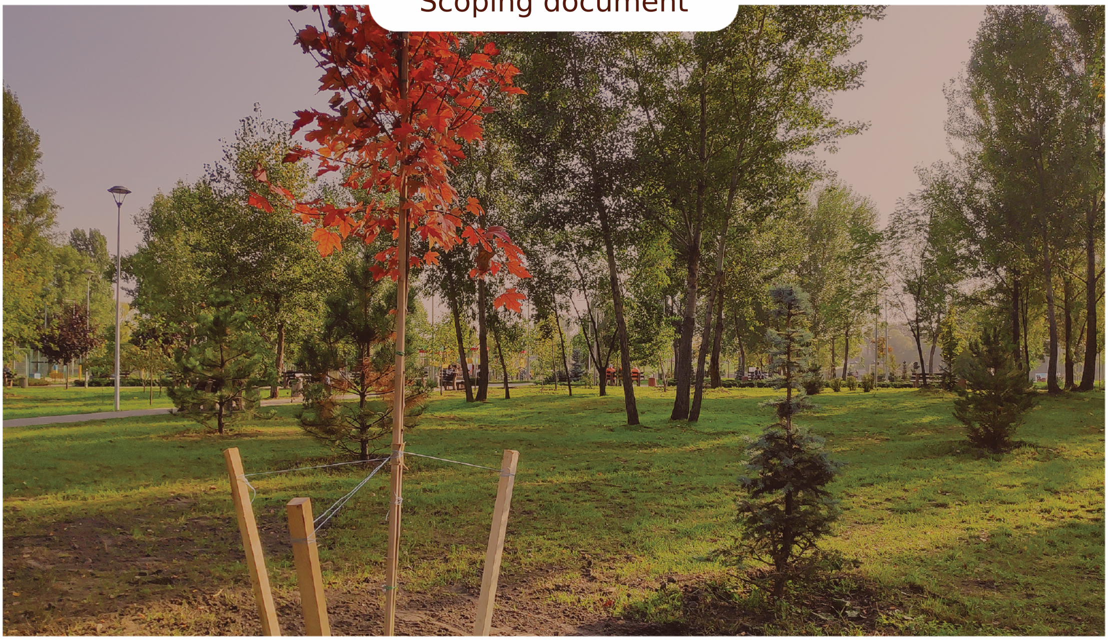
Soils for Europe 1: e149412
doi: 10.3897/soils4europe.e149412

SOILS FOR EUROPE
SOLO Soil sealing and urban soils

Scoping document



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Funded by the European Union

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doi: 10.3897/soils4europe.e149412
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Silvia Frezzi[‡], Chiara Cortinovis[‡], Christel Carlsson[§], Samuel Coussy[|], Antoine Decoville[¶], Kristina Flexman[#], Simona R. Gradinaru[¤], Jean-Marie Halleux[«], Peter Lacoere[»,˄], Federico Nahuel Lazzari[˅], Michele Munafò[¦], Rita Nicolau[ˀ], Stefan Siedentop[ˁ], Jaroslava Sobocká[₵], Eliška Vejchodská[ℓ], Davide Geneletti[‡]

‡ University of Trento, Trento, Italy
§ Swedish Geotechnical Institute, Linköping, Sweden
| Bureau de Recherches Géologiques Et Minières, BRGM, Orléans, France
¶ Department of Urban Development and Mobility, Luxembourg Institute of Socio-Economic Research (LISER), Esch-sur-Alzette, Luxembourg
# WSP, London, United Kingdom
¤ Swiss Federal Institute for Forest, Snow and Landscape Research WSL, Birmensdorf, Switzerland
« Université de Liège, Liège, Belgium
» HOGENT-DRUM, Gent, Belgium
˄ KU Leuven, Campus Ghent, Gent, Belgium
˅ Build Europe, Brussels, Belgium
¦ Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA), Rome, Italy
ˀ Direção-Geral do Território - DGT, Lisboa, Portugal
ˁ TU Dortmund University, Faculty of Spatial Planning, Department Urban Development, Dortmund, Germany
₵ National Agricultural and Food Centre, Soil Science and Conservation Research Institute, Bratislava, Slovakia
ℓ Faculty of Social Sciences, Charles University, Prague, Czech Republic

Corresponding author: Silvia Frezzi (silvia.frezzi@unitn.it), Chiara Cortinovis (chiara.cortinovis@unitn.it), Davide Geneletti (davide.geneletti@unitn.it)

Academic editor: Carlos Guerra

Received: 11 Feb 2025 | Accepted: 01 Jul 2025 | Published: 19 Sep 2025

Citation: Frezzi S, Cortinovis C, Carlsson C, Coussy S, Decoville A, Flexman K, Gradinaru SR, Halleux J-M, Lacoere P, Lazzari FN, Munafò M, Nicolau R, Siedentop S, Sobocká J, Vejchodská E, Geneletti D (2025) Outlook on the knowledge gaps to reduce soil sealing and increase the reuse of urban soil. Soils for Europe 1: e149412. https://doi.org/10.3897/soils4europe.e149412

List of abbreviations

EU - European Union

SOLO - Soils for Europe Project

Introduction

The third specific objective of the Soil Mission is to achieve "no net soil sealing and increase the reuse of urban soil" (*European Commission: Directorate-General for Research and Innovation 2022 p. 16*). Soil sealing is considered as the main process that causes land degradation in urban areas (European Environment Agency et al. 2022). When soil is sealed, an impermeable layer interrupts the connection between the soil and the atmosphere, leading to the loss of soil resources, biodiversity, and ecosystem services. The process of soil sealing is strictly linked to land take, i.e. the conversion of natural and semi-natural land into artificial land (see definitions in Table 1). The Soil Mission implementation plan estimates that the area with poor soil health due to soil sealing is probably <1% of EU land, but can be as high as 2.5%. These figures are based on the assumption that sealed areas represent around 50% of artificial areas, which cover 4.2% of the EU. Locally, sealed surfaces can reach very high levels, with some areas exhibiting rates as high as 70% (Decoville and Feltgen 2023). Both soil sealing and land take have been steadily growing during the last decades (European Environment Agency et al. 2022). Between 2000 and 2018, artificial areas expanded by 7.1%, with net land take averaging 440 km^2/year between 2012 and 2018, primarily at the expense of arable lands, pastures, and grasslands. Concerning the second part of the objective, soil reuse refers to the use of excavated soil from construction sites for other purposes (Reicosky and Wilts 2005). In many European countries, excavated soils are still classified as waste, contributing over 520 million tonnes to the total waste generated in the EU in 2018 (Scialpi and Perrotti 2022).

