineering can be low (l), moderate (m) or high (h). Circles with a ‘+’ sign indicate a higher ambition in the ecological engineering than plain circles.

We distinguish between four different initial states of the parcel’s urban or highly degraded soil. It can either be built on (B), sealed with a impervious surface (S), compacted (C), or polluted (P).

For the sake of simplicity, we exclude soils having multiple of these initial features (e.g., both sealed and polluted) from our scenarios.

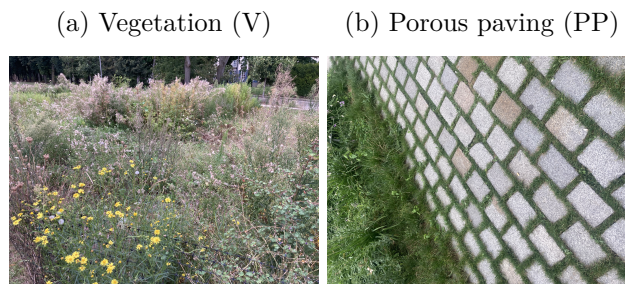
Figure 6: Typical pathways – Initial states



Source: Authors.

Then, we assume that two main final states can be reached: the soil is either covered with porous paving (PP) or vegetation (V). However, we focus on pathways where the situation between the initial and final improves: therefore, only soils that were initially built on or sealed can reach a “porous paving” final state.

Figure 7: Typical pathways – Final states

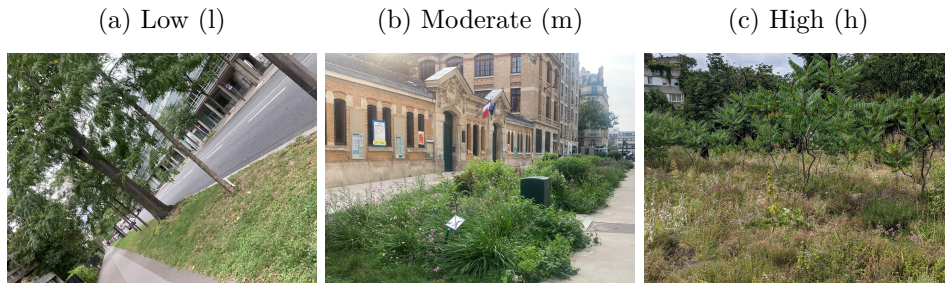


Source: Authors.

Finally, to move from the initial to the final state, we make a distinction between different levels of ecological engineering: low (l), moderate (m) or high (h), as characterized based on the grey literature (see Figure A4). In our typical pathways, a low level of ecological engineering translates into a bare excavation of the degraded or polluted soil, and its replacement with topsoil from agricultural areas taken by urbanization ([Programme SITERRE, 2015](#)). Then, the soil’s surface is only “greened” with single species grass and a few large trees, and subject to intense management (mowing, trimming, etc.), just like a traditional urban park ([Deboeuf de Los Ríos et al., 2022](#)). A moderate level of ecological engineering consists in trying to improve the (unpolluted) soil as it is, by decompacting and improving it with compost ([Taugourdeau et al., 2020](#)). If the soil is polluted, we consider that removing the contaminants on site or in situ with chemical, physical or thermal techniques also falls into the category of a moderate ecological engineering ([ADEME et al., 2018](#)). In the following vegetation phase, it consists in planting multi-species grass with younger trees (saplings) and limiting the intensity of the management to allow plants to develop more freely ([Deboeuf de Los Ríos et al., 2022](#)). Finally, we define a high level of ecological as the complete reconstruction of the (unpolluted) soil: construction waste or excavated ground is combined with compost to recreate soils’ horizons, following a pedological engineering approach ([Taugourdeau et al., 2020](#)). It is followed by an ambitious vegetation stage (planting of multi-species and local seeds, small trees, creation of habitats such as a pond) with no monitoring (free evolution). If the soil was initially polluted, however, we consider ambitious ecological

engineering consists in using phytodegradation to remove the pollutants, which implies that there is no soil reconstruction nor additional “planting” phase but that the management of the vegetation is rather intensive (to reap the plant extracting the pollutants). However, one should read these scenarios as “ideal types” used to gauge the effect of ecological engineering on costs but keep in mind that, in reality, what is possible to implement is very site-dependent.

Figure 8: Typical pathways – Ecological engineering involved



Source: Authors.

For each pathway, we then sum the costs of specific steps from our typology, shown in Figure 5 and detailed in Table A3. The cost *distribution* for each scenario is obtained in the following way: to compute the median (respectively Q1 and Q3) cost, we sum the median (respectively Q1 and Q3) cost of each technique involved in the scenario. In some scenarios, some techniques are given more weight than other, to reflect that they are involved only partially, or multiple times (Table A3). For example, for scenarios where a pond is created, we assume that it represents only 1/5 of the restored soil surface. Weights can also reflect that in certain scenarios, we can expect costs to be lower or higher than in their typical distribution - for example, in a case with little management of the vegetation, management costs are expected to be lower.

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4 Annex

4.1 Method

4.1.1 List of interviews

Exploratory interviews:

Table A1: List of exploratory interviews

Interview identifier	Position	Organisation	Date	Duration (min)
Itw_E1	Chairman	A professional union on ecological engineering	07/04/2023	70
Itw_E2	Head of Land Development and Biodiversity Coordinator	Private company specialised in brownfield site restoration, landscaping, reuse of excavated soil	18/04/2023	105
Itw_E3	Director & Manager ; Administrator	Soil and landscape design and engineering office ; Association for the promotion and development of research and experiments on nature in cities	26/04/2023	70
Itw_E4	Project Manager	Regional network helping to accelerate innovation in public works and civil engineering to support the transition to energy, ecology and digital infrastructure	02/05/2023	63
Itw_E5	Chief Executive Officer; Administrator	Ecological engineering design office; Professional union of environmental scientists	03/05/2023	30
Itw_E6	Senior lecturer in ecology; Member; Chairman	University ; Network on restoration ecology; Association of ecological engineering players	05/05/2023	30
Itw_E7	PhD Student, Member of a research project on soils' desealing ecological impacts	National public establishment for the ecological transition; Association for the promotion and development of research and experiments on nature in cities	09/05/2023	88
Itw_E8	Polluted sites project manager	National public establishment for the ecological transition	10/05/2023	115
Itw_E9	Ecologist	Regional biodiversity agency	16/05/2023	52
Itw_E10	Development engineer	Local public body responsible for establishing land reserves prior to the implementation phase of public development projects	23/05/2023	30

Interviews with questionnaire:

Table A2: List of interviews (with questionnaire)

Interview Identifier	Position	Organisation description	Type of organisation	Date	Duration (min)
Itw_01	Director	Engineering and consultancy firm specialising in urban regeneration strategies and techniques	Private company	20/06/2023	63
Itw_02	Scientific manager of a program on remediation of polluted sites and soils	National public body specialised in the application of earth sciences to the management of soil and subsoil resources and risks	Public institution	26/06/2023	60
Itw_03	President	Design and engineering office for phytomanagement and restoration of degraded soils	Private company	26/06/2023	59
Itw_04	Research engineer	Soil research and engineering office specialised in diagnosis, reconstitution or construction of soil, and creation of fertile substrate	Private company	26/06/2023	55
Itw_05	Co-founder	Landscape agency	Private company	28/06/2023	58
Itw_06	Sector manager	Public works company specialising in the deconstruction of buildings	Private company	30/06/2023	62
Itw_07	Coordinator of a program on Brownfields	National public establishment for the ecological transition	Public institution	30/06/2023	32
Itw_08	Director of Studies, Works, Estates and Environmental Remediation	Local public body responsible for establishing land reserves prior to the implementation phase of public development projects	Public institution	03/07/2023	65
Itw_09	Head of urban projects	Design and engineering office for agricultural soil decontamination by phytoremediation	Private company	03/07/2023	84
Itw_10	Deputy Director of Strategy and Land Operations	Governing body of a large metropolis (>1M inhabitants)	Local government	05/07/2023	60
Itw_11	Consultant in applied ecology	Design office and Consultancy in ecology and urban biodiversity	Private company	05/07/2023	56
Itw_12	Researcher	University, Research unit on soils and the environment	Research organisation	06/07/2023	63
Itw_13	Head of the Ecosystems Division	Consultancy and engineering firm specialising in polluted sites and soils	Private company	07/07/2023	120
Itw_14	Head of the « Nature in the city » service	Public works company specialising in the construction and maintenance of roads, transport infrastructure and public spaces	Private company	10/07/2023	25
Itw_15	Scientific and Technical Director	Company specialising in soil science consultancy (agronomy, pedology, ecology, ecotoxicology) and regional planning	Private company	10/07/2023	72
Itw_16	Architect and programmer	Architecture and urban planning agency	Private company	10/07/2023	73
Itw_17	Operations manager specialising in polluted sites and soils	Local public body responsible for establishing land reserves prior to the implementation phase of public development projects	Public institution	11/07/2023	78
Itw_18	Environmental engineer	National public body specialised in the application of earth sciences to the management of soil and subsoil resources and risks	Public institution	11/07/2023	52
Itw_19	Project manager on Assistance to environmental works	Multi-disciplinary company specialising in architecture, urban planning, design, engineering, programming, consultancy and project management, related to the ecological transition	Private company	11/07/2023	30
Itw_20	Project Manager on Polluted Sites and Soils	Local public body responsible for establishing land reserves prior to the implementation phase of public development projects	Public institution	13/07/2023	67
Itw_21	Sanitation and rainwater expert	Regional public body responsible for combating pollution and protecting aquatic environments	Public institution	13/07/2023	35
Itw_22	Head of studies and training	Association promoting and developing skills in integrated water management	Association	18/07/2023	40
Itw_23	Project manager	Urban hydrology consultancy	Private company	19/07/2023	90
Itw_24	Environmental engineer	Environmental design and engineering office (management of polluted sites and soils, redevelopment of brownfield sites, biodiversity impact studies)	Private company	19/07/2023	20
Itw_25	Ecological transition project manager	Local public body responsible for establishing land reserves prior to the implementation phase of public development projects	Public institution	20/07/2023	39
Itw_26	Manager	Design and engineering office on Soils	Private company	24/07/2023	14
Itw_27	Sector manager for ecological engineering in charge of "nature in city"	Subsidiary of a civil engineering company specialising in ecological engineering	Private company	26/07/2023	64
Itw_28	Regional Director	Company specialising in the treatment and recovery of organic waste, pollution control and soil remediation	Private company	27/07/2023	50

