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Carbon in Urban Soils

Final report for the Swiss Confederation, Federal office for the Environment FOEN, Soil and Biotechnology Division

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Author(s): Sarah Möller and Antoine Vialle, assisted by Aniella Goldinger and Jennifer Jiang, students from the Chair of Transitioning Urban Ecosystems at the Technische Universität Berlin
Source(s): Technische Universität Berlin

Fig. 21: Urban nature scenario illustrating Guideline D

Author(s): Sarah Möller and Antoine Vialle, assisted by Aniella Goldinger and Jennifer Jiang, students from the Chair of Transitioning Urban Ecosystems at the Technische Universität Berlin
Source(s): Technische Universität Berlin

Executive summary (EN)

Entitled "Carbon in Urban Soils," this project has demonstrated the importance and relevance of focusing on the issue of organic carbon sequestration in urban soils, which include not only highly anthropized soils, but also pseudo-natural soils and soils still in agricultural use within urbanized areas. The project has also shown that, in conjunction with agglomeration projects at cantonal level, local urban redevelopment operations (i.e., redevelopment of existing neighborhoods, spaces or infrastructures, in particular to adapt them to climate change – as opposed to development of new portions of city on agricultural land or natural areas) have the potential to protect and regenerate soils, and thus enhance their organic carbon sequestration function. Together with water regulation, such action on urban soils' organic carbon sequestration function thus improves the contribution of the urban environment to climate change mitigation and adaptation.
To this end, a transdisciplinary and interinstitutional team was set up to develop the project in the form of two work packages, one dedicated to soil science and the other to urban planning, design and management. The main output of these work packages can be summarized as follows:

WP I _ Measurements and characterization: the current state of carbon in urban soils and the drivers of its variations
The first work package had two main objectives:

- (a) to assess, through field survey and measurement (total carbon and nitrogen, inorganic and organic carbon, bulk density, texture, calculation of SOC and SOC stock, MO/clay), the current amount of carbon in Swiss urban soils (Lausanne and Zurich)
- (b) to interpret the SOC variation according to two main drivers: geomorphology (influencing soil texture, clay content) and vegetation cover and related management practices (influencing organic matter input)

The main results are:

- **Topsoil SOC values of Zurich and Lausanne's green spaces are relatively typical when compared to other global cities, slightly lower compared to Swiss grasslands and considerably higher than Swiss croplands**
- **Texture (clay content in Zurich and silt in Lausanne) in urban soils drives and establishes the SOC content**, while bulk density is a major correlate and potential driver of SOC dynamics (due to the limitation compaction can place on vegetation growth and on recent carbon sequestration, which often characterizes anthropogenic urban soils)

- While Lausanne displays a high degree of variability, making it difficult to identify any main trends related to vegetation cover types, in Zurich, lawns tended to have reduced SOC stocks compared to meadows, whereas urban forest soils contain the highest SOC (however, when comparing lawns, meadows and forests, the lack of significance of the influence of vegetation on SOC was attributed to the overriding factors like highly variable human soil disturbance and management practices)
- **Privately owned gardens exhibit significantly higher SOC levels than public green spaces in either city, likely due to differing management practices**

Two main takeaways from this work package must be underlined:

- **The present project supports the notion of sequestration *potential* to be used as a *target***, expressed as a SOC/clay ratio defined in accordance with specific soil function(s) sought as co-benefits. In the urban context, the co-benefit sought is not just food production, as is the case in the agricultural environment, but rather a more holistic notion *of territorial adaptation to climate change* (resistance and resilience), including in particular the water regulation functions. In future research developments, **the SOC/clay ratio expressing a carbon sequestration target (or potential) should be revised and refined as regards this objective of territorial adaptation (resistance and resilience)**
- In urban environments, the possible levers for increasing the total stock of organic carbon in soils are not limited to *protecting existing stocks* and *improving cultivation and management practices*, as is the case in agricultural environments, but also include the **regeneration of soils in currently artificialized and sealed areas** (in situ improvement, or reconstitution of functional substrates from organic and mineral waste)

WP II _ Analyses of soil management policies and recommendations: integration of soils to conservation and planning tools

The second work package builds on the results of parallel mandate for the Direction Générale du Territoire et du Logement (DGTL) of the Canton of Vaud (Vialle & Poyat, 2024). This mandate analyzed the influence of soil management, as well as urban planning and design policies, on carbon sequestration in urban soils through three case studies focusing on urban redevelopment operations, as well as their relation to the agglomeration project, cantonal planning and the federal legal framework. On this basis, the main objective of the second work package was to elaborate possible solutions to improve carbon sequestration in urban soils in the context of urban redevelopment projects.

The main results are:

- **An overall process** to increase the organic carbon sequestration capacity of urban soils was identified, according to the following steps:
  - **Preserving** existing functional soils
  - **Regenerating** soils on currently artificialized surfaces
  - **Improving and diversifying** the vegetation cover and related management
- This overall process was then developed in the form of **four guidelines focusing on the content of urban redevelopment projects**:
  - Guideline A. Urban morphology and preservation of functional soils
  - Guideline B. De-sealing artificial surfaces to regenerate functional soils
  - Guideline C. Reconstitution of functional substrates from circular management of urban waste or resources – soil nursery
  - Guideline D. Implementation of diversified vegetation cover and management practices conducive to organic carbon sequestration
- This overall process was also accompanied by **four guidelines focusing on methodology and tools**:
  - Guideline a. Promoting the multifunctionality and mixed uses of cultivated land in urban areas
  - Guideline b. Supporting a metabolic approach integrating waste/resource management into urban redevelopment projects – planning with a soil bank
  - Guideline c. Integrating soil diagnostics into project development and soil management
  - Guideline d. Planning and designing soil functions

Several areas for improvement must be underlined as takeaways from this work package:

- **At the federal level:**
  - In coordination with the various federal offices concerned and their respective strategies, promote a change in the culture of urban and territorial planning, involving a critical review of concepts such as compact built-up area, measured use of land, building culture (*Baukultur*) and urban agriculture in the light of urban soils and their functions.
  - In line with the Swiss National Soil Strategy for Sustainable Soil Management adopted by the Federal Council (FOEN, 2020), **define and promote a holistic approach to urban soil functions, formulated in terms of co-benefits and ecosystem services, aiming at territorial adaptation (resistance and resilience)** – not only

food production. Such holistic approach to urban soil functions should allow for the redefinition of optimal SOC/clay ratio(s) in order to set new targets (or potential) for improving carbon sequestration specifically adapted to the ecosystem services desired in the urban environments.

  - Support follow up of the promising research objective of the present project regarding the impact of various urban vegetation covers and related management practices (continuation of empirical data collection, implementation of site experiments and modeling), and **support current or future application-oriented research initiatives on surface de-sealing and soil regeneration solutions, sponge city solutions, circular (mineral and organic) waste management for soil reconstitution, development of coordinated data collection and their integration to a decision support tool (SQI) in coordination with the Soil Competence Centre (CCSols / KoBo).**
  - **Initiate a debate on certain limiting aspects of the current legal framework** and consider its possible evolution with regard to the monofunctional use of land for agriculture in the urban context; the operational management of polluted sites and materials; and its consequences on circular (mineral and organic) waste management for soil regeneration.
- At cantonal planning and agglomeration project level:
  - Develop cartographic project tools as decision support tools, such as monitoring of impervious surfaces, potential sites for circular waste management, resources in mineral waste and organic matter; collection, integration and adaptation of soil diagnostics (e.g., SQI); network of voids; green network and brown network.
  - Take a critical look at urban density targets in light of the need to preserve and regenerate urban soil functions, and define qualitative and quantitative targets for the proportion of land to be covered by vegetation (greening index), an agriculture (or) food production strategy and desirable soil functions (i.e., those to be preserved through the protection of existing soils and/or created through soil regeneration).
  - Identify possible incentives for surface de-sealing and soil regeneration, as well as the diversification of vegetation covers and the improvement of related management practices, on private land.
- At the level of urban redevelopment projects:
  - Highlight good examples of urban redevelopment to promote de-sealing; less harmful construction techniques and materials; soil reconstitution or soil nurseries as urban

proto-landscapes (transitional and mixed-used landscapes) and the diversification of vegetation covers.

- Explicitly reflect objectives related to soil protection and soil functions (previously defined at the cantonal level) in special or local regulations (e.g., plans de quartier), guidelines and briefs for urban redevelopment projects.
- Encourage the involvement of local actors in urban redevelopment operations to foster circular management of waste/resources and information feedback to cantonal level; mixed-used urban agriculture.

More generally, the approach proposed here, linking environmental functions to the social uses of urban soils, highlights the potential role that the latter can play as a medium for raising awareness. This project has demonstrated the need to train designers and project managers in soil challenges and, more broadly, in sustainability challenges.

Zusammenfassung (GR)

Das Projekt mit dem Titel „Kohlenstoff in urbanen Böden" hat die Bedeutung und Relevanz einer Fokussierung auf die Frage der Bindung von organischem Kohlenstoff in „urbanen Böden" aufgezeigt. Diese umfassen nicht nur stark anthropogen geprägte Böden, sondern auch naturnahe Böden („pseudo-natural soils") sowie Böden, die innerhalb urbanisierter Gebiete weiterhin landwirtschaftlich genutzt werden. Das Projekt hat zudem gezeigt, dass lokale Stadterneuerungsmaßnahmen (also die Umgestaltung bestehender Quartiere, Räume oder Infrastrukturen – insbesondere zur Anpassung an den Klimawandel und im Gegensatz zur Erschließung neuer Stadtflächen auf landwirtschaftlichen oder natürlichen Böden) das Potenzial haben, in Verbindung mit Agglomerationsprojekten auf kantonaler Ebene Böden zu schützen und zu regenerieren. Dadurch kann ihre Funktion zur Bindung von organischem Kohlenstoff verbessert werden. Zusammen mit der Wasserregulierung verbessert eine solche Förderung der organischen Kohlenstoffbindung in urbanen Böden somit den Beitrag des städtischen Umfelds zur Klimaschutz- und Anpassungsfähigkeit.

Zu diesem Zweck wurde ein transdisziplinäres und interinstitutionelles Team gebildet, um das Projekt in Form von zwei Arbeitspaketen zu entwickeln: ein Paket befasste sich mit der Bodenkunde, das andere mit Stadtplanung, -gestaltung und -management. Die wichtigsten Ergebnisse dieser Arbeitspakete lassen sich wie folgt zusammenfassen:

AP I – Messungen und Charakterisierung: aktueller Stand des Kohlenstoffs in urbanen Böden und Einflussfaktoren seiner Variationen

Das erste Arbeitspaket verfolgte zwei Hauptziele:

- (a) Mithilfe von Felduntersuchung und Messungen (Gesamt-Kohlenstoff- und Stickstoffgehalt, anorganischer und organischer Kohlenstoff, Bodendichte, Textur, Berechnung von SOC und SOC-Vorrat, MO/Ton-Verhältnis) die aktuelle Menge an Kohlenstoff in Schweizer Stadtböden (Lausanne und Zürich) zu erfassen;
- (b) Die SOC-Variation im Hinblick auf zwei Hauptfaktoren zu interpretieren: Geomorphologie (Einfluss auf Bodentextur und den Tongehalt) sowie Vegetationsdecke und damit zusammenhängende Bewirtschaftungspraktiken (Einfluss auf den Eintrag organischer Bodensubstanz).