Table 1.

Definitions

Soil is the upper layer of the earth in which plants grow (Nougues and Brills 2023).
Land is the ground, including the soil covering and any associated surface water, over which ownership rights are enforced (Nougues and Brills 2023).
Soil sealing is the loss of soil resources (nutrients and moisture) due to the covering of the soil surface with impervious materials, as a result of urban development and infrastructure construction (https://esdac.jrc.ec.europa.eu/themes/soil-sealing).
Land take is the conversion of natural and semi-natural land into artificial land (Soil Monitoring Law - Article 3 (European Commission: Directorate-General for Environment 2023). Land take is a process that transforms natural and semi-natural areas (including agricultural and forestry land, gardens and parks) into artificial land (e.g., residential and industrial areas), using soil as a platform for construction and infrastructure as a direct source of raw material, or as an archive for historic patrimony. This transformation may cause the loss, often irreversibly, of the capacity of soils to provide other ecosystem services (provision of food and biomass, water and nutrients cycling, basis for biodiversity and carbon storage). (Soil Monitoring Law - Preamble (30), European Commission: Directorate-General for Environment 2023).
Soil reuse involves the repurposing of excavated soil from construction sites, which may be reused on-site or off-site, taking into account its characteristics and ensuring that they are compatible with the new soil application (Hale et al. 2021).
Land recycling is defined as the reuse of abandoned, vacant or underused land for redevelopment (European Environment Agency 2021).

The European Commission proposal for a Directive on Soil Monitoring and Resilience drafted in 2023 and currently under trilogue negotiations, aims to specify the conditions for healthy soils and to lay out regulations to promote sustainable soil use and restoration. The proposal includes mandatory monitoring of land take and soil sealing by Member States, to be conducted according to a common framework of indicators and methodological criteria (European Commission: Directorate-General for Environment 2023). The proposed indicators include total artificial land; land take, including reverse land take (i.e., the renaturalization of previously developed land); net land take (i.e., total minus reverse land take); and soil sealing. Member States may also measure optional indicators such as land fragmentation, land take for specific uses, and impacts on ecosystem services. According to the Commission's proposal, the monitoring of soil sealing and land take indicators should be conducted at least annually.

The "no net soil sealing and increase the reuse of urban soils" objective is linked to several other strategies, goals, and targets of the EU, including those of the Roadmap to a Resource Efficient Europe (European Commission 2011) (which included especially the no net land take by 2050 target), the EU Biodiversity Strategy to 2030 (European Commission: Directorate-General for Environment 2020), the Nature Restoration Regulations (European Parliament and Council 2024), and the EU Action Plan “Towards Zero Pollution for Air, Water and Soil” (European Commission 2021). Achieving "no net soil sealing and increase the reuse of urban soil" would also contribute to other EU Missions and related policy areas, such as Oceans, Seas and Waters (management of water quality and quantity in urban areas), Adaptation to Climate Change (flood mitigation), and Climate Neutral and Smart Cities (climate mitigation and resource efficiency). In addition, the objective is directly linked to several targets of SDG 11 - Make cities and human settlements inclusive, safe, resilient and sustainable and SDG 15.3 – End Desertification and Restore Degraded Land.

This document provides an overview of the state of knowledge related to this objective, by identifying specific knowledge gaps, actions to address them and potential bottlenecks. This document was prepared by the members of the “Soil sealing and urban soils” Think Tank within the SOLO project, through the process illustrated in Fig. 1.

State-of-the-art

Fig. 2 illustrates the link between the two topics that form the objective, namely soil sealing and soil reuse. The next sub-section presents an overview of the state of the art for each of them.

Soil sealing

Despite being among the human activities with the greatest impacts on soil, data on sealing at the European level were lacking for a long time. In the past three decades, the extent of soil sealing has been estimated based on land take data, also reflecting the greater policy attention dedicated to the latter process, for which the “no net” target had been proposed already in 2011 (European Commission 2011).

At the EU level, the main land uses that generated land take during 2000-2018 were industrial and commercial, as well as extension of low-density residential areas and construction sites (European Environment Agency 2019). Most of the new land take was at the expense of agricultural soils, often highly fertile soils located in flat areas where cities have historically developed. As a result, the negative effects on ecosystem services are significant (European Environment Agency et al. 2022). More detailed data on land take and net land take are available at the level of individual cities and commuting zones based on the Urban Atlas database, which provides high-resolution land use land cover maps of 788 Functional Urban Areas (FUA), i.e. cities and related commuting zones, across Europe (European Environment Agency 2023). However, the fact that this database does not cover the area outside functional urban areas of the EU limits its application for large scale (national and continental) monitoring.

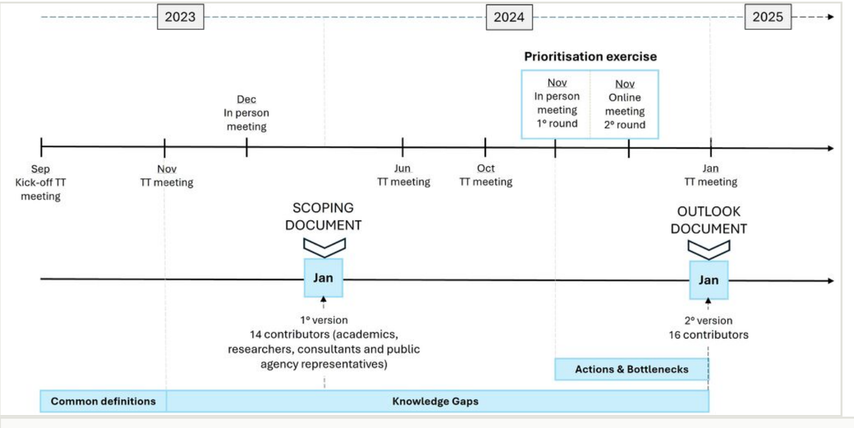

Figure 1. doi

Timeline and main activities of the “soil sealing and urban soils” Think Tank

In 2018, the Copernicus Land Monitoring Service (CLMS) released the Imperviousness Density (IMD) layer, a high-resolution raster map capturing the spatial distribution and changes of artificially sealed areas across the EEA-38 countries and the UK. While the IMD maps provide a homogeneous dataset for assessing soil sealing at the EU level, the change from the 20m resolution of the older maps (2006-2015) to the 10 m resolution of the newer maps (starting 2018) disrupted the consistency of the temporal series. The CLMS has recently released a harmonised IMD time series that overcomes the challenge of the mentioned resolution change and documents sealed cover evolution in a robust way. In addition to the IMD series, CLMS has produced the CORINE Land Cover (CLC) + Backbone Raster dataset for the years 2018 and 2021, which includes a thematic sealed class. The CLC+ Backbone represents a major improvement over the previous CORINE Land Cover system, offering enhanced land cover classification into 11 basic categories and a more robust framework for monitoring soil sealing across the EU (Maucha et al.