Table A3: List of interviews (with questionnaire) - Continued

Interview Identifier	Position	Organisation description	Type of organisation	Date	Duration (min)
Itw_29	Landscape and urban planning project manager	Landscape and urban planning agency	Private company	03/08/2023	64
Itw_30	Head of sustainable building R&D	Governing body of a large metropolis (>1M inhabitants), Public buildings and architecture department	Local government	03/08/2023	42
Itw_31	Works engineer	Environmental and ecological engineering consultancy	Private company	07/08/2023	46
Itw_32	Director and manager	Soil and landscape design and engineering office	Private company	9/08/2023	165
Itw_33	R&D Manager	Consulting and engineering firm in territorial water management	Private company	10/08/2023	34
Itw_34	Managing Director	Consultancy and engineering firm, advising on regional planning, construction and the environment	Private company	21/08/2023	48
Itw_35	Polluted sites and soils engineer	Electricity production and supply company	Company	21/08/2023	101
Itw_36	Water and Pollution Intervention Officer	Regional public body responsible for combating pollution and protecting aquatic environments	Public institution	21/08/2023	69
Itw_37	Manager	Public works company specialising in earthworks, demolition and roads and other networks	Private company	05/09/2023	55
Itw_38	Integrated rainwater management project manager	Regional public body responsible for combating pollution and protecting aquatic environments	Public institution	06/09/2023	50
Itw_39	Director	Ecological engineering company specialising in soil microbiology and green spaces	Private company	08/09/2023	54
Itw_40	Development Director	Company specialising in the reuse and agronomic recovery of inert earth from earthworks sites	Private company	11/09/2023	58
Itw_41	Urban planning and green spaces department	Governing body of a local municipality (>100 000 inhabitants)	Local government	15/09/2023	155
Itw_42	Project manager Project management assistance	Urban agriculture consultancy	Private company	06/10/2023	68
Itw_43	Integrated and sustainable rainwater management project manager	Department responsible for a local municipality (>100000 inhabitants)'s public water and wastewater services	Local government	12/10/2023	45
Itw_44	Head of operational infrastructure management	Governing body of a local municipality and conurbation (>50 000 inhabitants)	Local government	23/10/2023	63
Itw_45	Senior works manager	Public works company specialising in the construction and maintenance of roads, transport infrastructure and public spaces	Private company	08/11/2023	55
Itw_46	Head of public space projects	Governing body of a large metropolis (>1M inhabitants), Department of Territorial Affairs	Local government	07/11/2023	80

4.1.2 List of cost documents

Table A4: List of collected documents used to extract costs

	Type of document	Type of project	Date	ID in database
Doc_1	Price schedule (Bordereau de prix plafond)	Unsealing and revegetation of a schoolyard	2019	Feuil20
Doc_2	Internal quote analysis (Analyse interne d'un devis)	Unsealing and revegetation of a schoolyard	2019	Feuil22
Doc_3	Price schedule (Bordereau de prix plafond)	Unsealing and revegetation of a schoolyard	2019	Feuil21
Doc_4	Graph and Quote	Excavation and disposal of polluted soil	Unknown	Feuil19
Doc_5	Data table	Unknown	Unknown	Feuil18
Doc_6	Data table	Unknown	Unknown	Feuil17
Doc_7	Table with cost references	Demolitions of detached houses	2017 - 2019	Feuil17
Doc_8	Table with cost references	Demolition of semi-detached houses	2018 - 2019	Feuil17
Doc_9	Table with cost references	Demolition of tertiary structures	2019 - 2020	Feuil17
Doc_10	Table with cost references	Demolition of agricultural sheds	2019	Feuil17
Doc_11	Table with cost statistics	Demolitions	2017-2020	Feuil17
Doc_12	Table of indicative unit prices	Unsealing and rainwater management	2024	Feuil15
Doc_13	Table with cost statistics	Various steps in a restoration process	After 2010	Feuil14
Doc_14	Public presentation (slide show) and cost table (email)	Installation of constructed technosols on an unpolluted wasteland	Around 2019	Feuil10
Doc_15	Grant application file to the water agency	Unsealing and revegetation of a schoolyard	2020	Feuil8
Doc_16	Technico-economic study with provisional budget	Unsealing of four schoolyards, planting, pond, creation of habitats for biodiversity	2022	Feuil9
Doc_17	Grant application file to the water agency	Unsealing and redevelopment of rainwater management in public spaces	2022	Feuil7
Doc_18	Grant application file to the water agency	Redevelopment of a housing estate, unsealing and rainwater management	2022	Feuil6
Doc_19	Project sheet	Urban micro-forests	2021	Feuil11
Doc_20	Project sheet	Rain garden - Unsealing for rainwater management	2023	Feuil11
Doc_21	Project sheet	Urban 'oasis'/island of thermal comfort	2023	Feuil11
Doc_22	Project sheet	Urban 'oasis'/island of thermal comfort	2023	Feuil11
Doc_23	Webconference slide presentation	32 urban micro-forest projects	2023	Feuil11
Doc_24	Breakdown of Global and Unit prices - "Roads and Miscellaneous Networks" (DPGF, Décomposition du prix global et forfaitaire - lot VRD)	Unsealing and revegetation of a schoolyard	2021-2022	Feuil2
Doc_25	Breakdown of Global and Unit prices - "Green Spaces" (DPGF, Décomposition du prix global et forfaitaire - lot Espaces verts)	Unsealing and revegetation of a schoolyard	2021-2022	Feuil3
Doc_26	Description of works costs	Transformation of a car park into an urban forest	2021	Feuil4
Doc_27	Report	Remediation of industrial wasteland	2010	Feuil12
Doc_28	Management plan	Remediation of a polluted former factory	2019	Feuil13
Doc_29	Report	Landscaping incorporating alternative rainwater management	2022	Feuil16
Doc_30	Report	Final report on the Siterre programme - Soil construction using innovative materials to replace topsoil and quarry aggregates	2015	Feuil23
Doc_31	Report	ADEME report on the conversion of polluted wasteland	2018 (experience feedback from 2010-2016)	Feuil24
Doc_32	Report	BioTUBES report on soil remediation on unpolluted brownfield sites	2020	Feuil25
Doc_33	Report	Report on "Renaturing Cities"	2022	Feuil26
Doc_34	Website	Soil and groundwater remediation	Last update on 2019	Feuil27

4.1.3 Questionnaire

Interview procedure: We start by presenting the objective of our study, and the expert introduces herself and her field of expertise. We then show the expert our written questionnaire. When we conducted the interviews by videoconference, as is the case for the majority of them, we simply use the screen-sharing tool. When conducted in person (one interview), we show a printed version of the questionnaire. For interviews made by phone (with no video), we sent the expert the questionnaire via email.

Figure A1: Extract of the questionnaire (in French)

3. Structure du questionnaire pour chaque étape

- Définition de l'étape
- Description des sous-étapes
- Comment pensez-vous connaître cette étape ?
 - Très bien : c'est votre cœur de métier
 - Bien : vous côtoyez régulièrement des acteurs travaillant sur cette étape
- Vous allez donner des coûts :
 - HT
 - TTC

Coût des sous-étapes

Pour chaque sous-étape :

- Êtes-vous en mesure de donner une estimation des coûts de cette sous-étape ?
 - Oui
 - Non
- Pourriez-vous estimer un coût minimum pour cette sous-étape ? (merci de n'entrer que des nombres) _____
- Pourriez-vous estimer un coût maximum pour cette sous-étape ? (merci de n'entrer que des nombres) _____
- Quelle est l'unité de coût ?
 - €/m²
 - €/m³
 - €/t
 - Autre : _____
- Quels seraient les facteurs susceptibles de faire varier ces coûts ?

Figure A2: Extract of the questionnaire (English translation)

3. Structure of the questionnaire for each step

- Definition of the step
- Definition of the techniques involved by the step
- How well do you know this specific step?
 - Very well: this is the heart of your professional activity
 - Well: you are often in contact with experts of this step
- You will give costs:
 - Excluding VAT
 - Including VAT

Cost of techniques

For each technique:

- Are you able to give a cost estimation for this specific technique?
 - Yes
 - No
- Could you give a minimum cost for this technique? (numbers only)

- Could you give a maximum cost for this technique? (numbers only)

- What is the cost unit?
 - €/m²
 - €/m³
 - €/t
 - Other: _____
- What are the variables likely to affect these costs?

4.1.4 Raw database variables

Database structure and variables:

- **Source:** (*string*) Source of the data, takes the value 'Entretien' if it comes from directly from an expert interview, and 'Document' if the data was obtained from a document transmitted by an interviewed expert;
- **id_itw:** (*numeric*) Interview or document number.
- **Etape:** (*string*) Name of the step.
- **Sous_etape:** Name of the technique.
- **Point_min:** (*numeric*) Cost estimate, when it was given as a minimum
- **Point_median:** (*numeric*) Cost estimate, when it was given as a median
- **Point_max:** (*numeric*) Cost estimate, when it was given as a maximum

- **Plage_mediante_min:** (*numeric*) Cost estimate, when it was given as a median range (e.g. 'it is around 4-6€/m²'). This column takes the minimum of the given range (e.g., 4)
- **Plage_mediante_max:** (*numeric*) Cost estimate, when it was given as a median range (e.g. 'it is around 4-6€/m²'). This column takes the maximum of the given range (e.g., 6)
- **Observation:** (*numeric*) Cost estimate, when it was given as an observation (taken from a specific experience, quote, etc.);
- **facteur_conversion:** (*string*) Information given by the expert or the document helping with the conversion in €/m² or in €/majority unit
- **commentaire:** (*string*) Comment on the cost estimate (e.g., detailing what it includes)
- **Unite_cout:** (*string*) Cost unit (€/...).
- **unit_majoritaire_se:** (*string*) Majority unit at the technique level (e.g., the costs of planting trees is mostly given in €/tree).
- **vers_unite_majoritaire:** (*numeric*) Coefficient used to convert the given cost into €/majority unit of the technique it belongs to (based on hypotheses made in sheet 2 of the Excel)
- **vers_m²:** (*numeric*) Coefficient used to convert the given cost into €/m² (based on hypotheses made in sheet 2 of the Excel)
- **commentaire_vers_unite_majoritaire:** (*string*) Justification for the coefficient used to convert the given cost into €/majority unit of the technique it belongs to.
- **commentaire_vers_m²:** (*string*) Justification for the coefficient used to convert the given cost into €/m².

4.1.5 Hypotheses for the conversion of costs in €/m²

Table A5: Hypotheses for the conversion of costs in €/m²

Hypotheses	Baseline	Lower bound	Upper bound
Desealing			
Thickness of paving layer	0.3333 metre	0.15 metre	0.5 metre
Width of a 'linear meter'	1 metre	1.5 metre	0.5 metre
Thickness of permeous paving layer	0.15 metre	0.08 metre	0.25 metre
Thickness of gravel layer	0.15 metre	0.08 metre	0.25 metre
Soil remediation			
Depth of pollution	2 metre	1 metre	3 metre
One cube metre of excavated soil weights:	1.8 tonnes	1.5 tonnes	2 tonnes
Soil improvement			
Depth of soil improvement	1.5 metre	0.5 metre	2.5 metre
Thickness of the added topsoil layer	0.33 metre	0.15 metre	0.5 metre
Thickness of the added compost layer	0.1 metre	0.05 metre	0.15 metre
One cube metre of soil or topsoil weights:	1.8 tonnes	1.5 tonnes	2 tonnes
One cube metre of compost weights:	1.333 tonnes	1.1 tonnes	1.5 tonnes
Planting			
Number of m ² per tree	25 m ²	30 m ²	20 m ²
Number of m ² per sapling	2 m ²	4 m ²	1m ²
Number of m ² per plant	0.166 m ²	0.25 m ²	0.125 m ²
Number of m ² per shrub	0.5 m ²	1m ²	0.25 m ²
Thickness of the mulch layer	0.05 m	0.03 m	0.08 m
Surface of water body	100 m ²	150 m ²	50 m ²
Volume of a tree pit	8 m ³	6 m ³	10 m ³
Management and monitoring			
Management cost is given for:	1 year	1 year	1 year
Site surface	5000 m ²	7000 m ²	3000 m ²
Number of site visits per year	4 visits	2 visits	6 visits
We suppose one tree/sapling every:	5 m ²	8 m ²	3 m ²
Management of waste and excavated soil			
1m ³ of inert waste corresponds to	1.8 t	1.5 t	2 t
1m ³ of non-hazardous waste corresponds to	1.8 t	1.5 t	2 t
1m ³ of hazardous waste corresponds to	1.8 t	1.5 t	2 t
1m ³ of soil corresponds to	1.8 t	1.5 t	2 t
1m ³ of inert waste corresponds to	0.5 m ²	1 m ²	0.333 m ²
1m ³ of non-hazardous waste corresponds to	0.5 m ²	1 m ²	0.333 m ²
1m ³ of non-hazardous waste corresponds to	0.5 m ²	1 m ²	0.333 m ²
1m ³ of soil corresponds to	0.5 m ²	1 m ²	0.333 m ²

4.1.6 Hypotheses for the construction of typical pathways

NB:

- Preliminary analyses are included by assuming the same amount of analyses (5) with a cost of 4€/m² per analysis in all pathways.
- Table A3 below provides the scenarios presented in the Method section along with some variants to test the robustness of the results to pathway hypotheses. The results of the scenarios with the variants can be found in Annex 4.6.2.