Die wichtigsten Ergebnisse sind:

- **Die SOC-Werte im Oberboden der Grünflächen in Zürich und Lausanne sind im Vergleich zu denen anderer globaler Städte relativ typisch, liegen etwas unter denen von Schweizer Grünlandflächen und deutlich über denen von Schweizer Ackerböden.**
- **Die Bodentextur (Tongehalt in Zürich und Schluff in Lausanne) bestimmt den SOC-Gehalt in urbanen Böden,** während die Bodendichte ein wesentlicher Korrelatfaktor und potenzieller Treiber der SOC-Dynamik ist. (Dies liegt daran, dass Bodenverdichtung sowohl das Pflanzenwachstum als auch die jüngste Kohlenstoffbindung einschränken kann, die für anthropogene urbane Böden typisch ist.)
- Obwohl Lausanne eine hohe Variabilität aufweist, die es schwierig macht, klare Trends in Bezug auf Vegetationsdeckungstypen zu identifizieren, zeigen sich in Zürich geringer SOC-Vorräte in Rasenflächen im Vergleich zu Wiesen, während urbane Waldböden die höchsten SOC-Werte aufweisen. Allerdings wird beim Vergleich von Rasen, Wiesen und Wäldern die fehlende Signifikanz des Vegetationseinflusses auf SOC auf übergeordnete Faktoren wie die stark variierende menschliche Bodeneinwirkung und Bewirtschaftungspraktiken zurückgeführt.
- **Privatgärten weisen in beiden Städten signifikant höhere SOC-Werte auf als öffentliche Grünflächen, was wahrscheinlich auf unterschiedliche Bewirtschaftungspraktiken zurückzuführen ist.**

Zwei zentrale Erkenntnisse aus diesem Arbeitspaket sind hervorzuheben:

- **Das vorliegende Projekt unterstützt den Ansatz, das Kohlenstoffbindungspotenzial als Zielgröße zu verwenden,** ausgedrückt durch das SOC/Ton-Verhältnis, das in Übereinstimmung mit spezifischen Bodenfunktionen definiert wird, die als Zusatznutzen („co-benefits") angestrebt werden. Im urbanen Kontext umfasst dieser Zusatznutzen nicht nur die Nahrungsmittelproduktion, wie im landwirtschaftlichen Bereich, sondern vielmehr ein ganzheitliches Konzept der Anpassung urbaner Räume an den Klimawandel (Resistenz und Resilienz). Dazu gehören insbesondere Funktionen der Wasserregulierung. Im Rahmen zukünftiger Forschungsarbeiten **sollte das SOC/Ton-Verhältnis, das ein Ziel (bzw. Potenzial) der Kohlenstoffbindung ausdrückt, im Hinblick auf das Ziel der territorialen Anpassung (Resistenz und Resilienz) weiter überprüft und präzisiert werden.**
- In städtischen Umgebungen beschränken sich die möglichen Ansatzpunkte zur Erhöhung des Gesamtvorrats an organischem Kohlenstoff im Boden nicht – wie im Bereich Landwirtschaft

– auf den Schutz bestehender Vorräte und die Verbesserung von Bewirtschaftungs- und Anbaupraktiken. Sie umfassen auch **die Regeneration von Böden in derzeit versiegelten und künstlich überformten Flächen** (durch In-situ-Aufwertung oder die Rekonstruktion funktionaler Substrate aus organischen und mineralischen Abfällen).

AP II _ Analysen von Bodenmanagement-Strategien und Empfehlungen: Integration von Böden in Naturschutz- und Planungsinstrumente

Das zweite Arbeitspaket baut auf den Ergebnissen eines parallelen Auftrags für die Direction Générale du Territoire et du Logement (DGTL) des Kantons Waadt (Vialle & Poyat, 2024) auf. In diesem Auftrag wurde der Einfluss des Bodenmanagements sowie städtebaulicher und gestalterischer Strategien auf die Kohlenstoffbindung in urbanen Böden anhand von drei Fallstudien zu Stadterneuerungsmaßnahmen untersucht, ebenso wie deren Bezug zum Agglomerationsprojekt, zur kantonalen Planung und zum bundesrechtlichen Rahmen. Auf dieser Grundlage bestand das Hauptziel des zweiten Arbeitspakets darin, mögliche Lösungen zur Verbesserung der Kohlenstoffbindung in urbanen Böden im Kontext von Stadterneuerungsprojekten zu erarbeiten.

Die wichtigsten Ergebnisse sind:

- **Ein übergreifender Prozess** zur Erhöhung der organischen Kohlenstoffbindungskapazität wurde identifiziert, der folgende Schritte umfasst:
    - **Erhalt** bestehender funktionaler Böden
    - **Regeneration** von Böden auf derzeit künstlich versiegelten Flächen
    - **Verbesserung und Diversifizierung** der Vegetationsdecke und der damit verbundenen Bewirtschaftung
- Dieser Gesamtprozess wurde anschließend in Form von **vier Leitlinien für den Inhalt von Stadterneuerungsprojekten** ausgearbeitet, die den Inhalt von Stadterneuerungsprojekten in den Fokus nehmen:
    - Leitlinie A. Stadtmorphologie und Erhalt funktionaler Böden
    - Leitlinie B. Entsiegelung künstlicher Flächen zur Regeneration funktionaler Böden
    - Leitlinie C. Wiederherstellung funktionaler Substrate durch Kreislaufwirtschaft urbaner „Abfälle" bzw. Ressourcen – „Bodenschule"
    - Leitlinie D. Umsetzung einer diversifizierten Vegetationsdecke und von Bewirtschaftungspraktiken, die die Bindung von organischem Kohlenstoff fördern
- Der Gesamtprozess wurde außerdem von **vier weiteren Leitlinien begleitet, die sich auf Methodik und Instrumente beziehen**:

- Leitlinie a. Förderung der Multifunktionalität und Mischnutzung bewirtschafteter Flächen im urbanen Raum
- Leitlinie b. Unterstützung eines metabolischen Ansatzes durch Integration von „Abfall- und Ressourcenmanagement" in Stadterneuerungsprojekte – Planung mit einer „Bodenbank"
- Leitlinie c. Integration von Bodendiagnostik in die Projektentwicklung und das Bodenmanagement
- Leitlinie d. Planung und Gestaltung von Bodenfunktionen

Mehrere Verbesserungsbereiche müssen als zentrale Erkenntnisse aus diesem Arbeitspaket hervorzuheben:

- **Auf Bundesebene:**
    - In Abstimmung mit den jeweiligen Bundesämtern und ihren Strategien sollte ein Wandel in der Kultur der Stadt- und Raumplanung gefördert werden, einschließlich einer kritischen Überprüfung von Konzepten wie „kompakte Siedlung", „maßvoller Umgang mit Flächen", „Baukultur" und „urbaner Landwirtschaft" hinsichtlich urbaner Böden und deren Funktionen.
    - Im Einklang mit der vom Bundesrat verabschiedeten „Bodenstrategie Schweiz für einen nachhaltigen Umgang mit dem Boden" (FOEN, 2020) **sollten ein ganzheitlicher Ansatz für die Funktionen urbaner Böden definiert und gefördert werden, der darauf abzielt, Zusatznutzen und Ökosystemleistungen gezielt für die territoriale Anpassung – insbesondere im Sinne von Resistenz und Resilienz urbaner und territorialer Systeme – zu erschließen** und nicht nur die Nahrungsmittelproduktion zu fördern. Ein solcher ganzheitlicher Ansatz für die Funktionen urbaner Böden sollte es ermöglichen, das optimale SOC/Ton-Verhältnis neu zu definieren, um neue Zielwerte (bzw. Potenziale) zur Verbesserung der Kohlenstoffbindung spezifisch im Hinblick auf gewünschte Ökosystemleistungen im urbanen Raum festzulegen.
    - Die Weiterverfolgung des vielversprechenden Forschungsziels dieses Projekts hinsichtlich der Wirkung verschiedener urbaner Vegetationsdeckentypen und der damit verbundenen Bewirtschaftungspraktiken sollte unterstützt werden (Fortsetzung der empirischen Datenerhebung, Durchführung von Standortexperimenten und Modellierungen), sowie **aktuelle oder zukünftige anwendungsorientierte Forschungsinitiativen zu Entsiegelungs- und Bodenregenerationslösungen, „Schwammstadtkonzepten", zirkulärem (mineralischem und organischem)**

  Abfallmanagement für die Bodenregeneration sowie zur Entwicklung einer koordinierten Datenerhebung und deren Integration in ein Entscheidungsunterstützungssystem (SQI), jeweils in Kooperation mit dem Bodenkompetenzzentrum (CCSols / KoBo).
  - **Eine Debatte über bestimmte einschränkende Aspekte des aktuellen Rechtsrahmens sollte angestoßen** und eine mögliche Weiterentwicklung in Betracht gezogen werden, insbesondere im Hinblick auf die monofunktionale Nutzung von Flächen für die Landwirtschaft im urbanen Kontext, das operative Management belasteter Standorte und Materialien sowie die Auswirkungen auf das zirkuläre Abfallmanagement (mineralisch und organisch) im Zusammenhang mit der Bodensanierung.
- Auf Ebene der kantonalen Planung und des Agglomerationsprojekts:
  - Entwicklung kartografischer Projektinstrumente als Entscheidungsunterstützung, beispielsweise zur Überwachung versiegelter Flächen, zur Identifizierung potenzieller Standorte für zirkuläres Abfallmanagement, zur Erfassung von Ressourcen in mineralischen Abfällen und organischer Bodensubstanz; Erfassung, Integration und Anpassung von Bodendiagnostik (z. B. SQI); „Netzwerk von Freiräumen"; „grünes Netzwerk" und „braunes Netzwerk".
  - Kritische Prüfung der Ziele zur städtischen Dichte im Hinblick auf die Notwendigkeit, urbane Bodenfunktionen zu erhalten und wiederherzustellen, sowie Definition qualitativer und quantitativer Ziele für den Anteil der Fläche, der mit Vegetation bedeckt sein soll (Begrünungsindex), eine „Landwirtschafts- bzw. Ernährungsstrategie" und wünschenswerte Bodenfunktionen (d. h. solche, die durch den Schutz bestehender Böden zu erhalten und/oder durch Bodensanierung zu schaffen sind).
  - Mögliche Anreize für Flächenentsiegelung und Bodensanierung sowie für die Diversifizierung der Vegetationsdecke und die Verbesserung der damit verbundenen Bewirtschaftungspraktiken auf Privatflächen identifizieren.
- Auf Ebene der Stadterneuerungsprojekte:
  - Gute Beispiele für Stadterneuerung hervorheben, um die Entsiegelung zu fördern; weniger schädliche Bautechniken und -materialien; Bodenregeneration oder „Bodenschulen" als urbane Übergangs- und Mischnutzungslandschaften („proto-landscapes") sowie die Diversifizierung der Vegetationsdecke.