2024). However, the temporal coverage is limited and discrepancies remain, as the IMD dataset tends to underestimate sealed areas compared to CLC+ Backbone and reference datasets (Sannier et al. 2024). Moreover, it is important to note that both datasets estimate sealing based on remote sensing data. This data only captures surface sealing and does not account for underground structures, such as basements and parking garages, because these are not visible through remote acquisitions. These types of structures are common in urban areas and contribute to the reduction of soil ecosystem services like water infiltration and purification (Tobias et al. 2018).

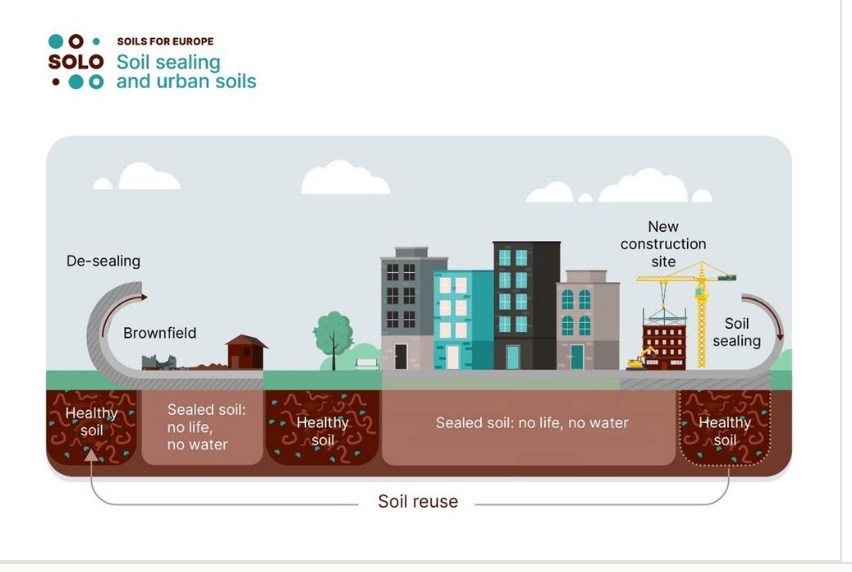

Figure 2. doi

Illustration of the Think Tank topics and their relationship

The description of the specific objective of "no net soil sealing and increase the reuse of urban soils" contained in the Soil Mission also mentions the increase of land recycling activities (European Environment Agency 2016). The term “land recycling” refers to the reuse of previously built-up or artificialised land (abandoned, vacant or underused land) for redevelopment. Land recycling was captured by one of the indicators developed by the EEA to monitor specific processes linked to land take. The land recycling indicator includes three components: “green recycling”, “grey recycling”, and “densification” which were assessed for the first time by the EEA in 2016 based on Urban Atlas data. Densification is defined as “land development within existing urban areas that makes maximum use of the existing infrastructure” (European Environment Agency 2021), thus minimising new land take and soil sealing. Between 2006 and 2012 densification accounted for the largest proportion of land recycling (9% of total land consumption*[1]). Grey recycling, i.e., the internal conversions between residential and/or nonresidential land cover types, was secondary to densification (3.2% of total land consumption), with country rates ranging from 14% of total land consumption in Latvia to less than 1% in

Slovakia, Slovenia, Luxembourg, and Lithuania. Green recycling, i.e., the development of green urban areas on previously built-up areas, including desealing activities, was a marginal process in all countries and, on average, accounted for only 0.2% of total land consumption between 2006 and 2012. The monitoring of these indicators by the EEA was discontinued, so more recent figures are not available. The Soil Mission has set a target of exceeding the value of 13% for land recycling. This figure refers to the period of 2006-2012, when land recycling contributed only 13% of the total land use changes involving urbanised areas in European FUAs.

The gaps identified in addressing soil sealing and land take highlight the necessity for cohesive and effective policies. Challenges include fragmented legal systems, as well as the difficulties in designing and implementing regulatory, fiscal, and incentive-based instruments (Ronchi et al. 2019). Urbanisation continues to cause land take, impacting biodiversity and ecosystem services. Public acceptance of no net soil sealing policies is hindered by limited awareness of soil functions and trade-offs between environmental goals and material welfare (Teixeira da Silva et al. 2018), with policies often overlooking socio-economic effects like housing affordability, urban congestion, and inequalities between landowners and non-owners (Vejchodská et al. 2022). There is a need for tools to support a better integration of soil health and soil ecosystem services into spatial planning processes (Calzolari et al. 2020), and of socially balanced policy tools to achieve the no net soil sealing target in a sustainable and equitable way.

Urban soil reuse

In most countries, soil excavated from construction sites is currently considered as waste and disposed in landfills, which makes it the biggest source of waste in the EU (more than 520 million tons only in 2018) (Scialpi and Perrotti 2022). To reduce this trend, the Soil Strategy aims to investigate the streams of excavated soils and considers proposing a “soil passport”, on the model of existing digital tools to track soil reuse in some EU countries (e.g., in Belgium and under development in France) (SOILveR (Soil and land research funding platform for Europe), 2022). These tools are sometimes also called or linked to ‘soil banks’, whose aim is to reconcile supply and demand of surplus soil from construction sites.

The legal frameworks on excavated soils and their potential reuse differs across Member States (European Commission: Directorate-General for Environment et al. 2024). In some countries, reuse is encouraged and even enforced for certain soils of high agricultural value. In other countries, reuse is allowed under certain conditions that usually refer to the quality of the soil and sometimes set temporal and spatial boundaries for the new application (e.g., in Sweden, reuse is allowed only on-site and within a reasonable period of time) (Hale et al. 2021). Often, additional permits or licenses are required, which impose a burden on reuse activities (Hale et al. 2021).