Figure A3: Steps and associated weights for each typical pathway

Step	Technique	B_PP	B_PP_asbestos	S_PP_cutting	B_V_I	B_V_m	B_V_m_soilwork	B_V_h_soilconstruction	S_V_I	S_V_m	S_V_h	C_V_I	C_V_m	C_V_h	P_V_I	P_V_I*	P_V_m	P_V_m_biopile	P_V_h	P_V_h_phytodegradation
1. Preliminary analyses	Total - Preliminary analyses	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
2. Building demolition	Asbestos removal	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2. Building demolition	Demolition	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
3. Desealing	Desealing by cutting	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3. Desealing	Desealing by scraping	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3. Desealing	Permeable paving installation	1	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
3. Desealing	Gravel installation	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4. Soil remediation	Soil decontamination: excavation of polluted soils	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4. Soil remediation	Soil decontamination: excavation of polluted soils*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4. Soil remediation	Soil decontamination: venting/bioventing	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4. Soil remediation	Soil decontamination: biopile	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4. Soil remediation	Soil decontamination: phytoextraction	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4. Soil remediation	Soil decontamination: myco-phytodegradation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5. Soil improvement	In situ soil improvement	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5. Soil improvement	Soil construction	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5. Soil improvement	Earthworks	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5. Soil improvement	Soil decompaction	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5. Soil improvement	Incorporation of compost	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5. Soil improvement	Incorporation of topsoil	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5. Soil improvement	Bioaugmentation/biostimulation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6. Management of waste and excavated soil	Disposal of non-hazardous waste	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6. Management of waste and excavated soil	Storage of inert waste	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6. Management of waste and excavated soil	Storage of hazardous waste	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7. Planting	Grass sowing	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7. Planting	Planting of herbaceous vegetation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7. Planting	Planting of ligneous vegetation - sapling	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7. Planting	Planting of ligneous vegetation - tree	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7. Planting	Creation of water bodies	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8. Management and monitoring	Pollution monitoring	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8. Management and monitoring	Ecological monitoring	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8. Management and monitoring	Soil cycle maintenance	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8. Management and monitoring	Maintenance of ligneous vegetation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8. Management and monitoring	Maintenance of herbaceous vegetation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		0	0	0	1,5	1	1	0	1,5	1	0	1,5	1	0	1,5	1,5	1	1,5	1,5	1,5

NB: Each line is then multiplied by the cost of the step (€/m²), which are then summed to obtain the total cost of each pathway (€/m²).
 *Here, excavation costs also including earthworks, transportation and storage.

Figure A4: Justifications for the scenarios and their associated level of ecological engineering

Restoration phase		Level of ecological engineering	Justification for the level of ecological engineering involved by each stage:
Phase #1: Surface cleaning	Demolition of buildings Desealing (Removal of impervious surface)	/	
Phase #2: Soil rehabilitation	Rehabilitation of non-polluted soil	Low	"Green space professionals currently use topsoil obtained from the stripping of agricultural land (and reclaimed by urbanisation)." "The use of [material like topsoil] poses problems on three levels: (i) non-renewable materials; (ii) ever greater distances to ensure supply (increasing economic and environmental costs); (iii) annually available resources are likely to become scarcer in the future given current urban planning policies aimed at limiting urban sprawl." (Programme SITERRE, 2015)
	(i) Soil excavation and replacement with topsoil	Medium	According to Taugourdeau et al. (2020), the "Ecological rehabilitation" of a soil is based on ecological engineering (but not pedological engineering) and implies the following techniques: working the soil (decompaction, planting pits); Addition of micro-organisms (fungi, bacteria); followed by sowing and young trees (saplings). The authors find that 30 months after the ecological rehabilitation of the soil ("M2" soil in their paper), the soil's carbon content is lower than that of grassland soils, the "nutrient retention and supply" function is moderately ensured. As the soil was severely disturbed during the implementation of ecological engineering techniques (in particular, decompaction), it has not yet regained a level of biodiversity equivalent to that of a constructed technosoil ("M3" soil in their paper, see below).
	(ii) Soil decompaction and improvement (e.g. with compost)	High	According to Taugourdeau et al. (2020), another way to improve the soil is to use « pedological engineering » techniques, and in particular to construct a soil, i.e. with the addition of large quantities of external materials. Soil construction implies excavation; addition and reuse of materials (e.g. from demolished buildings); a creation of soil horizons; followed by sowing and young trees (saplings). The authors find that 30 months after the soil construction ("M3" soil in their paper), the soil's carbon content is similar to that of grassland soils, the "nutrient retention and supply" function is ensured and M3 appears to be the soil with the greatest biodiversity (as compared to M2, see above)
Phase #3: Surface rehabilitation and management	Rehabilitation of polluted soil	Low	ADEME et al. (2018) states that « the majority of cases of management of brownfields and polluted sites (60% to 80%) is dealt with using "off-site management" (i.e. implying excavation). In particular, excavation and disposal in landfills "is mainly carried out on sites with small areas of pollution (...) and short deadlines (...) due to the remediation method itself, which has the advantage of being rapid." However, "on-site and in-situ soil decontamination techniques offer a better environmental balance (a priori, due to transport) than the disposal of polluted soil". (ADEME et al. (2018))
	(i) Thermal or chemical, in situ or on site depollution	Medium	ADEME et al., 2018: states that "in situ techniques (...) still appear to be poorly represented, such as venting/bioventing used in only 7% of operations or phytoremediation (3%)" In particular, "on-site or in situ techniques are preferred on sites with large volumes of impacted soil". However, "on-site and in-situ soil decontamination techniques offer a better environmental balance (a priori, due to transport) than the disposal of polluted soil". However, "on-site (ADEME et al. (2018)). See also SeleDepol. (2024) for more info on the use of each technique.
	(ii) Phytoremediation	High	According to Deboeuf De Los Rios et al. (2022) « Unlike civil engineering techniques (replacement, physical/chemical processes, etc.), ecological engineering techniques aim to limit energy costs arising from soil excavation, transport and infill with imported soil, instead opting for onsite restoration. To do this, the properties of certain micro-organisms such as bacteria and fungi (bioremediation) or of plant species (phytoremediation) can be used to decontaminate soil." However, Ademe et al. (2018) indicates "in situ techniques (...) are still poorly represented, such as (...) phytoremediation [used in only 3% of operations]." A view shared in SeleDepol. (2024).
Phase #3: Surface rehabilitation and management	(i) Permeous paving	/	Installing permeous paving is a way to restore some functions of the soil but is not urban soil restoration per se. Indeed, according to Deboeuf De Los Rios et al., 2022, « Renaturing is often confused with desealing, which involves restoring the permeability of topsoil, often using porous drainage pavements. Though an essential factor, desealing alone is not sufficient to restore the soil's ecological functions, however. »
	(ii) Greening	Low	We follow Deboeuf De Los Rios et al. (2022), which states that « Unlike ecological engineering, greening often takes place with no connection to the climatic or geographical context, uses ill-adapted horticultural species and requires numerous inputs (topsoil, fertiliser, energy, irrigation, etc.), which means that these areas are not self-sufficient and are reliant on intensive management. (...) The archetypes of greening are, for example, the French-style formal garden, lawns, monospecific planting, modular living walls, raised planters, flower meadows sown with non-local species, etc.» Goal and purpose : "Using plants to make the urban environment more attractive, ornamentation »
	(iii) Ecological engineering	Medium or High	According to Deboeuf De Los Rios et al. (2022), in urban soil restorations implying ecological engineering (what they call "renaturation") « the choice of plants is no longer only determined by aesthetic criteria, instead focusing on local species and taking interactions with wildlife, soil and local conditions into account". It aims to "Restoring ecological functionalities, creating viable habitats in relation to the green and blue grid, water management, adapting to climate change. »

¹ Soil "construction" involves bringing in materials from outside the site, whereas soil "reconstitution" (not included in our pathways) limits this input as much as possible.

Table A6: Summary statistics on cost estimates in the database

Step	Number of cost estimates	Observation	Median or interval
1. Preliminary analyses	57	23 %	77 %
2. Building demolition	95	81%	19 %
3. Desealing	110	51%	49 %
4. Soil remediation	79	8 %	92 %
5. Soil improvement	132	45 %	55 %
6. Management of waste and excavated soil	71	28 %	72 %
7. Planting	172	48 %	52 %
8. Management and monitoring	25	48 %	52 %

Step	Given in m ²	Converted	Converted from ha to m ²	Document	Interview
1. Preliminary analyses	11%	46 %	44 %	12 %	88 %
2. Building demolition	100 %	0 %	0 %	81%	19 %
3. Desealing	56 %	44 %	0 %	69 %	3 1%
4. Soil remediation	30 %	66 %	4 %	58 %	42 %
5. Soil improvement	33 %	61%	5 %	46 %	54 %
6. Management of waste and excavated soil	0 %	100 %	0 %	38 %	62 %
7. Planting	39 %	58 %	3 %	51%	49 %
8. Management and monitoring	16 %	76 %	8 %	52 %	48 %

4.3 Definition of steps and techniques

4.3.1 Planning

Planning encompasses the development of territorial strategies and the creation of cartographic documents aimed at integrating issues relating to soil restoration into regional or urban planning documents. During our survey, we identified planning actions relating to waste disposal,¹¹ desealing and revegetation. It should also be noted that the adoption of the ‘no net land take’ objective in the French ‘Climate and Resilience’ law seems to be stimulating the development of soil restoration planning services and the mapping of the ecological functions of soils. French public regional engineering bodies such as Cerema, Ademe and public planning agencies are making a significant contribution to these operations by developing datasets, maps and methodologies.

4.3.2 Land control

In the lexicon of land strategy, land control refers to the operation by which an organisation acquires all or part of the set of property rights over a piece of land, with a view to carrying out a specific action. It is not limited to acquisition, since many legal instruments and arrangements can be used to obtain or control real rights attached to land (Kamal et al., 2014).

In the context of the restoration of urban land, the aim of land control is to obtain the power to carry out the planned activities on the site, but also to control access to and use of the site over the long term. This is particularly important for ‘passive’ restoration operations, which are based on long-term ecological or soil engineering methods, such as phytoremediation techniques for polluted soil. Land ownership is generally undertaken by the project sponsor (local authority, property developer, State) or the project developer (private company, mixed company, local public company). In addition, public land establishments are playing an increasingly important role by making their resources available to landowners and developers to facilitate the restoration of urban wasteland and derelict land.

4.3.3 Preliminary analyses

Preliminary analyses cover all the diagnostics carried out prior to carrying out operations to guide the technical processes. The aim of these studies is to characterise certain properties of the soil, buildings or ecological environments concerned, and also to define and plan how the site will be managed post-restoration. They include pollution analyses (generally physical or chemical), Agronomic soil analyses, hydrological diagnoses and infiltration studies, as well as fauna, flora and habitat inventories. These tasks are carried out by design offices (in French, *bureaux d'études*) with specific skills. When these studies involve the production of maps, the parties involved can rely on the recommendations of standard NF X31-560,¹² which sets out the rules for acquiring and managing soil data and indicates the required sampling density according to the mapping scale.