- Explizit bodenschutz- und funktionsbezogene Ziele (bisher auf kantonaler Ebene definiert) in Sonder- oder lokalen Regelwerken (z.B. „plans de quartier‟), Leitlinien und Vorgaben für Stadterneuerungsprojekte berücksichtigen.
- Die Beteiligung lokaler Akteure an Stadterneuerungsmaßnahmen zur Stärkung des zirkulären Managements von Abfällen/Ressourcen und der Rückmeldung an die kantonale Ebene fördern; Mischnutzung und urbane Landwirtschaft einbeziehen.

Allgemeiner betrachtet hebt der hier vorgeschlagene Ansatz, der Umweltfunktionen mit den sozialen Nutzungen urbaner Böden verknüpft, die potenzielle Rolle hervor, die letztere als Medium der Bewusstseinsbildung spielen können. Das Projekt hat den Bedarf an Weiterbildung für Planende und Projektverantwortliche zu den Herausforderungen des Bodens unterstrichen – und darüber hinaus zu den Herausforderungen nachhaltiger Entwicklung.

Résumé (FR)

Intitulé « Le carbone dans les sols urbains » (Carbon in Urban Soils), ce projet a démontré l'importance et la pertinence d'une approche centrée sur la séquestration du carbone organique dans les « sols urbains » - intégrant non seulement les sols fortement anthropisés, mais aussi les sols pseudo-naturels et les sols encore utilisés à des fins agricoles dans les zones urbaines. Le projet a également montré que, en conjonction avec des projets d'agglomération au niveau cantonal, les opérations locales de requalification urbaine (c'est-à-dire le réaménagement de quartiers, d'espaces ou d'infrastructures existants, en particulier pour les adapter au changement climatique – par opposition au développement de nouvelles parties de la ville sur des terres agricoles ou des zones naturelles) ont le potentiel de protéger et de régénérer les sols, et donc d'améliorer leur fonction de séquestration du carbone organique. Associée à la régulation de l'eau, cette action sur la fonction de séquestration du carbone organique des sols urbains améliore ainsi la contribution de l'environnement urbain à l'atténuation et à l'adaptation au changement climatique. Pour ce faire, une équipe transdisciplinaire et interinstitutionnelle a été mise en place afin de développer le projet sous la forme de deux "work packages" (volets de travail), l'un consacré à la science des sols et l'autre à l'urbanisme. Les principaux résultats de ces deux work packages peuvent être résumés comme suit :

WP I _ Mesures et caractérisation : état actuel du carbone dans les sols urbains et facteurs déterminants de sa variation

Le premier work package a poursuivi deux principaux objectifs :

- (a) évaluer la quantité actuelle de carbone dans les sols urbains suisses (Lausanne et Zurich) à travers des relevés et des mesures sur le terrain (carbone et azote totaux, carbone inorganique et organique, densité apparente, texture, calcul du COS (carbon organic du sol) et du stock de COS, ratio MO/argile) ;
- (b) interpréter la variation du COS en fonction de deux principaux facteurs : la géomorphologie (qui influence la texture du sol et la teneur en argile) et la couverture végétale associées à des pratiques de gestion spécifiques (qui influencent l'apport en matière organique).

Les principaux résultats sont les suivants :

- **Les valeurs de SOC dans la couche supérieure du sol des espaces verts de Zurich et de Lausanne sont relativement typiques par rapport à celles d'autres villes dans le monde, légèrement inférieures à celles des prairies suisses et considérablement supérieures à celles des terres agricoles suisses ;**
- **La texture (teneur en argile à Zurich et en limon à Lausanne) des sols urbains détermine et établit la teneur en COS**, tandis que la densité apparente apparait comme un facteur corrélé majeur et un potentiel déterminant de la dynamique du COS (en raison des contraintes que le compactage peut exercer sur le cycle de vie de la végétation et donc sur la séquestration récente du carbone qui caractérise souvent les sols urbains anthropiques) ;
- Tandis que Lausanne présente une grande variabilité, ce qui rend difficile l'identification de grandes tendances liées aux types de couverture végétale, à Zurich, les pelouses ont tendance à avoir des stocks de COS réduits par rapport aux prairies, tandis que les sols urbains forestiers contiennent les COS les plus élevés (cependant, lorsque l'on compare les pelouses, les prairies et les forêts, l'absence d'influence significative de la végétation sur les COS a été attribuée à des facteurs prépondérants tels que la forte variabilité des pratiques de gestion et des perturbations humaines sur les sols) ;
- **Les jardins privés présentent des niveaux de SOC nettement plus élevés que les espaces verts publics dans les deux villes, probablement en raison de pratiques de gestion différentes.**

Deux points essentiels de ce work package doivent être soulignés :

- **Le présent projet soutient l'idée que le potentiel de séquestration doit être compris et utilisé comme un objectif**, exprimé sous la forme d'un rapport COS/argile défini selon les fonctions spécifiques du sol recherchées comme co-bénéfices. En contexte urbain, le co-bénéfice recherché n'est pas seulement la production alimentaire, comme c'est le cas en milieu agricole, mais plutôt une notion plus holistique d'adaptation territoriale au changement climatique (incluant résistance et résilience), comprenant notamment les fonctions de régulation hydrique. Dans les développements futurs de la recherche, **le rapport COS/argile exprimant un objectif (ou potentiel) de séquestration du carbone devrait être révisé et affiné au regard de cet objectif d'adaptation territoriale (résistance et résilience);**
- Dans les milieux urbains, les leviers possibles pour augmenter le stock total de carbone organique dans les sols ne se limitent pas à la protection des stocks existants et à l'amélioration des pratiques culturales et de gestion, comme c'est le cas dans les milieux agricoles, mais incluent également **la régénération des sols dans les zones actuellement**

artificialisées et imperméabilisées (amélioration in situ, ou reconstitution de substrats fonctionnels à partir de déchets organiques et minéraux).

WP II _ Analyses des politiques de gestion des sols et recommandations : intégration des sols dans les outils de conservation et d'aménagement urbain

Le deuxième work package s'est appuié sur les résultats d'un mandat parallèle pour la Direction générale du territoire et du logement (DGTL) du canton de Vaud (Vialle & Poyat, 2024). Ce mandat a analysé l'influence de la gestion des sols, ainsi que des politiques d'urbanisme et d'aménagement, sur la séquestration du carbone dans les sols urbains à travers trois études de cas axées sur des opérations de réaménagement urbain, ainsi que leur relation avec le projet d'agglomération, la planification cantonale et le cadre juridique fédéral. Sur cette base, l'objectif principal du deuxième volet de travail a été d'élaborer des solutions possibles pour améliorer la séquestration du carbone dans les sols urbains, dans le cadre de projets de requalification urbaine.

Les principaux résultats sont les suivants :

- **Un processus global** visant à augmenter la capacité de séquestration du carbone organique des sols urbains a été identifié, selon les étapes suivantes :
    - **Préserver** les sols fonctionnels existants ;
    - **Régénérer** les sols sur les surfaces actuellement artificialisées ;
    - **Améliorer et diversifier** le couvert végétal et sa gestion.
- Ce processus global a ensuite été développé sous la forme de **4 lignes directrices axées sur le contenu des projets de requalification urbaine** :
    - Ligne directrice A. Morphologie urbaine et préservation des sols fonctionnels
    - Ligne directrice B. Désimperméabilisation des surfaces artificielles pour régénérer les sols fonctionnels
    - Ligne directrice C. Reconstitution de substrats fonctionnels à partir de la gestion circulaire des « déchets » ou ressources urbains - « Pépinière de sols »
    - Ligne directrice D. Mise en œuvre d'une couverture végétale diversifiée et de pratiques de gestion favorables à la séquestration du carbone organique
- Ce processus global s'accompagne également de **4 lignes directrices axées sur la méthodologie et les outils :**
    - Ligne directrice a. Promouvoir la multifonctionnalité et les usages mixtes des terres cultivées en milieu urbain

- Ligne directrice b. Soutenir une approche métabolique intégrant la gestion des « déchets/ressources » dans les projets de requalification urbaine - Planifier avec une « banque de sols »
- Ligne directrice c. Intégrer le diagnostic des sols dans le développement des projets et la gestion des sols
- Ligne directrice d. Planifier les fonctions des sols et les intégrer a la conception urbaine

Plusieurs domaines d'amélioration peuvent être soulignés comme points à retenir de ce work package :

- **Au niveau fédéral :**
    - En coordination avec les différents offices fédéraux concernés et leurs stratégies respectives, promouvoir un changement de culture en matière d'aménagement urbain et territorial, impliquant une révision critique de concepts tels que « zone bâtie compacte », « utilisation mesurée du sol », « culture du bâti » et « agriculture urbaine » à la lumière des sols urbains et de leurs fonctions ;
    - Conformément à la « Stratégie nationale suisse pour une gestion durable des sols » adoptée par le Conseil fédéral (OFEV, 2020), **définir et promouvoir une approche holistique des fonctions des sols urbains, formulée en termes de co-bénéfices et de services écosystémiques, visant l'adaptation territoriale (résistance et résilience)** – et pas seulement la production alimentaire. Une telle approche holistique des fonctions des sols urbains devrait permettre de redéfinir des ratios COS/argile optimaux. Sur cette base desquels on pourra fixer de nouveaux objectifs (ou potentiels) pour améliorer la séquestration du carbone spécifiquement qui soient spécifiquement adaptés aux services écosystémiques souhaités dans en milieu urbain ;
    - Poursuivre l'objectif de recherche prometteur du présent projet concernant l'impact de divers types de couvertures végétales urbaines et des pratiques de gestion associées (poursuite de la collecte de données empiriques, mise en œuvre d'expériences sur le terrain et modélisation). **Soutenir également les initiatives de recherche actuelles ou futures visant des applications et solutions concrètes en matière de désimperméabilisation et de régénération des sols : approche « ville éponge », gestion circulaire des déchets (minéraux et organiques) pour la reconstitution de sols, développement d'une collecte coordonnée des données et intégration dans un outil d'aide à la décision (IQS) en coordination avec le Centre de compétence sur les sols (CCSols / KoBo) ;**

    - **Initier un débat sur certains aspects restrictifs du cadre juridique actuel et réfléchir à son évolution possible** en ce qui concerne : l'utilisation monofonctionnelle des terres agricoles en milieu urbain ; la gestion opérationnelle des sites et des matériaux pollués, et ses conséquences sur la gestion circulaire des déchets (minéraux et organiques) pour la régénération des sols.
- Au niveau cantonal et des projets d'agglomération :
    - Développer des outils cartographiques comme aides à la décision, tels que : suivi des surfaces imperméables, sites potentiels pour la gestion circulaire des déchets, ressources disponibles en termes de déchets minéraux et les matières organiques ; collecte, intégration et adaptation des diagnostics des sols (p. ex. IQS) ; « trame des vides » ; « trame verte » et « trame brune » ;
    - Examiner de façon critique les objectifs de densité urbaine à la lumière de la nécessité de préserver et de régénérer les fonctions des sols urbains, et définir des objectifs qualitatifs et quantitatifs pour : la proportion de surface à végétaliser (indice de verdissement), une « stratégie agricole (ou) de production alimentaire », les fonctions souhaitables des sols (c'est-à-dire celles à préserver par la protection des sols existants et/ou à créer par la régénération des sols) ;
    - Identifier les incitations possibles pour le désimperméabilisation des surfaces et la régénération des sols, ainsi que la diversification des couvertures végétales et l'amélioration des pratiques de gestion associées, sur les terrains privés.
- Au niveau des projets de requalification urbaine :
    - Mettre en avant les bonnes pratiques en matière de requalification urbaine afin de promouvoir : la désimperméabilisation ; les techniques et matériaux de construction moins impactants ; la reconstitution des sols ou les « pépinières de sols » en tant que proto-paysages urbains (paysages transitionnels et à usage mixte) ; la diversification des couvertures végétales ;
    - Intégrer explicitement les objectifs liés à la protection et aux fonctions des sols (définis au préalable au niveau cantonal) dans les réglementations spéciales ou locales (par exemple les « plans de quartier »), les directives et les cahiers des charges des projets de requalification urbaine.