The management of excavated soils and their potential reuse is strictly linked to the issue of pollution (addressed by the fourth specific objective of the Soil Mission), although only part of excavated soil is polluted. While potentially contaminated sites in EEA-39 amount to 2.8 million, diffuse pollution (including pollution due to microplastic) could be a major problem in urban soils, whose impacts are still largely unknown. Beyond these general issues, other local issues may emerge in specific contexts as an effect of the high levels of soil sealing and associated anthropic activities and management practices, including compaction, erosion, and other types of concentrated pollution, which may affect urban soils in different ways compared to natural soils.

A detailed knowledge of the quality of soils, not only in terms of contamination levels but also in terms of geotechnical properties, is a prerequisite for safe reuse (Hale et al. 2021). The current level of knowledge on urban soils is generally poor, also due to the high spatial variability of their properties (Pouyat et al. 2020). The LUCAS topsoil survey is the only database that provides soil properties from samples collected across the EU (Eurostat 2018), although it is important to note that the parameters measured in urban areas differ from those assessed in other land use categories. The Soil Monitoring Law includes measures to enhance the role of LUCAS by increasing the density of sampling points. However, more and more databases of urban soil quality are being developed at the regional level (e.g., the GeoBaPa in the Regions Ile de France and in Normandy, or similar examples in various Länder in Germany) and even at the national level (e.g., BDSolU in France).

Prioritisation of knowledge gaps

The initial list of knowledge gaps in the Suppl. material 1 was developed through a scoping review of relevant literature and refined through discussions within the Think Tank. Once consensus had been reached, a two-round prioritisation exercise was conducted. During the general project meeting in Sofia, Bulgaria (November 2024), Think Tank participants voted on the ten most relevant gaps. In the first round, all meeting attendees, including members from all SOLO Think Tanks, selected their top three gaps from this list. A second round was later conducted online to include those who were unable to attend in person. Final scores were calculated by summing the votes from both rounds. Table 2 presents the top 10 gaps. The following section details the state of the art for the top three gaps and provides an overview of the other priority gaps identified by the Think Tank members.

Table 2.

Ranking of the top 10 knowledge gaps identified (a full list of all identified knowledge gaps is given in the Suppl. material 1). Type of knowledge gap: KDG = knowledge development gap, KAG = knowledge application gap.

Rank	Knowledge gap	Type of knowledge gap
1	New policy approaches and instruments to reduce soil sealing	KDG
2	Best practices to promote the reuse of urban soils from construction sites	KAG
3*	Effectiveness of desealing interventions	KDG

Rank	Knowledge gap	Type of knowledge gap
3*	Legal and regulatory dimension of soil sealing	KDG
5	Socio-economic impacts of no net soil sealing policies	KDG
6	Minimum unsealed soil per person to ensure biodiversity and human health in urban areas	KDG
7	Drivers of soil sealing from individual to sectoral policies	KDG
8	Typologies of soil sealing and their impact on soil functions and services	KDG
9	Acceptability and legitimacy of no net soil sealing policies	KDG
10	Links between soil sealing and land take	KDG

Roadmap for "No net soil sealing and increase the reuse of urban soils" Think Tank

Key knowledge gaps

New policy approaches and instruments to reduce soil sealing

At the city level, the issues of soil sealing and land take are primarily addressed in spatial planning processes. During these processes, goals and strategies for urban development are defined and policy instruments are identified to implement them. Policy instruments at the city level can be broadly categorised into binding and non-binding instruments. Binding instruments include specific regulatory measures such as quantitative soil sealing targets, restrictions on developing existing green areas, zoning of agricultural priority areas, and limitations on specific types of developments. For instance, zoning regulations typically establish acceptable limits on soil sealing for different land uses and implement enforceable rules to safeguard natural resources (Redon and Mialot 2024). A relevant example can be found in the city of Eindhoven, which introduced the new Environmental Planning Act, known as the 'Omgevingswet,' in 2019. Non-binding instruments include, among others, strategic planning documents, and incentive-based instruments designed to guide and encourage sustainable land use without imposing mandatory requirements (Naumann et al. 2018). The implementation and effectiveness of instruments can differ due to various factors such as bureaucratic complexity, inadequate monitoring, limited human or financial resources, conflicting interests, counter-incentives, lack of enforcement, political issues, and the absence of regional contextualisation.

Across Europe, the presence and enforcement of land take policies vary significantly. Countries such as Estonia, Poland, and Czechia lack explicit policies limiting land take. In contrast, Germany, Italy, Belgium, and Switzerland have adopted national goals which are then implemented at the regional level. However, in Italy and Germany, these goals are not legally binding but instead serve as aspirational targets (D'Ascanio et al. 2024). France set national goals of a 50% reduction in all the land use processes occurring on or ending up in developed land, which apply to the whole of France and uniformly to each region and Luxembourg set these goals at the local level. Generally, reducing land take is a widely debated topic, while soil sealing has emerged more recently (D’Ascanio et al. 2024). Few countries have adopted fiscal policies to prevent soil sealing, and those that have implemented these measures typically set uniform thresholds without considering the local context, thereby undermining the policy's effectiveness (Ronchi et al. 2019). Instruments based on financial charges or incentives are rare and, when introduced, are seldom applied comprehensively (Vejchodská and Pelucha 2019). For example, Austria and Germany provide financial incentives for the reuse of brownfields and for desealing measures. Belgium has introduced fiscal measures that incentivise demolition and reconstruction projects to encourage urban regeneration. Similarly, the French government has established a "brownfield fund" to financially support both private and public redevelopment of brownfield sites (D’Ascanio et al. 2024). In the United Kingdom, authorities are actively promoting the economic redevelopment of brownfield sites for residential purposes while also allowing controlled development on greenfield sites (Build Europe 2022). Although these measures show potential, their scale and scope remain limited, restricting their broader impact. This underscores the urgent need for more tailored, evidence-based policy instruments that address local environmental, social, and economic conditions.

A key principle in designing land policy instruments should be the mitigation hierarchy, which prioritises actions based on their impacts. The hierarchy includes a sequence of approaches, ranging from avoidance of land take and soil sealing to mitigation of their effects, and finally to compensation and restoration of degraded land (European Commission: Directorate-General for Environment 2021). Ideally, policy instruments should be aligned with this hierarchy to achieve specific outcomes (European Commission: Directorate-General for Environment 2012). Particularly:

- Avoidance: instruments aimed at avoiding land take should focus on preventing new greenfield developments. Protective measures, such as zoning agricultural priority areas or imposing restrictions on greenfield developments, are crucial in achieving no net land take.
- Mitigation: policies that mitigate the negative impacts of soil sealing, such as requirements for permeable surfaces in urban areas or water management systems, help address the environmental consequences of urbanisation.
- Compensation: instruments designed to restore land and ecosystems, such as mandatory reforestation.
- Offset (compensation): redevelopment of abandoned urban areas into new green areas can compensate for unavoidable impacts.