¹¹In France, these include the National Waste Prevention Plan (Plan national de prévention des déchets) and the Regional Waste Prevention and Management Plans (Plans régionaux de prévention et de gestion des déchets, PRPGD).

¹²AFNOR, 2007. « Qualité des sols - Cartographie des sols appliquée à toutes les échelles - Acquisition et gestion informatique de données pédologiques en vue de leur utilisation en cartographie des sols ».

Table A7: Definitions of techniques for the ‘Preliminary studies’ step

Technique	Definition
Historical research (<i>Recherches historiques</i>)	Information gathering on past land use, activities carried out, products used and stored, management practices and accidents to establish a pre-diagnosis of the soil. [1]
Agronomic soil analysis (<i>Études agro-pédologiques</i>)	Characterisation of the agronomic potential of soils and their ability to support vegetation. This type of diagnosis is generally carried out by sampling soil profiles (using an auger) to analyse pedological parameters (texture, depth, compactness) and agronomic parameters (pH, level of organic matter, concentration of nutrients and other chemical elements).
Fauna, flora and habitat inventory (<i>Inventaire faune, flore et habitat</i>)	Statutory study aimed at characterising the initial state of a site, from the point of view of its ecological aspects, in particular by identifying protected species or natural habitats. For projects subject to an impact study in the context of the "EU Habitats directive", ^a carrying out an ecological inventory is compulsory and enables the possible ecological impacts to be assessed, and mitigation measures to be calibrated. [2]
Permeability test (<i>Test de perméabilité</i>)	Measurement of soil infiltration capacity. Essential for planning rainwater management and assessing the impact of construction or restoration on the hydrogeomorphological functions of soils. The most common methods are the ‘Porchet’, ‘Matsuo’ and ‘Lefranc’ tests.
Rainwater management study (<i>Étude de gestion des eaux pluviales</i>)	Analysis to assess and size the infrastructure needed to collect and manage rainwater on a site, based on soil permeability and other environmental factors.
Asbestos diagnosis (<i>Diagnostic amiante</i>)	Asbestos diagnosis before demolition (<i>Diagnostic amiante avant démolition</i> , DAAD) involves assessing the risks of exposure to asbestos for the general public and workers during the total or partial demolition of a building.
Soil pollution diagnosis (<i>Diagnostic pollution des sols</i>)	The aim of this diagnosis is to identify the presence of pollutants, to quantify it and characterise its source and mobility, to identify the transfer routes and the environments exposed, and to understand any propagation mechanisms. [1]
Quantitative health risk assessment (<i>Évaluation quantitative des risques sanitaires, EQRS</i>)	Aims to quantify the risks to people’s health caused by the pollution present, depending on the current or future use of the site. It is generally coupled with studies to interpret the state of the environment (IEM), which estimate the risks of contamination of the environments surrounding the source of pollution.
Products, equipment, materials and waste diagnosis (<i>Diagnostic produits, équipements, matériaux et déchets, PEMD</i>)	Diagnosis of the products, equipment, materials and waste expected from a significant demolition or renovation operation with a view to their reuse or recovery. [3]
Works Design Plan (<i>Plan de conception des travaux</i>)	This document is required by the French national methodology for managing polluted sites and soils (<i>méthodologie nationale de gestion des sites et sols pollués</i>). Its function is to bridge the gap between the studies and the works. On the basis of the different management scenarios studied, it must enable to check the feasibility of these scenarios, before any of them are implemented. The Works Design Plan thus foreshadows the drafting of specifications and/or the sizing of the works to be carried out. [4]
Pollution management plan (<i>Plan de gestion de la pollution</i>)	Guidance document designed to summarise the pollution characterisation studies of a site and its environment in order to study different pollution management scenarios and define the management strategy to be applied when carrying out works. [5]
Ecological management plan (<i>Plan de gestion écologique</i>)	Strategic document aimed at preserving and enhancing the biodiversity and ecological functions of a site, often included in restoration projects requiring environmental authorisation.

Unless explicitly stated, the definitions presented are taken from our expert survey. [1] Ministère de la Transition écologique et de la Cohésion des territoires (2023). Guide – diagnostic des sites et sols pollués.

<https://ssp-infoterre.brgm.fr/fr/methodologie/diagnostic-site> [2] Ministère de la transition écologique (2020). Note technique du 5 novembre 2020 relative au cadrage de la réalisation et de la mise à jour des inventaires faune-flore dans le cadre des projets soumis à autorisation environnementale.

<https://www.legifrance.gouv.fr/circulaire/id/45135> [3] Ministère de la Transition écologique et de la Cohésion des territoires (2024). Le diagnostic « produits, équipements, matériaux et déchets » (PEMD).

<https://www.ecologie.gouv.fr/politiques-publiques/diagnostic-produits-equipements-materiaux-dechets-pemd> [4] Ministère de l’Environnement, de l’Énergie et de la Mer (2017). Méthodologie nationale de gestion des sites et sols pollués.

<https://ssp-infoterre.brgm.fr/fr/methodologie/methodologie-nationale-gestion-ssp> [5]

Ministère en charge de l’environnement (2019). Guide méthodologique relatif au Plan de Conception des Travaux (PCT). <https://ssp-infoterre.brgm.fr/fr/guide/pct>

4.3.4 Building demolition

Demolition is an essential prerequisite for restoration projects involving built-up sites. This step involves the traditional players in the public works sector, as well as specialist organisations for the more complex deconstruction or dismantling of industrial sites. It may also require the involvement

of certified professionals to carry out work to treat asbestos and lead, which are subject to strict regulations.¹³

Table A8: Definitions of techniques for the ‘Building demolition’ step

Technique	Definition
Dismantling (<i>Curage du bâtiment, démantèlement, déconstruction sélective</i>)	The removal of non-constructive and non-structural elements from a building (joinery, partitions, cladding, etc.). While the aim of cleaning is to leave the building ‘bare’ (walls and floors), in the case of demolition it is mainly used to recover and reuse the building’s ancillary components. We talk about ‘selective dismantling’ when it involves a precise diagnostics of the resources, materials and equipment that can be recovered from the building and forms of dismantling that encourage their reuse.
Asbestos removal (<i>Désamiantage</i>)	Removal and treatment of materials and equipment containing asbestos in a building. Where the presence of asbestos is proven, asbestos removal must be carried out prior to demolition, to prevent the asbestos from spreading.
Lead removal (<i>Déplombage</i>)	Identification, removal and treatment of materials and equipment containing lead. It must be carried out prior to demolition.
Top-down deconstruction (<i>Ecrêtage</i>)	Used for high-rise buildings, topping involves demolishing the buildings level by level. A work platform installed at the top of the structure and inside allows the machines to ‘nibble’ at the building from top to bottom.
Demolition (<i>Démolition</i>)	Conventional demolition is carried out mechanically using public works equipment (mechanical shovel) or using explosive demolition methods.

Source: expert survey.

4.3.5 Desealing

Desealing involves rearranging the cover of urban soil, generally with the aim of improving its permeability. This operation involves removing impermeable ground coverings such as tar, concrete, paving stones or other asphalt mixes. These materials may eventually be replaced by permeable paving, such as draining concrete, in which case the process is known as re-permeabilisation. The people best qualified to carry out this operation are public works companies, particularly those specialising in roadworks. The structure of permeable pavements involves works that are generally deeper than a conventional pavement [Itw_45]. As a result, replacing a conventional pavement with a permeable pavement generally involves earthworks.

Table A9: Definitions of techniques for the ‘Desealing’ step

Technique	Definition
Desealing by cutting (<i>Descellement par découpage</i>)	Cutting the pavement or roadway, generally using a disc saw (or ‘floor saw’).
Desealing by scraping (<i>Descellement par décroulage</i>)	Removal of the pavement from the ground using mechanical shovels equipped with rock breakers or larger machines.
Installation of permeable surfacing (<i>Mise en place d’un revêtement perméable</i>)	Pavement construction using permeable materials (draining slabs, draining concrete, etc.). Depending on the material, infiltration coefficients are more or less important and leave more or less room for vegetation.
Addition of gravel (<i>Apport de graves</i>)	Addition of gravel and other aggregates for roadway construction or to fill in excavated areas.

Source: expert survey.

For desealing, the use of one method rather than another depends partly on the area of the surface to be treated. Cutting is more commonly used on small surfaces and is more precise [Itw_16]. The different desealing techniques can also be combined. For example, it is possible to use a saw to mark out the area to be unsealed (cutting) and then scrape the surface with a rock breaker [Itw_36]. In view of the paucity of data collected, we have excluded pavement milling/planing techniques, which use machines of the same name (milling machine or planer) to remove the top layer of a pavement.

¹³To be able to carry out asbestos diagnostics and removal work, a company must obtain a certification attesting to compliance with the criteria set out in standard NF X46-010.

For the sake of completeness, we should also take into account the treatment of the waste from the desealing process. Traditionally, it is taken to landfill (see below), but recycling processes are becoming increasingly widespread. For example, the material making up the structure can be melted down and reused, as can the backfill forming the sub-layers of the pavement [itw_45].

4.3.6 Soil remediation

Table A10: Definitions of techniques for the ‘Soil remediation’ step

Technique	Definition
Soil decontamination: excavation of polluted soil	Excavation is the simplest, most radical and quickest method of removing a source of pollution. It is carried out once the source of the pollution has been identified. It must necessarily be accompanied by methods for treating and/or storing the excavated soil. Physical, ex-situ (off-site or on-site) technique. <i>NB: Costs noted with a "*" include excavation, earthworks, transportation and storage. Costs with no "*" are for excavation alone.</i>
Soil decontamination: venting/bioventing	Venting consists of extracting volatile pollutants by depressurising the unsaturated zone. Bioventing is an aerobic biological treatment that stimulates biodegradation in the unsaturated zone by adding oxygen. Physical/biological, <i>in situ</i> technique.
Soil decontamination: <i>in situ</i> chemical oxidation/reduction	<i>in situ</i> chemical oxidation involves injecting an oxidant into the soil (saturated and unsaturated zones) without excavation. This oxidant will totally or partially destroy the pollutants. This process can result in the destruction of pollutants (leading to their transformation into water, carbon dioxide and salts) or the formation of degradation by-products that are generally more biodegradable. Chemical, <i>in situ</i> technique.
Soil decontamination: thermal desorption	Thermal desorption involves applying a heat source to the soil in place or excavated to extract certain volatile and semi-volatile pollutants. Thermal, off-site, on site or <i>in situ</i> technique.
Soil decontamination: soil flushing (<i>lavage</i>)	This process consists of washing the soil by injecting water (and mobilising agents in solution) upstream or at the source of the pollution. The polluted water is then recovered (or pumped), treated on the surface and then discharged into the wastewater/rainwater networks or, in some cases, reinjected into the groundwater. Chemical, off-site, on site or <i>in situ</i> technique.
Soil decontamination: <i>in situ</i> biodegradation	Biodegradation requires the addition of specific compounds to soil or groundwater in order to create favourable conditions for the activity of microorganisms responsible for the biodegradation of contaminants. To achieve this, the microorganisms are kept in optimal conditions (oxygen, pH, temperature, oxidation-reduction potential). Biological, <i>in situ</i> technique.
Soil decontamination: biopile (<i>biotertre</i>)	Biopile consists of piling up polluted soil for biological treatment. To do this, the polluted soil is generally amended and the conditions in the biopile are controlled (aeration, addition of nutrients, etc.). Biological, on-site or off-site technique.
Soil decontamination: phytoextraction	Phytoextraction involves extracting pollutants from the soil using plant species, with or without the addition of soil improvers. Plants absorb pollutants from the soil via their roots, and transfer and accumulate the pollutants in their harvestable aerial parts (stems, leaves), thereby reducing pollutant concentrations in the soil. This is a partial remediation process, as the plant only has access to the bioavailable fraction of the pollutants. Biological, <i>in situ</i> technique.
Soil decontamination: myco-phytodegradation	Phytodegradation is a decontamination technique that consists of breaking down organic pollutants into simpler, less toxic compounds using plant species and micro-organisms, with or without the addition of soil improvers. This is a partial remediation technique, as only the so-called ‘bioavailable’ fraction of the pollutants is accessible to them. Biological, <i>in situ</i> technique.
Constructive measures: phytosequestration	Phytosequestration involves immobilising inorganic pollutants using plant species, with or without the addition of soil improvers. Plants reduce the horizontal and vertical transfer of pollutants by reducing their mobility in the soil, water and air. This is not a depollution technique (the pollutants remain in place). Biological, <i>in situ</i> technique.
Constructive measures: pollution containment	Pollution containment is used here to refer to all physical containment techniques using a cover (earthen, semi-permeable or impermeable). These methods are designed to isolate contaminants and prevent them from spreading. Physical (by containing pollution), <i>in situ</i> technique.
Groundwater decontamination: pump and treat	Pump and treat involves extracting polluted groundwater and treating it on site before discharge (or disposing of it in approved centres). The type of treatment varies according to the pollutants, flow rates and purification percentages to be achieved. Physical (by evacuating pollution), <i>in situ</i> technique.
Groundwater decontamination: sparging (<i>barbotage</i>)	Sparging is based on the same principle as venting, but is applied to the saturated zone and the capillary fringe. The air injected into the water table (and not into the unsaturated zone as with venting) encourages the volatilisation of pollutants, which are then extracted from the vadose (also called unsaturated) zone and treated on site. Physical (by evacuating pollution), <i>in situ</i> technique.