De manière générale, l'approche proposée ici, associant les fonctions environnementales aux usages sociaux des sols urbains, met en évidence le rôle potentiel que ces derniers peuvent jouer en tant que vecteur de sensibilisation. Ce projet a démontré la nécessité de former les concepteurs et les chefs de projet aux défis liés aux sols et, plus largement, aux défis liés à la durabilité.

INTRODUCTION

Context of the project

NB: excerpt from the contract of the project, signed August 11, 2022.

Anthropogenic climate change and its effects are a transnational issue. By ratifying the Paris Climate Agreement in 2015, Switzerland committed itself to take measures to reduce greenhouse gas (GHG) emissions both nationally and internationally and to achieve climate neutrality by 2050. The Swiss National Soil Strategy, adopted by the Federal Council in 2020 (FOEN, 2020), focuses on the functions of soils and on a multifunctional approach to sustainable soil management. The strategy identified the loss of soil organic matter (SOM) as a phenomenon of concern, as this phenomenon plays a decisive role in the ecological functions of the soil. It supports the maintenance of the biodiversity of soil organisms, which are mainly responsible for soil functions.

In the context of the report in response to the Bourgeois postulate (19.3639) regarding the potential for organic carbon sequestration in Swiss soils, it was established that gaps in knowledge make it impossible to define the sequestration potential of Swiss soils, or to establish a catalog of measures that would make it possible to maintain or increase the carbon stock in different types of soils. According to the land use statistics from the Federal Statistical Office, 7.9% of Switzerland's surface area is covered by agglomerations. Settlement areas are not limited to building zones but also include roads and railroad lines with their approaches, airports and supply and disposal facilities (infrastructure areas), as well as parks and gardens. While 64% of these soils are covered by buildings or impervious surfaces, approximately 118,000 ha of urban open soils remain. These open areas are mainly composed of young, artificially created soils, which therefore generally show little soil evolution (reduced thickness, low biological activity, reduced soil organic matter SOC, etc.). Due to the lack of soil maps, estimates of the SOC content of urban soils are based solely on bibliographic data collected abroad and on data from agricultural and forestry areas. Nevertheless, based on these indirect data, as well as data from Swiss area statistics, a theoretical average value of about 60 t C per hectare is obtained. The total amount of SOC stored in agglomeration soils is estimated to be 7 Mt C. Maintaining or increasing organic carbon in urban soils has direct benefits in terms of soil quality, as well as co-benefits in terms of biodiversity, climate regulation (mitigation and adaptation to heat waves) and natural hazard management (flooding).

The project aims (i) to assess the current/potential amount of carbon in Swiss urban soils and its potential for enhancement, (ii) to identify the drivers of carbon variations in the urban soils and (iii) to develop guidelines for urban soil best management and regeneration practices.
The project is in line with the research priority themes defined for the FOEN (Research Master Plan 2021–2024), in particular:

- Climate change (17): climate change control and hazard prevention; contribution to optimal measures to mitigate climate change
- Soil (9): assessment of soil organic carbon content and study of its dynamics

State of the art and knowledge gaps

CARBON ANS SOILS: Facing the growing challenges and threats of global climate change, soils' functions play a central role by providing a wide range of ecosystem services (Adhikari & Hartemink, 2016; FOEN, 2020). These functions are essential to the implementation of climate change mitigation and adaptation strategies. In particular, the role played by soils in carbon sequestration is all the more important as it depends to a large extent on human soil management practices (Six et al., 1999; *The "4 per 1000" Initiative*, n.d.). In response to increasing societal and political expectations (see for example Bourgeois, n.d.), the carbon dynamics in Swiss agricultural soils have recently been the subject of several in-depth studies, especially regarding the organic matter and soil/texture ratio (Dupla et al., 2022; Guillaume et al., 2022).
SOILS IN URBAN AREAS: Some studies have shown the role of technosols in carbon sequestration (Allory et al., 2022), as an illustration of the various ecosystem services provided by soils situated within agglomeration areas – referred to here as urban soils, including not only highly anthropized soils, but also pseudo-natural soils and soils under agricultural uses (Levin et al., 2017). However, as a societal and political objective (see for example Fivaz, n.d.), the contribution of urban soils to climate change adaptation and mitigation is still hampered by the lack of knowledge about their variable quality and functions, especially with regard to the past and futures dynamics induced by their management (Morel et al., 2014). Currently, in the absence of empirical data and mapping, the carbon sequestration potential in soils located in inhabited Swiss areas is only estimated on the basis of the processes and data observed for other land uses, or for urban soils situated in other geographical contexts.
The functional potential of urban soils deserves to be investigated in greater depth because agglomeration areas host the majority of the human population (United Nations, Department of Economic and Social Affairs, Population Division, n.d.), therefore concentrating anthropogenic

impacts, environmental risks and related needs in provisioning and mitigating ecosystem services (see SDG 11 in Economic and Social Council, 2019; Louwagie et al., 2016).

NEEDS OF IMPLEMENTATION TOOLS: From the perspective of a strategy for the integrated management of organic matter including all soil types of Switzerland, it is necessary to grow a local and empirical body of knowledge and know-how regarding Swiss urban soils and their potential for long term carbon sequestration. Although soil is rarely and superficially taken into account in territorial planning and urban design practices today, this innovative and transdisciplinary approach is key to planning, designing and maintaining cities as an opportunity to actively enhance the social environmental performances of urban soils and provide solutions for global/local climate change adaptation/mitigation. In particular, understanding the negative and positive effects of soil management practices, as well as urban planning and design, on the variable urban soil organic carbon content would bring valuable inputs to the soil quality index and function models currently under developments (see Steiger et al., 2018 and follow up projects in the cantons of Zurich and Vaud). As support for strategy and decision making, the field-based documentation and systemic analysis of carbon variations in Swiss urban soils should contribute to identifying measures that could be taken to ultimately improve the carbon balance, as well as the challenges and opportunities in terms of ecological co-benefits and urban redevelopment associated with these measures.

Main objectives of the project

The project is developed through two main case studies representative of the Swiss Plateau’s agglomerations:

- The Lausanne-Morges agglomeration: With a total surface area of 66.7 km^2, this agglomeration, which has developed primarily since the early 20th century, is characteristic of contemporary urban morphology, with its great spatial heterogeneity.
- The city of Zurich: With a total surface area of 91.8 km^2, the city's current form crystallized in the 19th century, then underwent major urban redevelopments (post-industrial), and is now characterized by greater spatial homogeneity, also due to its less complex geomorphology than that of Lausanne.

The objectives of this project are as follows:

- Complementing the few existing data on carbon in urban soils (Tresch et al., 2018) with a field-based approach of soil measurements across the urban habitats/land uses spectrum, and therefore contributing to a more accurate estimation of current Swiss urban soil organic carbon content and its potential for enhancement.

- Explaining the variations of urban SOC as a function of several natural and anthropogenic variables.
- Relating the variation of urban SOC and its potential enhancement to the practices and policies of soil management and urban development. This objective will make it possible to consider the benefits of improvement measures in light of contextualized local data.

Methodology: work packages and deliverables

The proposal is divided into two work packages (WP) with deliverables as follows:

WP 1 _ Soil measurements and characterization: the current state of carbon in urban soils and the drivers of its variations

Objectives:

- Assess the current/potential amount of carbon in Swiss urban soils (Lausanne/Zurich)
- Identify the drivers of carbon variations in the selected soils

Method:

- State of the art on existing urban soil data sets (Lausanne/Zurich)
- Sampling strategy: identification of sampling sites according to a preliminary mapping of geomorphology and vegetation cover type
- Field campaign: soil sample, lab analysis
- Calculation of actual SOC
- Statistical analysis and interpretation

Deliverables:

- Urban soil survey (dataset), with a characterization of each studied soil including, in particular: total carbon and nitrogen; inorganic and organic carbon; bulk density; texture; calculation of SOC and SOC stock; MO/clay
- Interpretation of the SOC variation according to the influence of soil texture and organic matter input (vegetation cover and management practices)

WP 2 _ Analyses of soil management policies and recommendations: integration of soils into conservation and planning tools

Objectives:

- As part of a parallel mandate for the Direction Générale du Territoire et du Logement (DGTL) of the Canton of Vaud: analyzing the influence of soil management, as well as urban planning and design policies, on carbon sequestration in urban soils
- Elaboration of possible solutions to improve carbon sequestration in urban soils in the context of urban redevelopment projects

Method:

- As part of a parallel mandate for the Direction Générale du Territoire et du Logement (DGTL) of the Canton of Vaud: three case studies on urban redevelopment operations their relation to the agglomeration project, the cantonal planning and federal legal framework (project reviews, interviews of experts, analytic mapping, workshop with stakeholders)
- Identification of an overall process to increase the organic carbon sequestration capacity of urban soils, then developed in the form of four guidelines focusing of the content of urban redevelopment projects, accompanied by four guidelines focusing on methodology and tools

Deliverables:

- Analysis of the influence of soil management, as well as urban planning and design policies, on SOC variations
- Guidelines for urban soil best management (protection, regeneration/reconstitution and improvement of management practices) in the context of urban redevelopment projects

PART I. Soil measurements and characterization: the current state of carbon in urban soils and the drivers of its variations

1.1 Methods

1.1.1 Geomorphology and vegetation

The study area encompasses the surface area within Zurich's city (municipal) borders, with an area of approximately 92 km^2 (Gebäude-Wohnungsregister, 2023) and within the border of the Lausanne metropolitan area (compact perimeter, as defined in the Projet d'Agglomeration Lausanne-Morges) which is approximately 67 km^2.

The aim of this project is to provide an understanding of carbon dynamics in urban soils. From a scientific point of view, carbon sequestration in soils is influenced by two factors:

- **Soil texture**, or more precisely its content of clays and fine silts. These minerals are the only ones capable of creating bonds with decomposed organic matter (humus), and therefore of permanently fixing the carbon contained in this organic matter.
- **Vegetation cover** (forest, lawns, etc.) and **the way it is managed/maintained** (regular mowing, manure, etc.). The organic carbon fixed by the soil is largely derived from the degradation of above-ground (leaves, branches) and below-ground (roots) plant residues.