Effective policies should align with the mitigation hierarchy to balance development needs and environmental sustainability. For instance, development instruments should prioritise grey and green recycling and brownfield redevelopment to achieve 100% land recycling in the long-term, minimising the need for new greenfield projects (Lacoere and Leinfelder 2023). To achieve the ambitious no-net targets, a single instrument is insufficient, and a policy mix of various instruments is necessary (Spyra et al. 2025). There is a lack of integration among different policy instruments.

Designing effective land policy instruments is a complex process, requiring innovative approaches that balance competing public and private interests. One such approach could be the combined use of compensation and incentive mechanisms. These mechanisms address both the costs of inaction (push factors) and the benefits of sustainable soil use (pull factors), creating a dual approach to promote better land management. For example, developers could be required to compensate for soil sealing by investing in restoration projects, while also receiving incentives for adopting sustainable practices. Another innovative approach involves integrating soil functions and ecosystem services into the assessment of compensation measures (Calzolari et al. 2020), thus making explicit the value of soil and of its ecological benefits. For instance, incentives could be linked to preserving or enhancing ecosystem services such as carbon storage, water filtration, or biodiversity (Jost et al. 2021). By valuing these services, policies can encourage sustainable soil use while discouraging practices that degrade soil quality. Tradable permits could also be considered a promising economic policy instrument aimed at reducing land take, still lacking large scale implementation (Henger et al. 2023).

The specific questions associated with this gap are:

1. What types of policy instruments proved to be effective in supporting the no net soil sealing target in different contexts?
2. What innovative instruments and policy mixes can be designed to achieve the no net soil sealing target?

Best practices to promote the reuse of urban soils from construction sites

In a rapidly urbanising world, the importance of urban soil quality has grown significantly (Burghardt et al. 2022, Lehmann and Stahr 2007). Soil quality refers to the capacity of soil to function within ecosystems, supporting biological productivity, maintaining environmental quality, and promoting the health of plants, animals, and humans (Tresch et al. 2018). Urban soils, however, differ substantially from natural soils due to their altered physical, chemical, and biological characteristics caused by human activities (Kim et al. 2021, Pavao-Zuckerman 2008). Rapid urbanisation increases construction and demolition activities, generating large volumes of excavated soil (Hale et al. 2021). An example of these activities is road construction. Between 2012 and 2018, 189 km² of agricultural and natural land was converted in the EU for the expansion of the transport network (Damme and Keller 2023). The reuse potential of excavated soils depends on their geochemical compatibility with the receiving site (Sauvaget et al. 2020).

The excavated soils that cannot be reused on-site are classified as waste and managed under national policies. Member States have developed distinct regulations for the reuse of soil, leading to significant variation across countries. For example, in France, guidelines require contamination assessments for excavated soils. If the soil is contaminated, it must be treated or transported as waste. Non-contaminated soils, however, can be reused provided they meet geotechnical requirements. In Norway, surplus excavated soil is also classified as waste, with threshold values used to distinguish clean from contaminated soils. Sweden, by contrast, does not classify excavated soil as waste if it is reused on the same site within a reasonable timeframe (Hale et al. 2021). Despite these efforts, there is no unified European framework with standard regulations and threshold values for excavated soils, leaving soil reuse to be governed by national policies (Blanc et al. 2012, Hale et al. 2021).

The European Soil Strategy (European Commission: Directorate-General for Environment 2021) has proposed investigating excavated soil streams and assessing the feasibility of a "soil passport" or digital tracking system to enhance circular economy efforts. This initiative aims to promote the safe reuse of clean soils in all Member States. Some countries have already implemented soil passport systems. For example, Flanders in Belgium has incorporated soil passports into its contamination legislation, while Austria operates a similar system. In France, a national regulatory traceability system is in place for excavated soils, while in the UK, the Definition of Waste: Code of Practice (DoW CoP) outlines processes for reusing excavated materials on-site or moving them between sites. Digital tools, such as the TERRASS database, provide interactive online systems for monitoring soil quality and reuse (Blanc et al. 2012). However, there remains a critical lack of standardised indicators, protocols, methods, and tools for assessing urban soil quality and tracking its movement, making it difficult to implement these solutions (Llatas 2011, Ittner and Naumann 2022). In addition, tools to analyse soil quality and monitor its movement through a standardised "soil passport" system are still underdeveloped (Ittner and Naumann 2022, SOILveR (Soil and land research funding platform for Europe), 2022).

Many European Member States have proposed measures and set targets to increase the recovery and reuse of construction and demolition waste, but these initiatives often lack clarity regarding their implementation, especially for excavated soils (European Commission: Directorate-General for Environment et al. 2024). For instance, Estonia has set a target of recovering more than 75% of construction and demolition waste, though it is unclear whether this includes soil. Hungary is preparing legislation to establish a waste transfer system, which will include collection points and incentives for reusing and recycling construction waste. In Finland, the city of Helsinki has initiated a project to optimise the reuse of excavated soil within urban construction projects. While government-funded initiatives dominate efforts to promote soil reuse, the private sector has started to contribute in some cases, as demonstrated by the Helsinki project (European Commission: Directorate-General for Environment et al. 2024).

Despite progress, significant gaps remain in the development of cohesive European policies and best practices to promote soil reuse. The limited coordination between Member States and the absence of harmonised regulations exacerbate these challenges. Furthermore, current initiatives often fail to account for local contexts, resulting in less effective implementation. Addressing these issues requires a unified European framework that includes standard guidelines and evaluation metrics. To overcome these challenges, it is crucial to implement evidence-based, context-specific policies supported by robust tools and monitoring mechanisms. By promoting cohesive strategies, fostering collaboration between the public and private sectors, and raising awareness of the benefits of sustainable soil management, governments can advance the circular economy and ensure better urban soil management.

The specific questions associated with this gap are:

1. What are existing best practices of certifying soil quality and tracking soil transportation ("soil passport")? How could they be scaled at the EU level?
2. What are the most effective policy instruments to promote the reuse of urban soils?