Source: All the definitions in this table are taken from the <https://selecdepol.fr/> resource centre (consulted on 27/06/2024).

In the European Commission’s proposal for a Directive on Soil Monitoring and Resilience, soil remediation refers to actions that ‘reduces, isolates or immobilizes contaminant concentrations in the soil.’ (COM/2023/416 final, Article 3). It includes various remediation techniques, but also constructive

measures to contain or confine contaminants. The ‘SelecDépol’ resource centre, managed by Ademe and BRGM, lists 38 remediation techniques and 26 constructive measures, more or less widely used, classified into four process categories: physico-chemical, thermal, biological and containment. They are also distinguished by the way in which they are applied: *in situ* techniques are applied directly to the soil in place, without excavation, whereas *ex situ* techniques are applied after excavation, either on site or off site in suitable treatment centres.

In France, soil remediation is subject to a strict and precise legal framework aimed at reducing the health and environmental risks associated with soil pollution. The aim of soil remediation is not so much to improve the health of the soil as to bring it into compliance with health standards. To facilitate the implementation of this legal regime, the Ministry of the Environment has produced a ‘national methodology for the management of polluted sites and soils’ (*méthodologie nationale pour la gestion des sites et sols pollués*), which sets out the various stages and procedures to be followed when bringing a site into compliance with health regulations. This methodology has been translated into a series of mandatory NF X31-620 standards,¹⁴ which provide a framework for action by organisations in the sector.

4.3.7 Soil improvement

A key step in the restoration process, soil improvement covers a range of interventions designed to affect the composition, structure or geomorphology of soils, with the aim of improving their biological, geochemical and hydrogeomorphological functions (Taugourdeau et al., 2020). Broadly speaking, two situations can be distinguished. In cases where the aim is to work on existing soils, refunctionalisation generally involves physical or biological decompaction operations, or changes to the morphology, to achieve landscape objectives or improve infiltration. These practices are typically carried out by earthmoving or landscaping companies.

Table A11: Definitions of techniques for the ‘Soil improvement’ step

Technique	Definition
<i>in situ</i> soil improvement (<i>Travail du sol en place</i>)	Generic name for all techniques for improvement of soil processes (e.g. decompacting, adding compost, adding topsoil) that do not involve excavating or replacing the soil with imported materials (i.e. <i>in situ</i>).
Soil construction	Creation of an anthroposol ensuring a high level of functionality, but differing in structure and function from the original. This soil engineering method creates a soil structured into functional layers or horizons constructed mainly from technical materials (gravel, construction waste, compost, etc.), and created according to the ecosystem services desired. [1]
Soil reconstitution	Soil reconstitution takes place when the soil in place does not have agronomic properties favourable to plant growth and development. The aim is to combine soil materials <i>from the site</i> with materials that have been transported, reworked and installed on site to improve the fertility of soils used for gardens, parks and green spaces. [1]
Earthworks (<i>Terrassement</i>)	All excavation, transport and earth placement work carried out to modify the topography of a plot of land, to enable certain structures to be built or reinforced. [2]
Soil decompaction	Technique designed to bring air in the soil to improve its biological and hydrological functions. It is generally carried out mechanically (using farm tools), but can also be based on biological methods.
Incorporation of compost	Addition of organic soil improvers to stimulate the fertility of existing soil or as part of soil reconstitution operations.
Incorporation of topsoil	The addition of fertile substrates that meet the ‘growing medium’ product standard. ^a Traditionally, these substrates are taken from agricultural land, but there are now structured processes for producing ‘growing media’ from recycled excavated earth and other urban waste.
Bioaugmentation/biostim	The addition of a fungal or bacterial consortium on or off site to stimulate biological processes in the soil or as a growing medium.
Soil compaction	A civil engineering technique designed to reduce air and water pore spaces in the soil. As part of soil restoration operations, it can also be used to create traffic lanes with sufficient load-bearing capacity for site machinery, or to create permeable pavements.

Source: Unless explicitly stated, the definitions presented are taken from our expert survey. [1] Quadru F, Bâlon P., Limasset E., Malherbe A. (2021). Le génie pédologique pour recréer des sols fertiles - Projet SOILval. [2] Trésor de la langue française informatisé (dictionary).

¹⁴AFNOR (2021). NF X31-620 “Prestations de services relatives aux sites et sols pollués”

A second case occurs when the original soil has been excavated, for example as part of a wastewater treatment project, it is generally filled in with gravel and various excavation products, sometimes supplemented with topsoil. These cases can also be dealt with by soil engineering processes, which are still experimental, aimed at reconstituting or creating functional ‘soils’ from scratch, referred to as ‘reconstituted anthroposols’ and ‘constructed anthroposols’ in the Référentiel pédologique of the Association française d’étude du sol (Baize and Girard, 2009, p. 92-94; Séré et al., 2008; Vidal-Beaudet, 2018). In addition to design offices and engineering firms specialised on soils, these operations also involve producers and distributors of the various materials used (building site waste, topsoil, fertile soil improvers and composts). Finally, all the techniques involved in soil improvement can be combined with chemical or biological fertilisation and soil revegetation.

4.3.8 Management of waste and excavated soil

The management of waste and excavated soil covers the removal, treatment, storage and recycling of excavated soil and technical waste from the demolition of buildings or the desealing of pavements. These materials are generally transported by public works companies to specialised centres for sorting, disposal and storage. The European Directive on waste,¹⁵ transposed into the Environment Code,¹⁶ distinguishes three categories of waste: inert non-hazardous waste (known as inert waste), non-hazardous waste and hazardous waste.¹⁷

These three categories of waste correspond to three types of treatment and storage centres: inert waste storage facilities (*installations de stockage de déchets inertes*, ISDI), non-hazardous waste storage facilities (*installations de stockage de déchets non-dangereux*, ISDND) and hazardous waste storage facilities (*installations de stockage de déchets dangereux*, ISDD). These facilities are subject to the legal regime of *Installations Classées pour la Protection de l’Environnement* (ICPE), with levels of technical and regulatory requirements increasing with the category of waste.

Table A12: Definitions of techniques for the ‘Management of waste and excavated soil’ step

Technique	Definition
Disposal of inert waste	Transport of inert waste to appropriate treatment centres
Disposal of non-hazardous waste	Transport of non-hazardous waste to appropriate treatment centres
Disposal of hazardous waste	Transport of hazardous waste to appropriate treatment centres
Storage of inert waste	Waste is treated and stored in an appropriate facility (inert waste landfill site, <i>ISDI</i>).
Storage of non-hazardous waste	Waste is treated and stored in an appropriate facility (non-dangerous waste landfill site, <i>ISDND</i>).
Storage of hazardous waste in an ISDD (dangerous waste landfill site)	Waste is treated and stored in an appropriate facility (dangerous waste landfill site, <i>ISDD</i>).
Biocentre waste treatment	Biocentres are used to biologically treat certain types of pollution from excavated soil.
Crushing of inert waste (<i>Concassage</i>)	Crushing is a destruction method used to reduce materials that are often heavy and cumbersome, such as rock or concrete, into small aggregates.

Source: expert survey.

4.3.9 Planting

Planting covers all intentional planting and maintenance of plants in the ground (herbaceous vegetation, mature trees or seedlings). These operations can be aimed at re-functionalising the soil. At the

¹⁵Directive (EU) 2018/851 of the European Parliament and of the Council of 30 May 2018 amending Directive 2008/98/EC on waste (Text with EEA relevance)

¹⁶See section « Installations de traitement des déchets » (Code de l’environnement, articles L541-22 à L541-30-3).

¹⁷See Ministère de la Transition écologique et de la Cohésion des Territoires (2024). Différentes catégories de déchets. <https://www.ecologie.gouv.fr/politiques-publiques/differentes-categorie-dechets> (consulted on 08/07/2024).

crossroads between ecological engineering and soil engineering, plant engineering in particular relies on the mechanical and biological properties of plants to remediate (phytoremediation, see above), stabilise or decompact urbanised soils (Rey et al., 2015). However, the majority of revegetation projects are not explicitly aimed at restoring the soil, but rather at developing vegetated urban spaces for landscape, agronomic or ecological reasons (Aragau, 2022; Baysse-Lainé et al., 2022; Clergeau and Blanco, 2022). It involves horticulture, landscaping, urban agronomy, urban ecology and ecological engineering.

Table A13: Definitions of techniques for the ‘Planting’ step

Technique	Definition
Grass sowing	Grass cover consists of seeding the soil. This can be done to stabilise the soil, prevent erosion, stimulate biological processes or for ornamental or landscaping purposes.
Planting of herbaceous vegetation	Planting of herbaceous plants, often supplied in pots.
Planting of ligneous vegetation - sapling	Plantation of woody vegetation in the form of young trees (sapling) of a few centimeters.
Planting of ligneous vegetation - tree	Planting of ligneous vegetation in the form of mature trees.
Mulching	Mulching consists of covering the soil with organic, mineral or artificial materials to nourish and/or protect it.
Removal of ligneous vegetation	Removal of undesirable woody plants to restore or maintain habitats and landscapes.
Creation of water bodies	Development of an area to form a pond, pool or basin, with the aim of managing run-off water, encouraging aquatic biodiversity and creating wetland habitats.

Source: expert survey.