Therefore, two working hypotheses were tested with regard to the two factors presented above.

The first hypothesis concerns the influence of geomorphology and related parent material on soil physical properties, particularly texture, bulk density, soil depth. In view of the diversity of geological substrates in the Lausanne and Zurich regions shown in Figures 1 and 2, we hypothesized that this geomorphological diversity has an influence on the soil's texture, and therefore on its capacity to sequester organic carbon. To categorize soil parent materials, we use the Carte des géotypes du Canton de Vaud (Parriaux & Turberg, 2007) for Lausanne, and the cantonal geomorphological maps Geologisch-geomorphologische Landschaften des Kantons Zürich (Zürich, 2023) as well as the Geological Atlas of Switzerland (tile 1091-Zürich) for Zurich. We grouped surficial deposits into six broad categories: 1) molasse and marlstone, 2) basal till, 3) ablation till and coarse alluvium, 4) lacustrine and fine alluvial deposits, 5) anthropogenic soil filling and 6) other (either unknown or not representative). This classification of the geomorphology is represented by a color code in the form of a color swatch used systematically in the maps produced for the Part I of this report (Figs. 1, 2, 5 and 6).

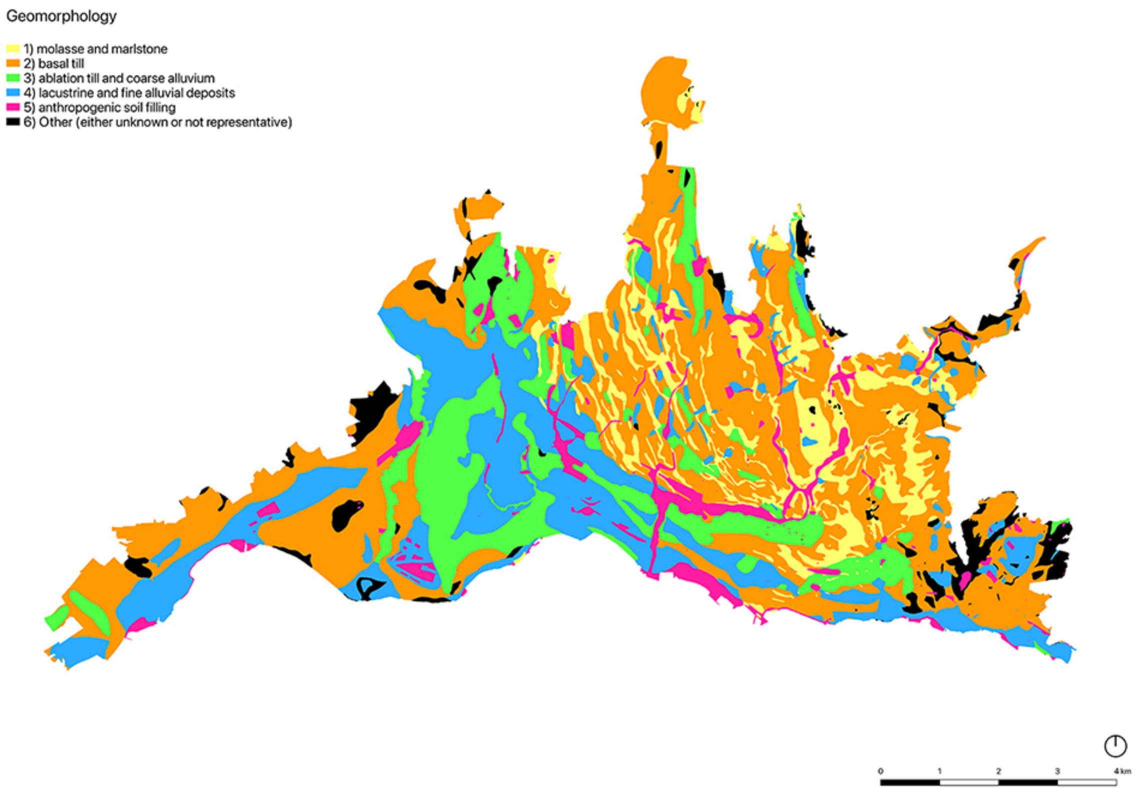


Fig. 1: Simplified geomorphology map of Lausanne (compact perimeter of the Lausanne-Morges agglomeration). The color swatch representing the different geo-morphologies is used systematically in Figs. 1, 2, 5 and 6.

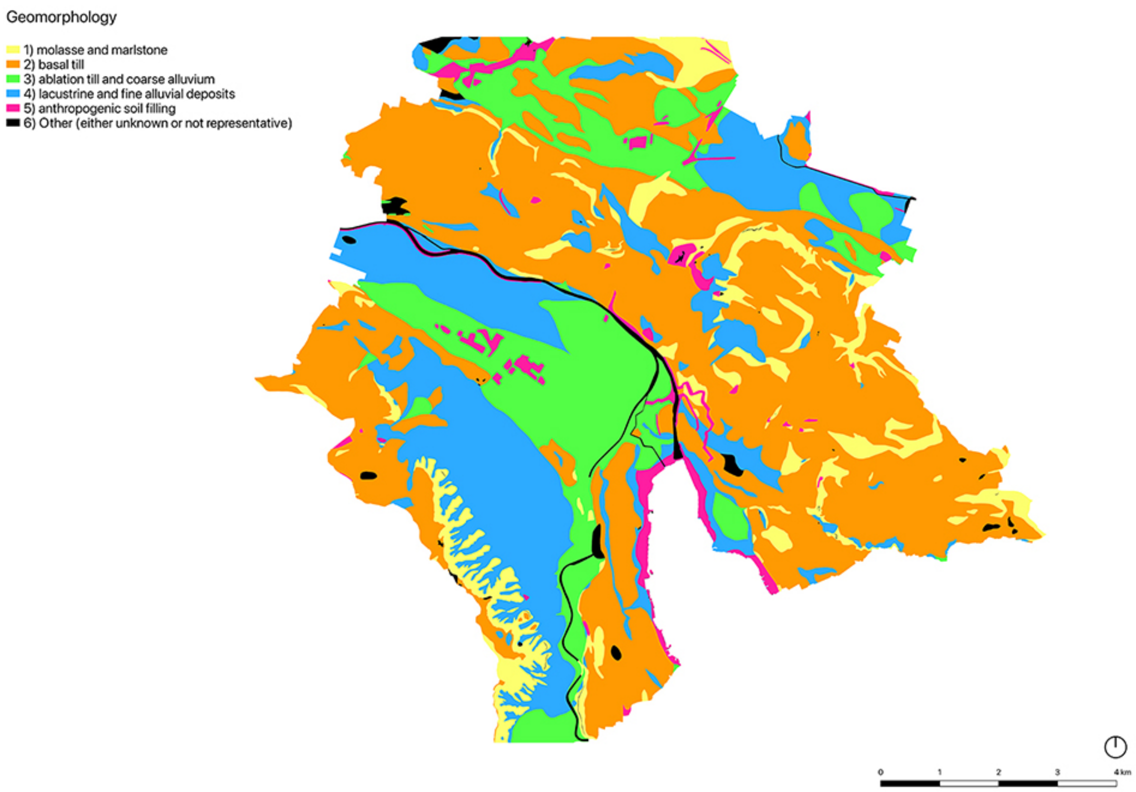


Fig. 2: Simplified geomorphology map of Zurich (city). The color swatch representing the different geo-morphologies is used systematically in Figs. 1, 2, 5 and 6.

The second hypothesis concerns the influence of vegetation cover and related management practices on soil organic carbon content (SOC). As previously mentioned, the type of vegetation cover is closely linked to the quantity of biomass returned to the soil. This biomass is the main source of natural carbon in the soil. We therefore hypothesized that it has a direct influence on SOC. We additionally hypothesized that management practices also have a significant influence on SOC, insofar as they help to control the plant biomass returned to the soil, as well as contributing to the rapid evolution of certain soil properties, such as organic matter content (mature compost inputs) and bulk density. In Figures 3 and 4, we catalogued, synthesized and mapped vegetation cover data from satellite imagery (Google Earth), georeferenced habitat data for Lausanne (Price et al., 2021) and Grün Stadt Zurich biotopkartierung for Zurich (Stadt Zürich, 2020). Zurich and Lausanne were found to support similar vegetation types, which we summarized into seven primary vegetation types: 1) forest, 2) vegetable gardens, 3) urban plantations, 4) meadow, 5) lawn, 6) ruderal and 7) other (sealed surfaces and surfaces under professional agricultural uses, which are not the focus of this project). This classification of the vegetation cover types is represented by a color code in the form of shades of gray, used systematically in the maps and diagrams produced for the Part I of this report (Figs. 3 to 14): this choice illustrates the (non-verified) initial hypothesis that the different vegetation cover types and related maintenance practices have an impact on carbon sequestration, which can be characterized in the form of a gradient.

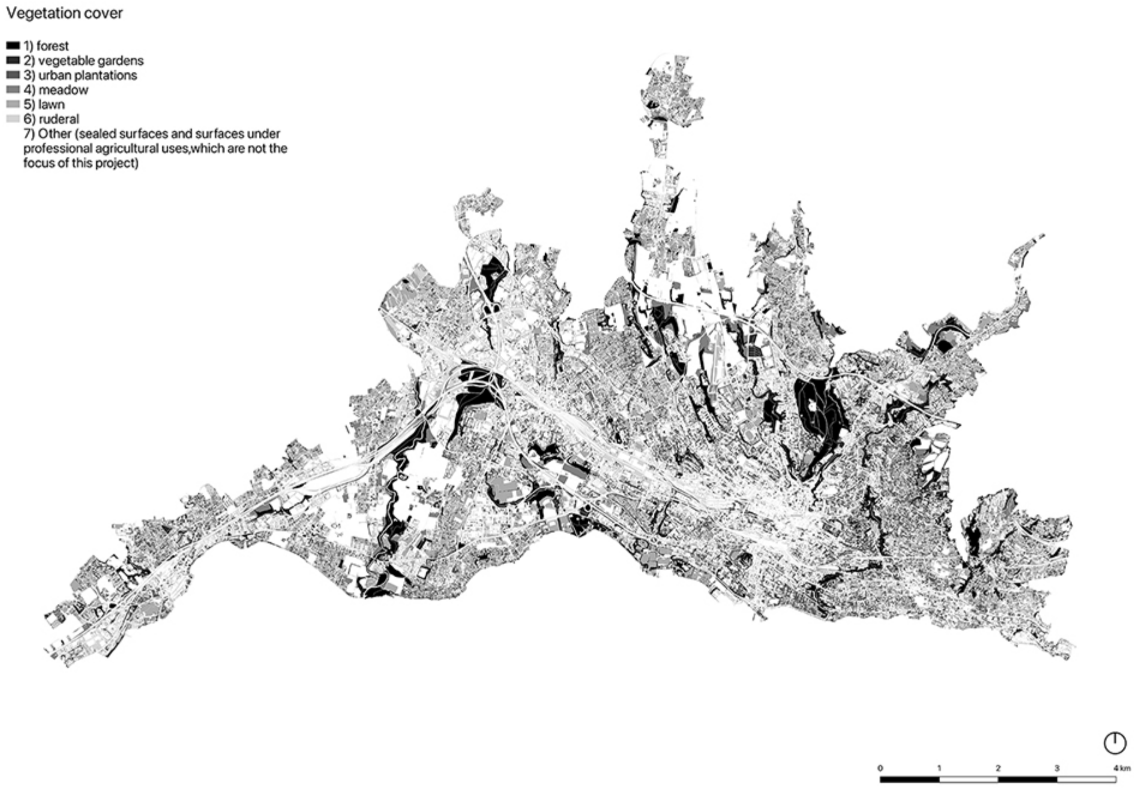


Fig. 3: Simplified map of vegetation cover of Lausanne (compact perimeter of the Lausanne-Morges agglomeration). The shades of gray representing the different vegetation cover types and related maintenance practices is used systematically in Figs. 3 to 14.