Effectiveness of desealing interventions

Desealing is the process of removing artificial, impervious structures such as roads, buildings, and parking lots to restore soil permeability and, ideally, its ecosystem services. In many countries and regions, desealing actions are being proposed as a means of adapting urban areas to climate change, thus contributing to urban resilience. The amount of unsealed area, soil quality, and urban green infrastructure are used to map urban environmentally sensitive areas, which play a crucial role in maintaining ecological balance (Sobocká et al. 2020). Besides restoring permeability to improve rainwater management and reduce urban heat, desealing interventions may also promote biodiversity and the provision of other ecosystem services, particularly if desealed patches are sufficiently large and well connected.

It is important to acknowledge that desealed soils are anthropogenic and often exhibit reduced multifunctionality compared to undisturbed soils. Using agricultural topsoil for restoration is a common practice, but it is not environmentally sustainable as it implies the extraction and relocation of high-quality soil from rural to urban areas. Indeed, research shows that desealed soils can, in some cases, regain their biological quality and fertility without needing additional topsoil (Maienza et al. 2021). Studies on the effectiveness of desealing in restoring soil functions in the long term are limited (Tobias et al. 2018) and many desealing projects lack systematic evaluations of their environmental and social benefits (Vieillard et al. 2024). As an exception, the PermèaSoil project (https://www.strasbourg.eu/permeasol) provided valuable insights into the potential benefits of desealing. Over a three-year period, researchers observed the ecological development of desealed urban soils. Initially, these soils exhibited minimal organic matter, low biological activity, and an absence of vegetation. However, vegetation began to emerge within just one month, including both pioneer species and plants adapted to asphalt environments. Following the removal of impervious surfaces, water infiltration rates improved significantly, and over subsequent months, increases in water storage and organic matter content were anticipated.

Estimating the potential recovery of soil functions after desealing and the benefits generated in different contexts can help prioritise interventions. For example, areas with higher potential for restoring permeability, fertility, or biodiversity may be given precedence in urban planning efforts. At the regional level, urban population dynamics - whether a region is experiencing growth or decline - should also be considered. Research suggests a possible correlation between population growth and the extent of soil sealing, emphasising the need for tailored desealing strategies that account for these variables (Colsaet et al. 2018). For shrinking regions, desealing interventions may focus on reclaiming unused or abandoned spaces, restoring natural functions, and promoting ecological resilience (Decoville and Feltgen 2025). Rapidly growing urban areas may prioritise desealing as a means of mitigating risks such as flooding and heat stress. Despite these considerations, there remains a need for more rigorous and standardised methodologies to identify suitable areas for desealing. Establishing clear criteria for prioritising interventions will ensure that resources are allocated effectively and that desealing projects achieve their intended outcomes (Ittner and Naumann 2022). Cost-benefit analyses that also consider energy input required, CO_2 emissions, and waste produced could be a valuable support in prioritising interventions.

The specific questions associated with this gap are:

1. How effective are desealing/unsealing actions in restoring soil functions and services?
2. What is the potential for desealing in different contexts (urban vs. non-urban areas, different types of settlements)?
3. How do we identify and prioritise suitable areas for desealing interventions based on their environmental and social impact?

Legal and regulatory dimension of soil sealing

To gain a deeper understanding of soil, it is important to consider both its environmental dimension, which is in constant interaction with the natural world, and the dimension of private property along with all its associated rights. These elements are interrelated and play a crucial role in how soil issues are understood and legally addressed (Fox 2024, Gradinaru et al. 2023).

The definition and regulation of soil vary significantly across EU Member States, reflecting the diverse legal frameworks of each country (Kaplinsky 2023). This diversity has led to a fragmented approach to soil governance, with little coherence across national borders (Ronchi et al. 2019). Few national governments have implemented comprehensive strategies to address issues such as urbanisation, land take, and land use changes. The EU's target of achieving no net land take by 2050, launched in 2011, was an ambitious goal supported by non-binding measures, such as the "Guidelines on Best Practices to Limit, Mitigate, or Compensate Soil Sealing" (European Commission: Directorate-General for Environment 2012). However, progress has been limited due to the lack of enforceable actions. Similarly, the target of no net soil sealing requires supportive legislation. The Strategic Environmental Assessment (SEA) and the Environmental Impact Assessment (EIA) are promising legal instruments that can encourage the consideration of environmental impacts of plans and projects by promoting the identification of more environmentally friendly alternatives, hence contributing to a more systematic and transparent planning process to curb land take and soil sealing (Schatz et al. 2021).

Some Member States have taken significant steps toward soil conservation, but the approaches differ substantially. Ronchi et al. provide a review of instruments for soil protection across EU member states (Ronchi et al. 2019). In Austria, federal planning laws address soil protection, particularly in the state of the Land Salzburg. Belgium's Wallonia region has adopted an Agricultural Code (2014) that identifies soil as a natural resource requiring protection from urban expansion. Local legislation encourages limiting soil sealing through measures such as rules for water management systems and filtering plants, which help reduce surface runoff and overflows. Additionally, federal urban planning instruments aim to regulate land use changes, fostering greater sustainability and mitigating land take. Luxembourg offers another example of integrated soil conservation policies. The "Law Concerning the Evaluation of the Environmental Impacts of Certain Plans and Programmes" acknowledges the direct influence of planning instruments on soil health. Since 2003, the country has implemented a Master Programme for Spatial Planning, which outlines long-term strategies for protecting soil functions and promoting sustainable resource management. This programme coordinates various planning levels (regional, local, and sectoral) while addressing transport systems, infrastructure, and urban development to curb soil sealing and safeguard the natural environment. While these examples illustrate progress, the legal frameworks governing soil sealing and urban expansion remain inconsistent across Member States. The diversity of approaches underscores the pressing need for a unified European approach to ensure cohesive soil management practices.

One area requiring particular attention is the legal treatment of property rights, which significantly influences soil use and conservation. Property rights are central to land management, encompassing ownership by individuals, groups, or entities such as the state. These rights can be classified as private, common, or public and determine the permissible actions on land and soil (Lawry et al. 2014). However, the current property rights regime often limits public authorities' ability to impose stricter regulations on land take and urbanisation. For example, in Romania, a country where property rights are strong, authorities have a hard time rejecting requests for building permits aimed at the development of residential areas, even on fertile soils (Gradinaru et al. 2023). Property rights are a complex issue in soil management, particularly in urban contexts. While they have been widely discussed in the agricultural sector (Amentae et al. 2024), their implications for urban soil conservation remain underexplored. Development rights, often granted to private property owners, can constrain public sector interventions aimed at limiting soil sealing. There is growing recognition that private property rights should come with social obligations, such as the duty to manage soil sustainably. However, the current legal frameworks do not adequately incorporate these responsibilities (Halleux et al. 2012). For example, landowners are rarely required to account for the environmental impacts of soil sealing or urban expansion. Strengthening the legal framework to emphasise these social obligations is essential for advancing sustainable soil management and achieving the EU's no net land take goal.