4.3.10 Management and monitoring

Table A14: Definitions of techniques for the ‘Management and monitoring’ step

Technique	Definition
Pollution monitoring	The national methodology for managing polluted sites and soils provides for monitoring and ex-post evaluation of the effectiveness of the methods used to bring treated sites into line with health standards.
Surveillance of access and use	When the remediation methods selected require long-term deployment (such as phytoremediation), the treated site must be fenced off. In such cases, site monitoring systems must be put in place.
Management of invasive alien species	Any lethal or non-lethal action aimed at eradicating, controlling or containing a population of an invasive alien species, while minimising the impact on non-target species and their habitats. [1]
Ecological monitoring	Monitoring of the site’s ecological values over time. This is particularly mandatory in cases where the operation requires environmental authorisation - under water law or for protected species - in order to check the effectiveness of the reduction and compensation measures over time.
Soil cycle maintenance	Soil maintenance consists of maintaining and stimulating the development of its properties in line with the ecosystem services sought by the restoration operation. This may involve maintaining soil fertility or permeability, using mechanical, chemical or biological techniques.
Vegetation maintenance, including the following techniques: Maintenance of ligneous vegetation, Maintenance of herbaceous vegetation, Green waste recycling, Green waste disposal, Irrigation	Upkeep, maintenance and care of the green spaces and plants planted by the restoration operation (mowing, pruning, trimming, watering, management of green waste).

Source: Unless explicitly stated, the definitions presented are taken from our survey. [1] Article 3 of the Regulation (EU) No 1143/2014 of the European Parliament and of the Council of 22 October 2014 on the prevention and management of the introduction and spread of invasive alien species.

<https://eur-lex.europa.eu/eli/reg/2014/1143/oj>

This step covers all the operations required to ensure the proper ecological functioning of the restored soils and environments. This includes the maintenance and upkeep of habitats, soil and plants, as well as site monitoring systems.

These management operations may result from the implementation of legal and regulatory obligations. In the case of remediation operations, the national SSP (Methodology for Polluted sites and soils, *Sites et Sols Pollués*) methodology may require monitoring operations ('environmental surveillance') to be carried out in order to verify the effectiveness of the sanitary compliance measures over time. In cases where the restoration operation has required environmental authorisation for 'protected species' or wetland protection, management may consist of ensuring that the prescribed reduction, compensation and support measures are effectively implemented over time.

Responsibility for management operations generally depends on the ownership of the areas concerned: private operators or local authorities in urban public areas, sometimes public establishments.

4.3.11 References

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4.4 Illustration of real urban soil restoration projects

Figure A6: Jardins joyeux - Aubervilliers

(a) Before



(b) After



Photo Credits: Wagon Landscaping (Left) and Authors (Right).

Note on the project: The project consisted in converting a sealed soil (parking lot) into a soil with carefully selected vegetation (sapling, diversity of local plants adapted to poor soils). The paving was only broken but not removed to limit transportation costs, and the management of the vegetation is very limited (close to free evolution).

Figure A7: Oasis Schoolyard - Paris

(a) Before



(b) After



Photo Credits: CAUE de Paris

Figure A8: Rue de la Providence - Paris

(a) Before



(b) After



Photo Credits: LPLT — Travail personnel, CC BY-SA 4.0, <https://commons.wikimedia.org/w/index.php?curid=104745596> (left) and Authors (right)

Figure A9: Le 8ème Cèdre - Lyon

(a) Before



(b) After



Photo Credits: Google Earth Pro (left) and Place au Terreau / Le Grand Romanesco (right)
Note on the project: The project consisted in converting a sealed soil (parking lot) into an urban kitchen garden (*potager*).

Figure A10: Lisière d'une Tierce Forêt - Aubervilliers

(a) Before



(b) After



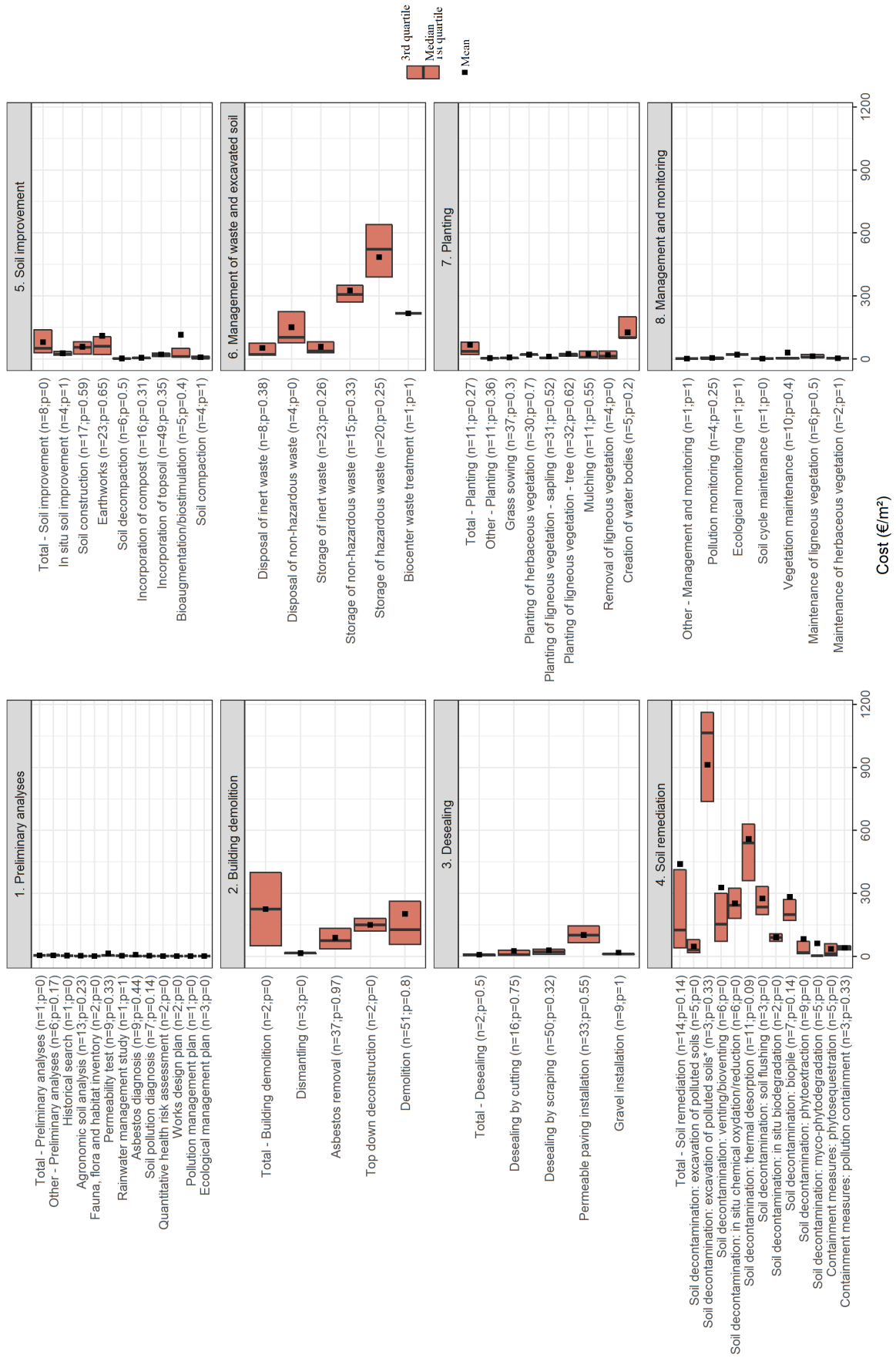
Photo Credits: Fieldwork Architecture (Left) and Authors (Right)

Note on the project: The project consisted in converting a sealed soil (parking lot) into an urban forest with porous paving. In this paper, we however argue that although porous paving improved certain functions of the soil, it cannot be considered "soil restoration" *per se*.