Fig. 4: Simplified map of vegetation cover of Zurich (city). The shades of gray representing the different vegetation cover types and related maintenance practices is used systematically in Figs. 3 to 14.

1.1.2 Soil sampling

Based on the abovementioned hypothesis and related mapping operations, sampling sites were chosen to ensure a representative number of samples from the five geomorphologies: 1) molasse and marlstone, 2) basal till, 3) ablation till and coarse alluvium, 4) lacustrine and fine alluvial deposits and 5) anthropogenic soil filling. In terms of land cover, we chose to focus our efforts on primarily public and semipublic green spaces with the highest potential for carbon sequestration improvement. Thus, we focused our analysis on four primary public vegetation cover types in Lausanne and Zurich: 1) forest, 2) vegetable gardens, 4) meadow, 5) lawn. To ensure accurate vegetation effects, each vegetation cover type was confirmed through visual on-site inspections. In particular, meadows and lawns were differentiated by assessing the plant species composition typically associated with meadow environments (Vega & Küffer, 2021). In the maps produced for Part I of this report (Figs. 5 and 6), the dual criterion for selecting sampling sites is represented by a color code combining the color swatch associated with simplified geomorphology and the shades of gray associated with vegetation cover types.

The Lausanne dataset was complemented by ten soil samples from a variety of vegetation types and geomorphologies provided by a former master's thesis project conducted jointly at the University of Lausanne and the University of Neuchatel (Singer, 2023) These samples were collected at an equivalent topsoil depth around the walls of a single soil profile. Bulk density cylinders were collected in triplicate in the same soil profile. The Zurich dataset was supplemented with garden data from 141 private and allotment gardens (referred to as P-garden) and private lawns (referred to as P-lawns) provided by the Better Gardens project (Tresch et al., 2018), for a total of 248 studied sites, as summarized in table 1 and mapped in Figures 5 and 6.

Vegetation cover types	**Total numbers of samples**	**Lausanne**	**Zurich**	**This project**	**Tresch et al., 2018**	**Singer, 2023**
Forest	30	11	19	30	0	0
Garden (vegetable)	10	10	0	10	0	0
(Private) P-garden (vegetable)	83	0	83	0	83	0
Meadow	33	12	21	31	0	2
Lawn	34	12	22	26	0	8
(Private) P-lawn	58	0	58	0	58	0
Total	**248**	**45**	**203**	**97**	**141**	**10**

Table 1: Summary of samples by vegetation types, cities and sources.

Fig. 5: Map of soil sampling sites in the Lausanne-Morges agglomeration. The colors given to the sampling points correspond to a combination of the color swatch representing the geomorphology (Figs. 1 and 2) and the shades of gray representing the vegetation cover types (Figs. 3 and 4).

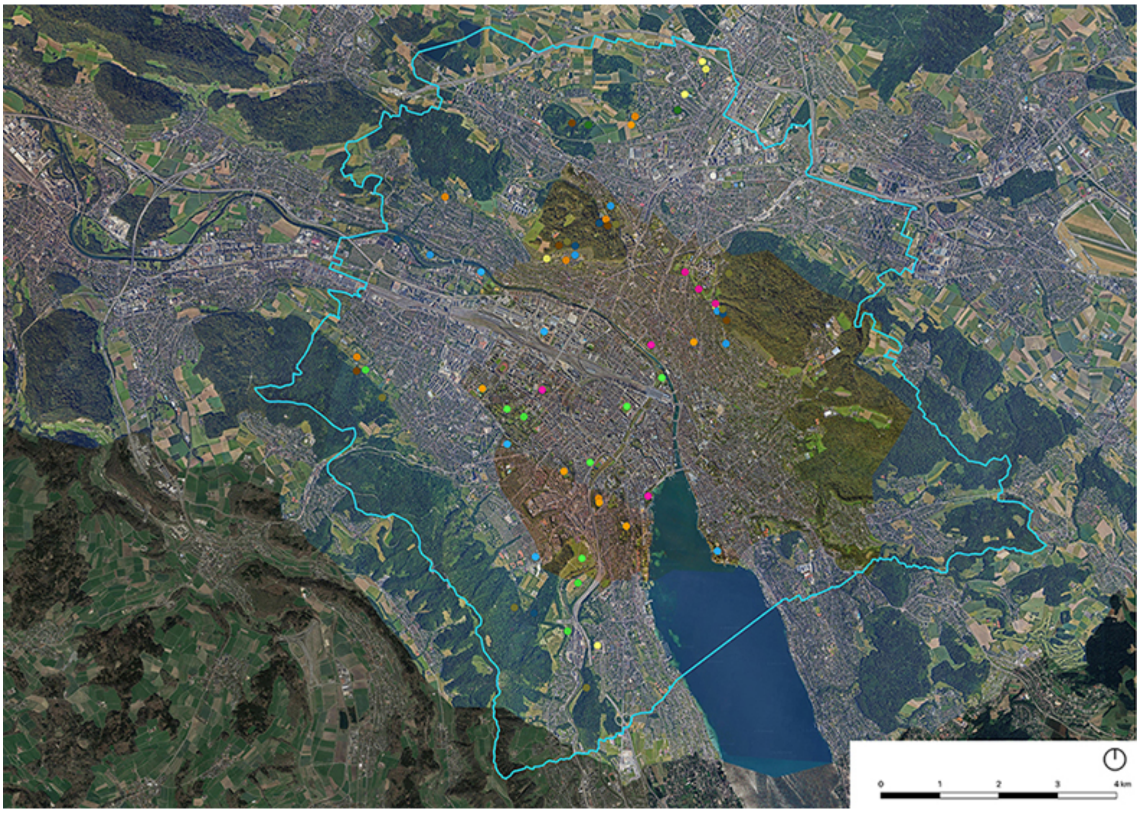


Fig. 6: Map of soil sampling sites in Zurich City. The colors given to the sampling points correspond to a combination of the color swatch representing the geomorphology (Figs. 1 and 2) and the shades of gray representing the vegetation cover types (Figs. 3 and 4).

As detailed in Table 2, the selection of sampling spots encompassed various locations corresponding to different land uses including parks, sports facilities, cemeteries, bathing facilities, school buildings, residential settlements and forests.

Vegetation cover	**Urban land uses**
Forest	Urban forests
Garden (vegetable)	Lausanne semiprivate vegetable gardens
(Private) P-garden (ornamental and vegetable gardens)	Zurich allotment and private vegetable gardens
Meadow (mowed seasonally, allowed to flower, high floral diversity)	Abandoned pastures, cemeteries, residential greens, parks
Lawn (mowed regularly very short turf, low floral diversity)	Parks, sport fields, school playgrounds, cemeteries
(Private) P-lawn (regularly mown turf lawns)	Zurich allotment and private turf lawns

Table 2: Summary of vegetation types sampled in Lausanne and Zurich, and corresponding land uses.

The samples were collected from July 2022 to April 2023, at 97 sites across the city of Zürich and Lausanne. At each of the 97 sampling sites, a composite soil sample was collected. As illustrated in Figure 7, this composite sample was created by combining and thoroughly mixing five individual soil subsamples, collected with an auger within a 2 × 2 m square area, at a depth of 0 to 20 cm. Before sampling, any organic layer originating from vegetation or litterfall was removed from the soil surface. This step was taken to limit any unintended influence of fresh plant material on soil organic carbon (SOC) content. Additionally, three undisturbed soil cores were collected at a 10 to 15 cm soil depth to determine soil bulk density (BD). These cores each consisted of a cylinder with a 5 cm height and a 2.5 cm radius. The sampling procedure involved digging a 20 cm x 20 cm x 20 cm soil pit. The undisturbed soil core was extracted from the side of the pit, where minimal compaction had occurred. Finally, a visual evaluation of soil structure (VESS) was performed to assess the soil's structure based on its appearance and feel. The VESS scale ranges from 1 (indicating good structure), to 5 (indicating poor structure), following the methodology outlined by Cloy et al. (2012).

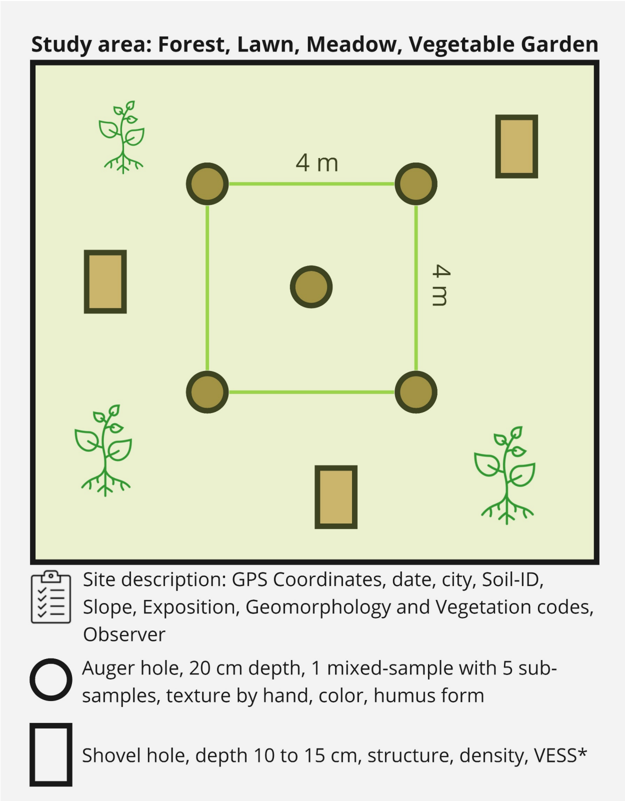


Fig. 7: Sampling protocol diagram

1.1.3 Laboratory analyses

Lab analyses included the determination of bulk density, soil carbon and nitrogen, texture and pH.

Sample preparation: After the fieldwork, all soil samples were gently disaggregated by hand, air-dried and sieved to 2 mm. A fraction of the composite samples was ground to a fine powder (~ 20 microns). The hygroscopic moisture content was determined as the difference between the air-dried and oven-dried (105 °C) soil mass.

Bulk density: In undisturbed soil cores, the mass of coarse fragments was recorded, as well as the mass of fine earths following oven-drying at 105°C.