The specific questions associated with this gap are:

1. How does the legal dimension of soil sealing and land take vary across Member States and what are the opportunities and challenges to integrate the no net soil sealing objective?
2. How do property rights and property regimes affect soil sealing?

Prioritised knowledge gaps

Socio-economic impacts of no net soil sealing policies

The policies of no net soil sealing and no net land take have both positive and negative impacts on society. The positive aspects include the enhancement of people's health and well-being and the long-term sustainability of human development. The negative aspects include significant adverse impacts on individual material welfare: decreased housing affordability and, as a result, higher urban rents due to the increased scarcity of land allocated for housing development (Vejchodská et al. 2022). Increased congestion after the densification of cities, and consequently, a decrease in quality of life, have also been mentioned as potential negative effects (Decoville and Feltgen 2023), which trigger resistance from residents to further construction as they seek to protect natural resources and preserve social harmony (Götze and Hartmann 2021). Exacerbated income and wealth inequality between different societal groups (the owners and non-owners of urban land) might be another outcome of higher scarcity of urban land. There is a significant knowledge gap in how to design public no net soil sealing policies that effectively minimise these adverse impacts.

Addressing these challenges will require the integration of different types of policies including fiscal instruments, such as property taxes, jointly with specific planning and land policies. A theoretical/analytical framework is needed to qualify policy measures according to their ability to reduce land take and sealing while minimising the risks of exacerbating socio-spatial injustices, depending on each region's spatial/demographic/economic context.

The specific questions associated with this gap are:

1. Which instrument mixes should be applied in different institutional settings for minimising the negative impacts of no net soil sealing and no net land take policies on housing affordability and other areas of material welfare?
2. How to ensure that policies aimed at halting land take and soil sealing do not exacerbate inequalities?

Minimum unsealed soil per person to ensure biodiversity and human health in urban areas

The rate of soil sealing in urban areas has a significant impact on both biodiversity and human health. Sealed surfaces significantly reduce the richness and abundance of various species by limiting habitat availability and disrupting ecological balance. For instance, Yan et al. (2019) found that in Wuhan, plant diversity sharply declines when impervious surfaces exceed a threshold of 40–60%. Additionally, the increase in sealed surfaces leads to a greater proportion of exotic plants, which can be detrimental to native biodiversity. The authors recommend keeping the share of soil sealing below 40% in cities to help preserve urban biodiversity.

In addition to biodiversity, the demand expressed by the population for the numerous ecosystem services provided by unsealed soils could be used as a basis to define minimum rates of unsealed surfaces to maintain in urban areas. For instance, green spaces promote well-being through cultural benefits such as beauty, inspiration, and belonging (O'Riordan et al. 2021). Various studies (Jungels et al. 2013, Rugel 2019) demonstrate the positive impact of visible greenery on mental health and well-being. Recently, the “3-30-300 rule” has been proposed as a set of specific targets to ensure residents have adequate access to nature and can enjoy the benefits of natural environments. These targets include the ability for everyone to see at least three mature trees from their home, workplace, or school, a minimum of 30% tree canopy cover in their neighborhood, and living within 300 meters of a high-quality public green space that is at least 0.5 hectares in size (Konijnendijk 2021). As shown by this simple rule, the benefits are not just a matter of total amount of green spaces or unsealed soil, but also of its spatial distribution, which should ensure equal benefits for all. Similar thresholds to steer spatial planning decisions could be developed having soil sealing and its impacts in mind.

The specific questions associated with this gap are:

1. What is the minimum area of unsealed soil needed in urban areas to effectively support biodiversity?
2. What is the minimum area of unsealed soil per person required in urban areas to promote human health and well-being?

Drivers of soil sealing from individual decisions to sectoral policies

Spatial planning is a primary factor determining soil sealing and land take, as decisions on urban expansion, densification, regeneration, and greening shape land use changes. Different spatial planning strategies impact soil sealing and land take in various ways: densification can limit urban expansion and reduce land take but may increase soil sealing in urban areas, while greening and nature-based solutions can promote desealing but might require new land take. For example, despite efforts toward sustainable urban development, only very few European cities have successfully halted land take between 2006 and 2012, with some paradoxical trends. In fact, growing cities densified but expanded inefficiently through abandonment of urbanised areas and fragmentation, while most shrinking cities increased residential areas despite population decline (Cortinovis et al. 2019). Evaluating the combined effects of multiple strategies is therefore critical to achieving no net land take and no net soil sealing targets.

Beyond spatial development policies, it is crucial to capture the impact of sectoral policies that can generate high demand for land. Sectors like tourism (Kizos et al. 2017), transport infrastructure (Oliveira et al. 2018), and commerce (Munafò 2023) contribute significantly to soil sealing and land take. Tourism demands facilities, roads, and parking, while transport and commercial developments, such as logistics hubs, exacerbate land take. These are often deemed activities of “public interest,” hence they bypass standard planning regulations, as seen in Italy, where logistic hubs have significantly contributed to land take and soil sealing in recent years, even in regions where targets are in place (Munafò 2023). Addressing the impacts of these sectoral policies requires tailored protocols.

Individual decisions also play a role in soil sealing (Künzel et al. 2024). Landowners and land managers influence sealing rates within private areas, and while differences exist across Europe, the social, economic, and cultural drivers of these decisions remain underexplored (Bouma 2018). Understanding these drivers is crucial for formulating effective strategies to mitigate soil sealing and land take. In conclusion, achieving no net land take and soil sealing targets demands a multifaceted approach that integrates spatial planning with assessments of sectoral policies and individual decision-making processes.

The specific questions associated with this gap are:

1. What is the impact of different spatial planning strategies (e.g., densification, regeneration, greening) on soil sealing and land take?
2. What other sectoral policies have an indirect impact on soil sealing and land take? How do we ensure that this impact is considered in their evaluation?
3. What social, economic, and cultural factors drive soil sealing decisions by landowners and land managers?