4.5 Additional results

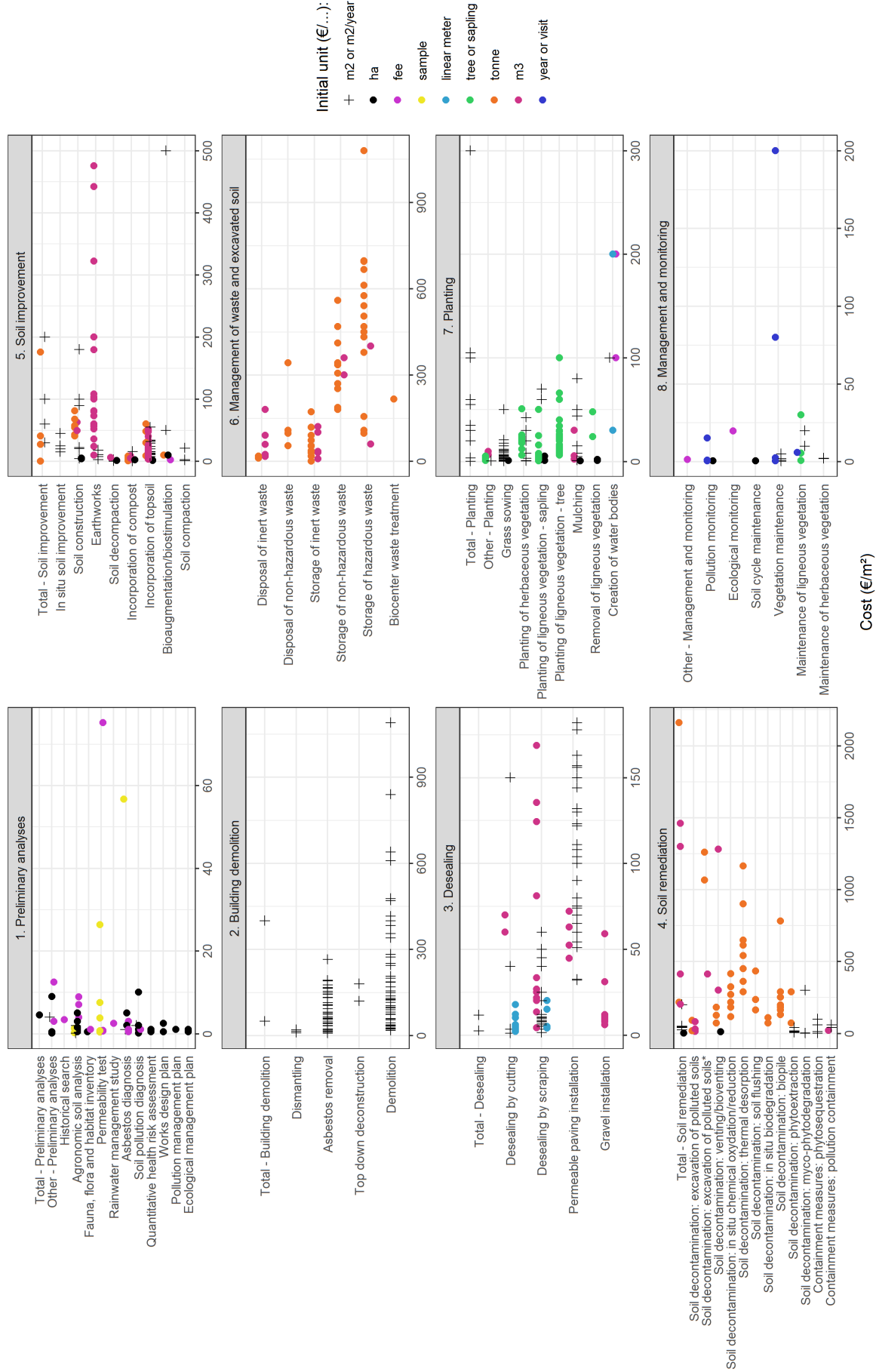
4.5.1 Costs in €/m²

Figure A11: Costs of techniques (in €/m²) - Distribution with same x-axis



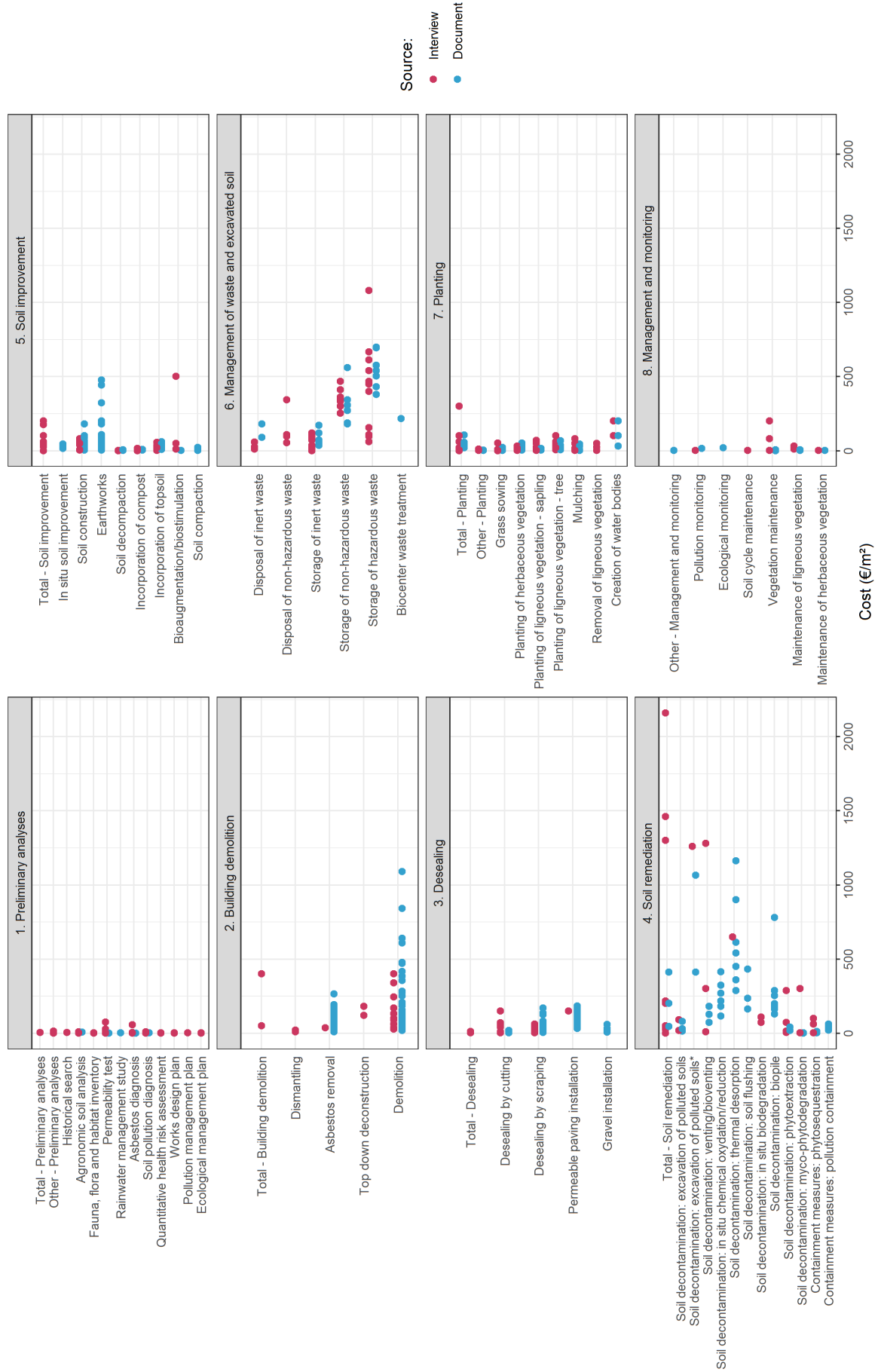
Note: *n* indicates the number of costs used to build the distribution, *p* indicates the share of those costs which are of the type 'observation' as opposed to statistics.
 *Here, excavation costs also including earthworks, transportation and storage.

Figure A12: Costs of techniques (in €/m²) - By initial unit of cost



*Here, excavation costs also including earthworks, transportation and storage.

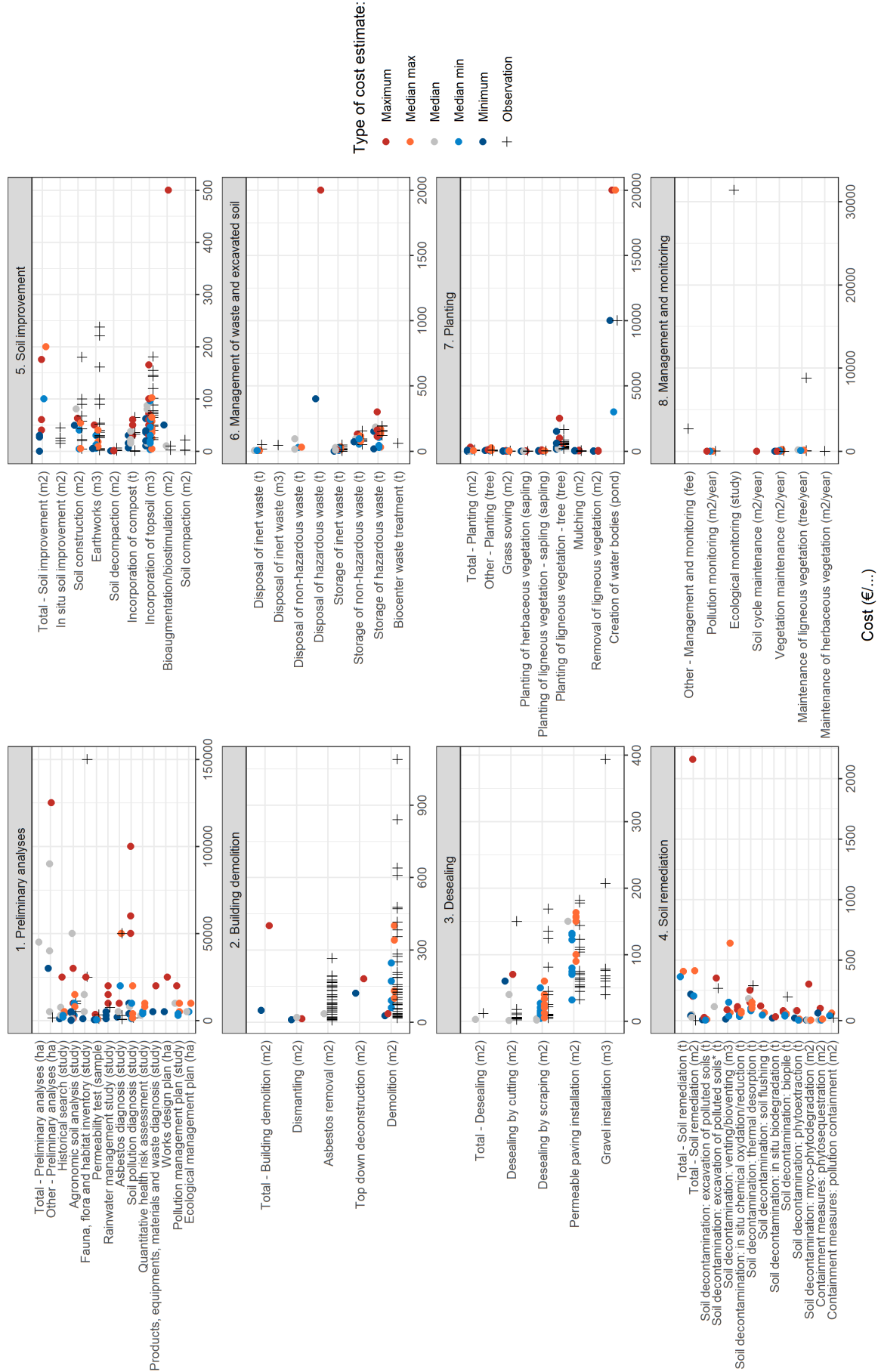
Figure A13: Costs of techniques (in €/m²) - By source of information



*Here, excavation costs also including earthworks, transportation and storage.

4.5.2 Costs in other units

Figure A14: Costs of techniques (in majority unit at the technique level)

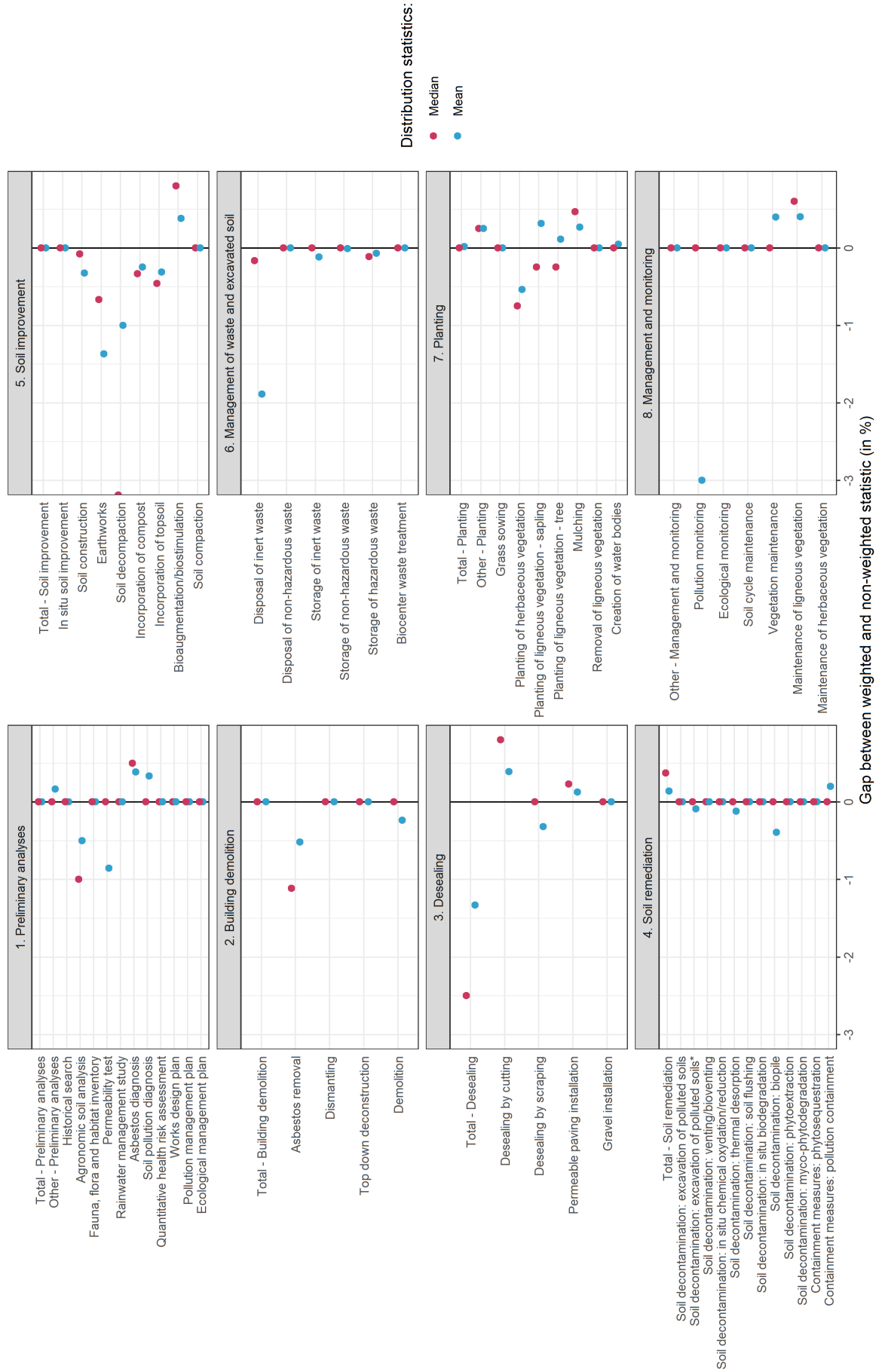


*Here, excavation costs also including earthworks, transportation and storage.