Using these data, three parameters were calculated to represent soil bulk density:

1. The total bulk density, calculated as the total mass of material in the undisturbed core (coarse fragments + fine earths), divided by the total core volume.
2. The fine earth bulk density, calculated as the mass of fine earth divided by the volume of fine earth in the core. The volume of fine earth was determined by subtracting the volume of coarse fragments from the total core volume. The volume of coarse fragments was estimated by dividing their mass by a particle density of 2.65 $g.cm^{-3}$, assuming most of them were of felsic composition.

3. The fine earth abundance, calculated as the mass of fine earth divided by the total core volume.

The fine earth bulk density allows for a direct comparison of samples with differing coarse fragment content. Unless stated otherwise, the bulk density results presented in this report are fine earth bulk density. The fine earth abundance is used to calculate soil carbon stocks (see below).

Soil carbon and nitrogen: The analysis of total soil carbon and nitrogen was carried out on ground samples via dry combustion in a CHN elemental analyzer (LECO CHN 628 in Zürich and Thermo Scientific Flash EA 1112 in Lausanne). Quality assurance procedures included the use of appropriate quality check samples and 10% blind duplicate analyses.
Soil inorganic carbon (SIC) was measured using a RE6 pyrolizer (Turbo model, Vinci Technologies) in Lausanne and the modified pressure-calcimeter method (Sherrod et al., 2002) in Zurich. Each sample was acidified with 1.8 ml of a concentrated 6 M HCl/ 3% $FeCl_2$ solution, causing the release of CO_2, which was then measured with a pressure-calcimeter. The analysis was conducted in duplicate.

All results are reported on an oven-dried basis (i.e., corrected for hygroscopic moisture content). The SOC content for each soil sample was calculated as the difference between total C and SIC. The SOC abundance (amount of SOC per unit volume) was then calculated by multiplying the SOC by the fine earth abundance. This then allowed us to calculate the organic carbon stocks for the 0–20 cm slice by multiplying this abundance by the volume of the slice and then expressed in tons per hectare. The carbon to nitrogen (C:N) ratio was calculated as the ratio between SOC and total nitrogen.

Soil texture: To evaluate soil texture, a laser diffraction particle size analyzer (LS 13 320, Beckman Coulter) was used. In the laboratory, 0.5 to 0.7 g of sieved soil was pretreated with hydrogen peroxide (35% H_2O_2) and dispersed with sodium hexametaphosphate (10%). The proportion of clay was calculated as the sum of size classes < 2 µm, silt as the sum of size classes between 2 and 50 µm, and sand as the sum of size classes > 50 µm.

1.1.4 Statistical and graphical analyses

All statistical analyses were performed using the R Studio version 4.3.1 (R Core Team, 2023). The alpha level for significance was set to 0.05 unless otherwise specified. The initial statistical analysis began with the creation of boxplots, using the package *ggplot2* (Hadley, 2016), to highlight the differences between the means of each vegetation and geomorphological category. To test for differences between means, the Kruskal-Wallis test was chosen as an alternative to parametric tests due to the failure to meet assumptions for normality of errors and equal variance. Normality of errors was assessed through a visual examination using a normal QQ-Plot and further validated with the Shapiro-Wilks test. While data transformation such as using log10 or square root would have led to normality, variance violations could not be rectified. The commonly used Bonferroni adjustment method was used in cases where it helped mitigate error rates. It was generally used for the Dunn's test ver 1.3.5 (Dinno, 2017), where the likelihood of observing at least one significant result by random chance increases. When performing correlation analysis, the overall normality of residuals was assessed with a Levene test using the DHARMa package ver 0.4.6, (Hartig, 2022). The soil texture package was used to create a soil texture triangle ver 1.5.1 (Moeys, 2018).

1.2 Results and Discussion

The following section contains our report of the results and a discussion of their implications. The portions concerning the city of Zurich are adapted and expanded on from their first descriptions in the master's thesis of Tess Giacobbo (Giacobbo, 2023).

1.2.1 Soils

As illustrated in Figure 8, large variation was found in the soils both between and within cities.

- **Forest** soils exhibited the least visual diversity, being characterized overall by an abundance of stones, large tree roots and earthworms. In forest soils, it was common to observe a darker coloration within the first 5–10 cm of the humus-rich topsoil, indicating the presence of organic material.
- **Vegetable garden soils**, especially in private settings, are highly heterogeneous but generally characterized by elevated organic carbon content, fine textures rich in clay, and low compaction—reflecting diverse and often favorable management practices such as compost application and minimal soil disturbance.
- **Meadow** soils exhibited remarkable diversity, ranging from an abundance of small roots and many soil organisms to the presence of numerous stones, some bricks and low biological activity.
- **Lawn** soils displayed a wide diversity, from highly anthropogenic material (bricks, plastic, rubber) and gravel to samples with lots of earthworms. In contrast to forest and similar to lawns, the color variation was less noticeable. In meadow and lawn vegetation cover types, the color tended to remain uniform throughout the soil depth, or in some cases, the topsoil was limited to a superficial depth by the presence of stones or very light-colored sand underneath.

Our analysis of soil properties was made for each city and then comparisons were made between the five geomorphologies and vegetations. Although the parent material differs notably between regions, the distinctions in soil types are less pronounced. Notably, soil fillings (areas where the soil has been artificially built-up) are an important characteristic of urban soils and are usually created as part of terrain alterations (Zürich, 2023); they can be recognized from observing the anthropogenic landscape of the city. However, the exact nature of what soil is moved and where to is not consistently categorized and catalogued. Therefore, geomorphology class, as we categorized, was not found to have a significant effect on any of our soil properties. We attribute this to a dissonance between our documented soil morphologies and the reality on the ground, especially and specifically within the topsoil. Anthropogenic influences within cities are both heterogeneous and rapid enough that existing soil geomorphology interpolation techniques are ill-equipped to reflect the nature of the materials that currently exist within the topsoil. An analysis of subsoil properties would be more likely to directly reflect the attributed geomorphologies due to subsoil's closer association with parental material and reduced impact of recent anthropogenic surface changes. Thus, the geomorphology classes we defined will be set aside for the remainder of the report and our focus will be kept on vegetation.

Fig. 8: Pedological observations on the first 20 cm of soil, for the four different types of vegetation covers studied

1.2.2 Soil texture

Based on data acquired from the lab (texture analysis), each soil can be classified into particle size classes, which can be visualized in the texture triangle shown in Figure 9. These triangles show the soil characteristics (grain sizes) of various vegetation classes (forest, lawn, meadow and gardens, represented by [private] P-garden and P-lawn in Zurich), including public green spaces and private green spaces. The textures of the soils of Zurich and Lausanne were broadly similar: silt, silty loam, and loam; however, distinct differences remained. Lausanne's soils had significantly less clay content and were, overall, siltier than Zurich's, which reflects the glacial history Lausanne. Thus, the geologic history of both cities is clearly reflected in their soils' texture despite the significant anthropogenic changes of the last centuries.

Comparing the textures of the vegetation types revealed more subtle differences. As highlighted in yellow in Figure 9. b), forests and meadows in Zurich were found to have a finer texture than lawns (p-value <0.01), whereas Lausanne's vegetation types did not differ from one another in texture. Interestingly, as represented by blue and red dots in Figure 9. b), private P-gardens and P-lawns are both very similar to each other, but dissimilar to the other public vegetation samples of both Zurich and Lausanne because of their significantly higher clay content and slightly higher sand content. Although we are confident in our analysis, we mention here that Tresch et al. (2018) utilized a less advanced method for analyzing particle size distributions, potentially introducing a slight bias in these texture analyses. We suggest that future studies resample private gardens to confirm our findings.

Complementing the differences between Lausanne and Zurich as a reflection of geology, the stark difference of the private gardens and lawns could reflect recent anthropogenic soil changes through the addition of substrates of higher quality, aiming at both better vegetable growth and drainage. The purpose of an improved soil drainage is also likely the reason explaining the presence of a higher sand content in Zurich's lawn anthropogenic soils.

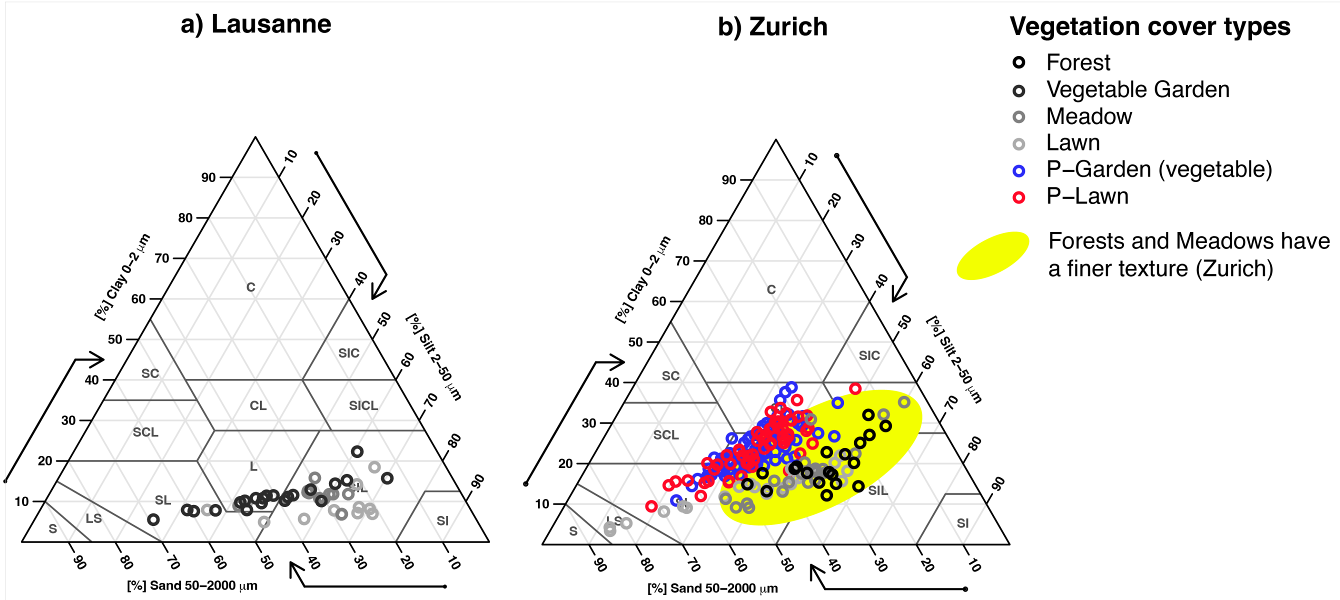


Fig.9: USDA texture triangle showing the distribution of grain sizes in soils, by vegetation type. The composition of clay, silt and sand within the soil sample determines the overall classification of the soil.

1.2.3 Soil bulk density

As summarized in Table 3 and shown in Figure 10, the analysis revealed a wide range of bulk densities from 0.56 g/cm^3 to 1.79 g/cm^3; however, the mean and median bulk densities were found to be 1.09 and 1.11 g/cm^{3,} respectively (Lausanne: 1.05 g/cm^3 and Zurich: 1.1 g/cm^3). This is somewhat lower than reported values of urban bulk density on average. Generally, despite soil compaction being a common issue in urban areas, Zurich and Lausanne's public soils exhibited a medium density. In comparison, another urban soil study at equal depth has reported mean values of 1.28 g/cm^3 in recreational districts of Kainfeng (Sun et al., 2010) and between 1.1–1.4 g/cm^3 in Berlin green spaces (Klingenfuß et al., 2020), whereas agricultural soils have been found to have lower bulk density – 1.12 g/cm^3 in England, for example (Prout et al., 2021), using similar methods.