Typologies of soil sealing and their impact on soil functions and services

The EU Soil Mission defines soil health as the continued ability of soils to support ecosystem services (European Commission: Directorate-General for Research and Innovation 2022). Soil sealing compromises the functions of soils and, consequently, their ability to provide ecosystem services (Tóth et al. 2022). However, unsealed soil does not necessarily mean healthy soil. In urban areas, other processes may impair the capacity of soil to provide ecosystem services. For example, compaction may limit water infiltration. Hence, a more in-depth analysis of soil characteristics, and of their contribution to soil health, is needed to overcome the simplistic “sealed vs unsealed” classification (Decoville and Schneider 2016, Drobnik et al. 2018).

Examples of approaches that include the analysis of soil properties and functions exist in both literature and practice. Several studies have assessed soil health using a variety of indicators and methods, such as the Soil Assessment System that assigns different weights to individual soil characteristics, including texture, humus content, and depth of soil horizon (Toth et al. 2023). Studies like these can be used as a starting point to develop and test approaches that offer more insights into actual soil health. For example, in Sweden, the Biotope Area Factor was designed to enhance microclimate and air quality, protect soil function, improve water management efficiency, and increase habitat availability for plants and animals (Stange et al. 2022).

A specific challenge to be addressed by these new approaches is the treatment of underground processes of soil sealing, and their impacts on soil properties and functions (Tobias et al. 2018). These include, for example, the construction of underground parking places in residential developments, which are covered by green areas. The challenges include developing operational methods to assess the impacts of these processes on soil health, as well as mapping and inventorying them.

The specific questions associated with this gap are:

1. What are the most suitable methods and indicators to assess the impacts of soil sealing on key soil functions and services?
2. How can we operationally transition from the “sealed vs. unsealed” classification towards a more detailed assessment based on key soil properties? How can this be used to support the design of innovative no net soil sealing policies?
3. How can underground soil sealing be assessed?

Acceptability and legitimacy of no net soil sealing policies

Societal acceptance and acceptability are key aspects in promoting policies related to no net soil sealing and no net land take. Acceptance refers to the response following the implementation of a policy, while acceptability pertains to favorable or unfavorable perceptions prior to any policy interventions (Dreyer and Walker 2013). Societal support is essential as, without it, policymakers are often hesitant to enact tangible measures. This reluctance of public authorities to take decisive action is a significant factor contributing to the failure of environmental policies (Zvěřinová et al. 2014). At the local level, land take is often viewed positively, yet the relationship decision-makers have with this concept has not been thoroughly examined (Gradinaru et al. 2023).

Improving the social acceptability of no net soil sealing and no net land take policies is therefore crucial (Decoville and Feltgen 2025). A factor that highly affects social acceptance and acceptability of such policies is their impact on the material welfare of individuals, such as housing affordability or the decrease in quality of living due to densification (discussed in socio-economic impacts of no net soil sealing policies). Citizens’ awareness of the impact of soil sealing and mitigation strategies is another factor affecting social acceptability.

At the individual level, acceptability is influenced by various socio-economic factors, such as income, nationality, education, personal experiences, and environmental knowledge (Vanino et al. 2022). The latter is linked to the awareness of soil multiple functions, hence to the level of soil literacy in our societies. Even if the awareness of soil importance is increasing, there is a need to further promote knowledge about soil functions and services not only among citizens but also among professionals, for example in areas such as urban planning (Teixeira da Silva et al. 2018). This issue still receives little consideration in politics and society (Dazzi and Lo Papa 2022).

The specific questions associated with this gap are:

1. How do different actors perceive the relevance and need for the no net soil sealing and no net land take targets? What actors are likely to oppose the most, and why?
2. Which factors affect the level of societal acceptance of no net soil sealing policies and to which extent?
3. What are effective ways to strengthen acceptance of slowing soil sealing and accelerating unsealing among different societal actors?

Links between soil sealing and land take

Soil sealing, the covering of soil with impervious materials, is closely linked to land take, which refers to artificialisation processes tied to urban development and infrastructure construction. Land take involves artificial land uses for purposes like housing, industry, transport, and recreation. Soil sealing varies considerably within artificial land use categories. This complicates estimates based on land use data alone. In maps like Corine Land Cover and Urban Atlas, soil sealing values are used to classify residential classes with different densities (e.g., between 50% and 80% for the “discontinuous dense urban fabric” of the Urban Atlas).

Some studies highlight variability in soil sealing across contexts. For instance, in Italian cities, industrial areas showed soil sealing rates between 53.1% and 62.4%, while commercial zones ranged from 65.3% to 74.6% (Salata et al. 2019). A broader European study using Copernicus Imperviousness Density High-Resolution Layer data revealed soil sealing rates in the urban areas of 100 largest cities ranging from 31.5% to 72.6%, with a North-South gradient (Decoville and Feltgen 2023). These findings underscore the complexity of linking soil sealing with land take and the importance of detailed data to support policies aimed at sustainable land management. A clear understanding of the degree of soil sealing across different land use categories, land take processes, and its variability across contexts is essential to assess how achieving no net land take contributes to the no net soil sealing target, and vice versa. Without this understanding, the relationship between these objectives remains uncertain.

The specific questions associated with this gap are:

1. What is the degree of soil sealing associated with different land take processes? How does it vary in different contexts (e.g., for the same land use class across different countries)?
2. To what extent do the no net soil sealing and no net land take targets overlap?
3. What levels of soil sealing in urban areas allow for efficient land use and high density while also preserving ecosystem services with sufficient urban green spaces?

Overview

The initial list of knowledge gaps includes ten gaps presented in Table 2, along with four additional ones. These four additional knowledge gaps are:

1. Methods, indicators, and data to monitor soil sealing and land take;
2. Lack of consistent approaches for monitoring soil sealing/land take across Member States;
3. Quality of urban soils;
4. Social acceptance of soil reuse.

These additional gaps were assigned a lower priority during the first round of the prioritisation exercise and were therefore excluded from the main text.

The ten knowledge gaps in Table 2 are categorised into key and prioritised gaps, with a more detailed state-of-the-art analysis provided for the key gaps. Finally, the actions and associated bottlenecks related to all the gaps were identified, discussed within the Think Tank, and summarised in Suppl. material 1.

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Supplementary material

Suppl. material 1: knowledge gaps, bottlenecks and actions doi

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Endnotes

*1 In the context of the EEA monitoring, land consumption was defined as the sum of “all land use processes occurring on or ending up in developed land”, thus including both new land take as well as any other land use change involving artificial uses either as the initial or as the final use of the land.