4.6 Sensitivity analysis

4.6.1 Costs of techniques

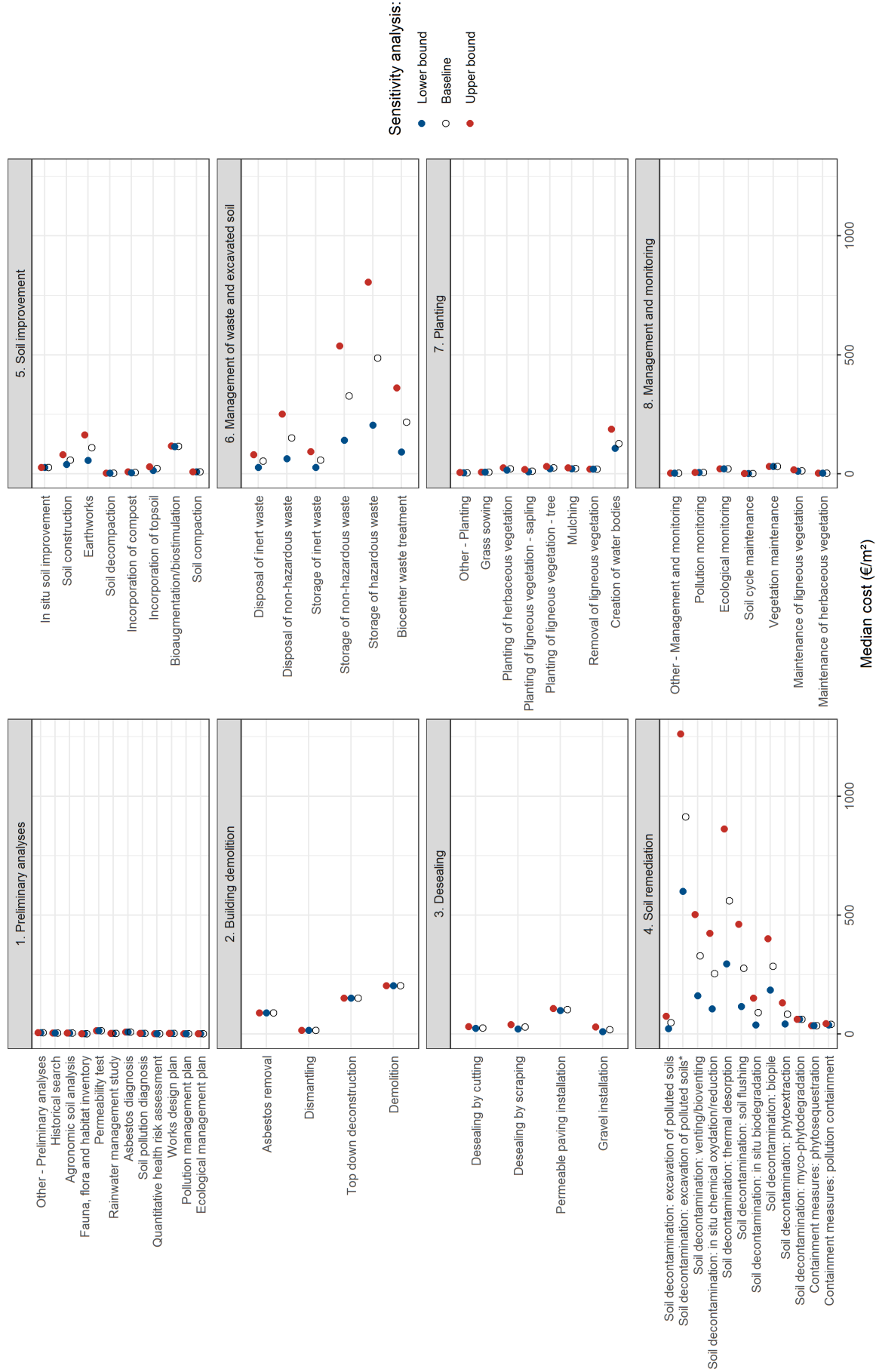
Figure A15: Average and median costs of techniques - Sensitivity to weight of statistics vs. observations



Note: Cost observations (from quotes, or specific experiences) are given a weight of 1, while costs given by experts or documents as statistics (e.g., median, minimum, etc.) are given a weight of 50.

*Excavation costs also including earthworks, transportation and storage.

Figure A16: Median costs of techniques - Sensitivity to hypotheses for conversion in €/m²

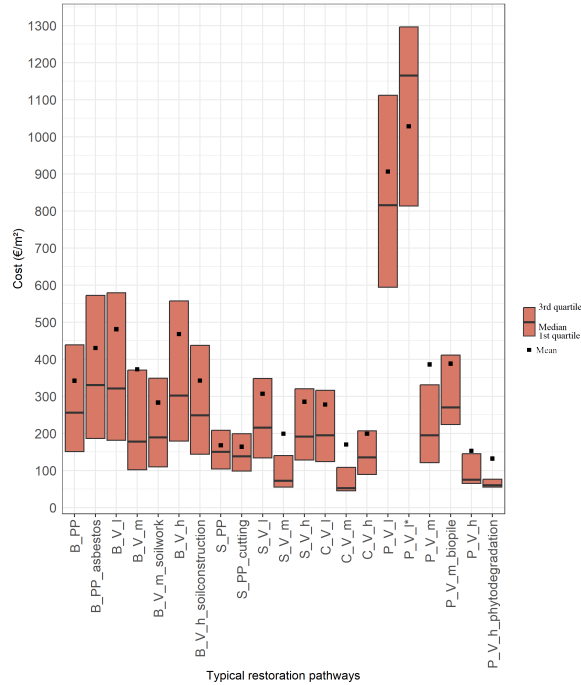


Note: the hypothesis to convert the cost units in €/m² for the baseline, lower and upper bound are in Table A5.
 *Excavation costs also including earthworks, transportation and storage.

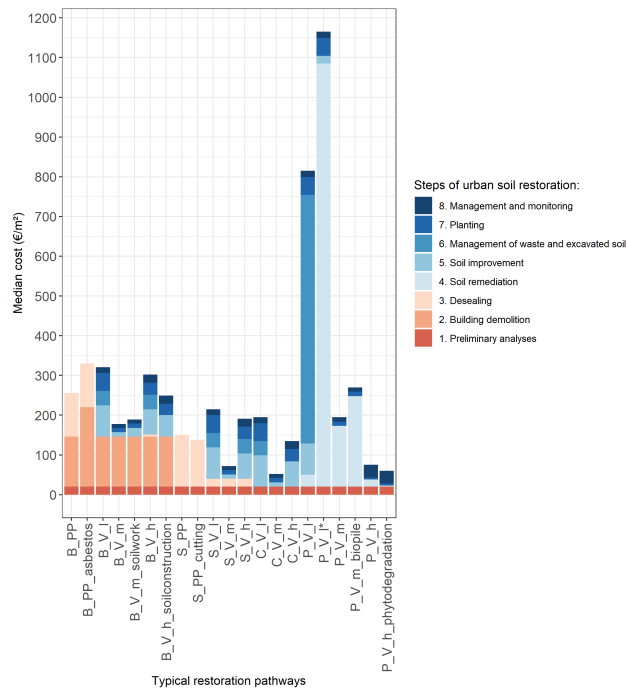
4.6.2 Typical restoration Pathways

Figure A17: Cost of typical pathways (in €/m²) - Including variants

(a) Cost distribution



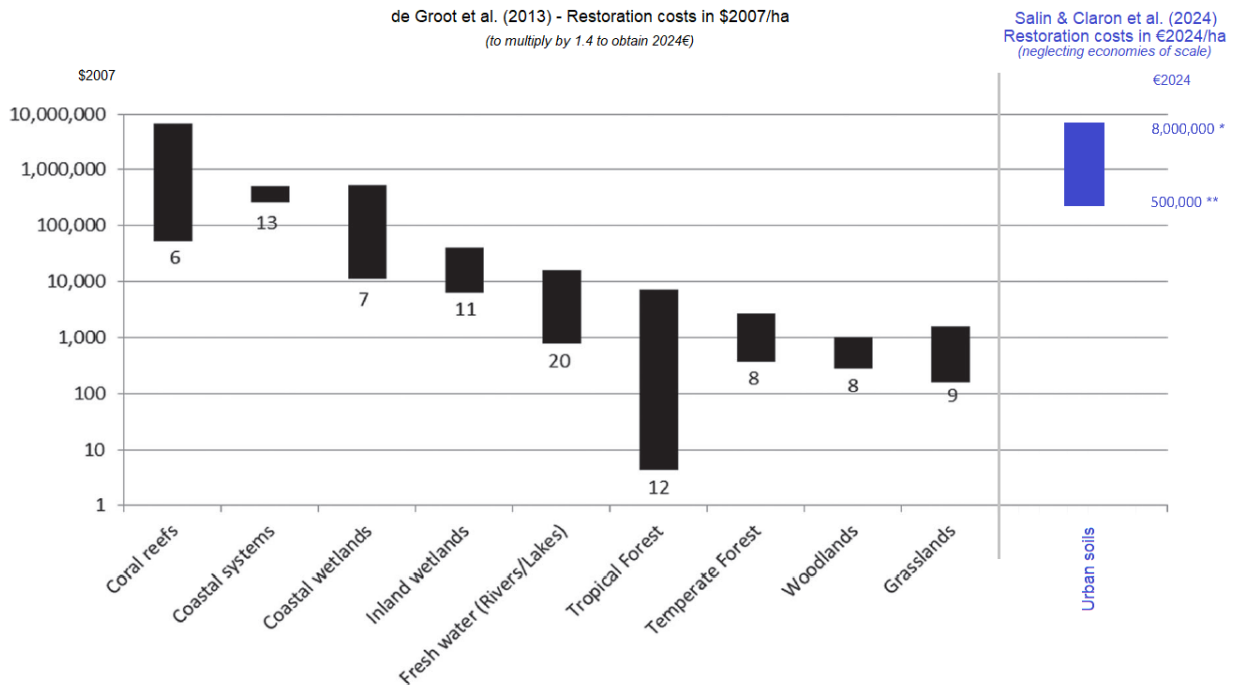
(b) Decomposition of median cost



Note: The name of each pathway have the following structure: *InitialState_FinalState_EcologicalEngineering*, where *Initial state* can be built-up (B), sealed with an impervious surface (S), compacted (C), or polluted (P); *Final State* can be porous paving (PP) or vegetation (V); *Ecological engineering* can be low (l), moderate (m) or high (h). Hypotheses for each pathway can be found in Annex 4.1.6.

4.7 Urban restoration costs in perspective

Figure A18: Comparison with restoration costs for other ecosystems



* Median cost in a scenario with initially polluted soil, restored into a green area using soil excavation and disposal in landfill (800€/m²)

** Median cost in a scenario with a soil initially compacted, restored into a vegetation area with low level of ecological engineering (50€/m²)

Source: Authors, adapted from *De Groot et al. (2013)*. NB: one important limitation to this comparison relates to the fact that *De Groot et al. (2013)* estimate restoration costs at the global level – estimates may therefore be driven by lower labour costs in developing countries.