Typically, compacted soils exhibit reduced pore space, limiting water retention, drainage and root growth. Overall, then, Zurich and Lausanne soils are as or less compacted than those of other cities. Comparing the bulk density across different vegetation types and between cities is difficult, as Lausanne had fewer samples and thus variance was high. Therefore, no significant difference in bulk density could be identified between vegetation types in Lausanne. However, this still acts as a useful point of comparison overall. As noted, bulk density was slightly higher in the city of Zurich. This was the case across all vegetation types. Within Zurich, the highest mean bulk density was observed for lawns (μ = 1.2 g/cm^3), followed by (private) gardens (μ = 1.14 g/cm^3), meadows (μ = 1.12 g/cm^3), forests (μ = 1.12 g/cm^3) and, finally, (private) P-lawns (μ = 0.99 g/cm^3). While public lawns tended to have the highest bulk density, their high variance resulted in only P-lawns having a significantly difference to public lawns, P-gardens and meadows.

In Zurich, it is not surprising that the highest mean bulk density was observed for lawn samples (μ = 1.2 g/cm^3), likely resulting from a combination of factors, including the use of heavy equipment during nearby building construction, as well as higher foot traffic and other forms of human activity (Lotze et al., 2023). Furthermore, this aligns with research findings by Brady & Weil (2017), who explained that sandy soils tend to have higher bulk density. On the other hand, the elevated biological activity in forests promotes aggregation, leading to a reduction in bulk density (Vasconcellos et al., 2013). This observation aligns with the finding that the second lowest bulk density was found in forests. P-lawns, being private and largely ornamental and used rarely for intense recreation, are subjected to less heavy machinery and less trampling; this can explain their lower bulk density than public lawns, but their below average bulk density compared to even forests and gardens is still an open question. Overall, it is clear that 1) urban topsoils of Lausanne and Zurich are as or less compacted than similar soils in other cities, with levels similar to some agricultural soils, and 2) vegetation and management can directly impact soil compaction.

Location	Vegetation	Mean bulk density	Bulk density variation	Citation
Lausanne	Forest	0.97	0.72	-
Lausanne	Vegetable gardens	1.0	0.47	-
Lausanne	Meadow	1.17	0.38	-
Lausanne	Lawn	1.07	0.56	-
Zurich	Forest	1.12	0.53	-
Zurich	(Private) P-garden (vegetable)	1.14	0.68	Tresch et al. 2018
Zurich	Meadow	1.12	0.37	-
Zurich	Lawn	1.2	0.3	-
Zurich	(Private) P-lawn	0.99	0.51	Tresch et al. 2018
Berlin	Urban green space	1.1–1.4	-	Klingenfuß et al., 2020
Kainfeng	Recreational green space	1.28	-	Sun et al., 2010
England	Agricultural Field	1.12	-	Prout et al., 2021

Table 3: Summary table of bulk density (g/cm3), as well as the variation (given as the interquartile range), for each of the vegetation types and cities. Additionally, results found in the literature were included as a point of comparison.

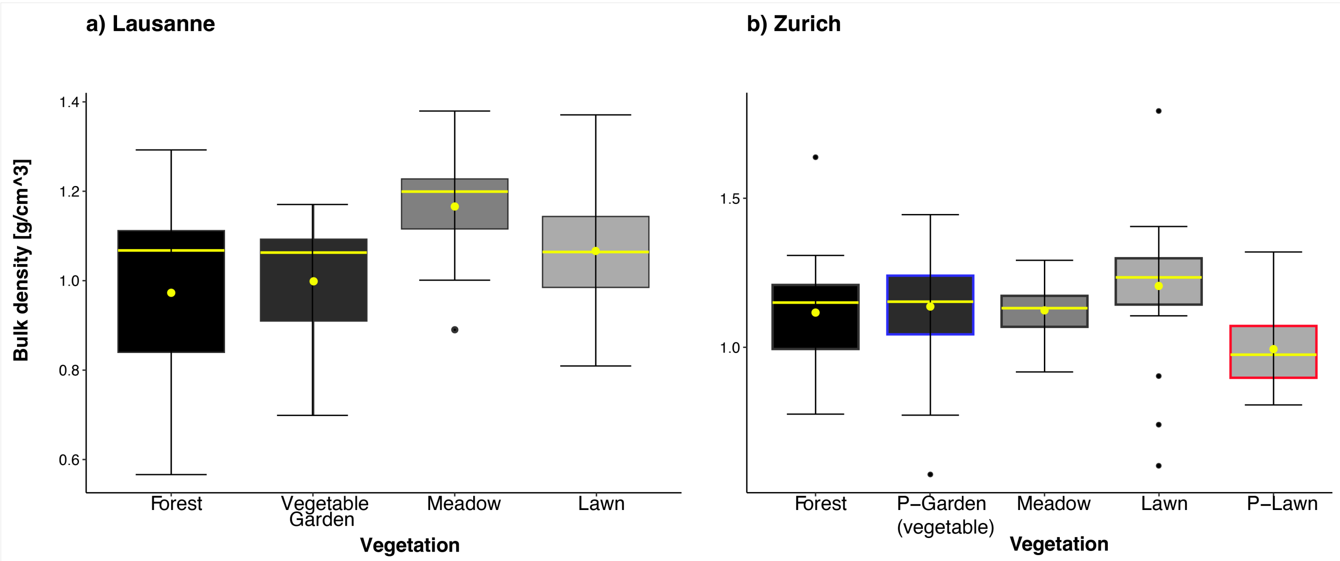


Fig.10: Boxplots showing the distribution of bulk density for each vegetation type. Graphs display median (horizontal yellow line), mean (yellow circles), the 25% and 75% quartiles and the range of the bulk density (minimum non-outlier, maximum non-outlier), displayed by the whiskers. Data beyond the end of the whiskers (outliers) are plotted individually as black circles.

1.2.4 Soil organic carbon (SOC) content and SOC stocks

The distribution of SOC content in the two cities and across the vegetation types is summarized in Table 4 and shown in Figure 11. The SOC content in Lausanne's green spaces varied greatly, ranging from 0.42 to 6.77%, with an average of 3.0 ± 1.2% (mean ± sd) while Zurich's SOC content in just public green spaces varied slightly less and was overall higher, ranging from 1.15 to 6.00%, with an average of 3.60 ± 1.04%. This was true both with and without the private soils included in Zurich's dataset; including the private green spaces in Zurich raises its average SOC to 4.33 ± 1.5%.

Neither Zurich nor Lausanne was found to have significant differences between SOC percentage among their public vegetation soils. However, private gardens and lawns in Zurich were found to have significantly higher SOC percentage than other soils both within Zurich and Lausanne. When comparing the public and the private green spaces, it is evident that (private) P-gardens are the most enriched with SOC (4.85 ± 1.57%), closely followed by P-lawns (4.38 ± 1.41%). Both (private) P-lawns and P-gardens have relatively bigger SOC variabilities compared to private green space data ($var_{P\text{-}lawn}$ = 1.98, $var_{P\text{-}garden}$ = 2.47). In Zurich, P-gardens is significantly higher than the means of lawns and meadows ($p < 0.01$), while P-lawns is significantly higher than public lawns ($p > 0.01$). Both of these soils are significantly richer in SOC than any soils in Lausanne.

Looking a bit deeper into the SOC values for public vegetation reveals some nonsignificant trends. In Lausanne, there appears to be no discernable difference in SOC in lawns (μ = 3.59%, var= 1.31) which, together with gardens (μ = 3.3%, var= 1.43), have higher than average SOC percentage but also higher than average variability. Meanwhile, in Zurich, there is the opposite trend as lawns have the lowest SOC content (μ = 3.31%), while forests and meadows have higher SOC (μ_{Meadow} = 3.70%, μ_{forest} = 3.82%). While meadows' distribution is particularly influenced by extreme values (var = 1.45), forests show a slightly smaller variability (1.42), and lawns show by far the narrowest variability (0.38).

Placing these values into a larger context: SOC content (%) in Swiss cropland has been found to be notably lower, with a percentage of 1.45% in Canton Vaud (Dupla et al., 2021), 2.3% in Canton Jura (Johannes et al., 2023) and 2.7% in Canton Zurich (Kanton Zurich, 2022) in contrast to the 3.0% of Lausanne's public green spaces, 3.6% of Zurich public green spaces and 4.4–4.8% in Zurich's private garden and lawn soils. This highlights the potential of urban soils, especially private soils, to contain carbon. Private soils were found to have significantly higher SOC percentage than their public counterparts, underlining the important role played by garden owners. This observation aligns with findings from previous studies (Edmondson et al., 2012; Klingenfuß et al., 2019), which reported that domestic gardens hold greater SOC than non-domestic greenspaces. The high SOC variability in private green spaces could result from individually differing lawn management and gardening practices, where some private owners might contribute more to soil disturbance by frequent digging, which changes soil biological activity and decrease SOC, whereas some might add lots of fertilizer or compost. It's worth noting that (private) P-gardens and P-lawns were sampled in March before any fertilizer application, while public green spaces were mostly sampled in April. Given that the application of fertilizers (nitrogen, phosphorus and potassium fertilizers) or manure has been shown to promote SOC contents in different soils (Bhattacharyya et al., 2011; Dheri & Nazir, 2021; Li et al., 2010; Poeplau et al., 2018), sampling privately owned garden and lawn soil in April might have resulted in even higher SOC values (at least temporarily), capturing the impact of increased fertilizer usage during that period. Taken together, the importance of individual management practices – with gardens benefiting from humus-promoting horticultural practices, including the supplementation of water, mulching and compost to maximize grass productivity and soil quality – becomes clear (Klingenfuß et al., 2019). With these private and semiprivate spaces seemingly some of the highest stores of SOC within topsoils, cities must consider what regulations can be put in place to help conserve and regenerate these soils.

Our examination of the SOC stock in tons per hectare is exclusively using the data set of public green spaces, as Tresch et al. (2018) did not find earth abundance (see above, section 1.1.3). Fig. 11 a-II and b-II visually illustrate that all vegetation groups tend to cluster around quite similar values. The SOC stock of Lausanne's public green spaces varies between 9.09 and 149.0 t/ha with an average of 61.8 t/ha, while those of Zurich varies between 29.54 and 141.15 t/ha with an average of 75.56 t/ha. Thus, once again, Zurich soils appear to have the greater amount of organic carbon, even outside of the carbon-rich private soils. Neither Zurich nor Lausanne were found to have significant differences between SOC stock among their public vegetation soils. Zurich's lawns have the lowest mean SOC of 70.30 t/ha, while meadows have higher SOC (76.62 t/ha), and forests exhibit the highest average SOC stock of 80.49 t/ha.

This analysis reveals that despite the dramatic differences in anthropogenic management and vegetation type, urban topsoil SOC stocks remain rather similar to one another. These averages are comparable to the stocks reported by Richter et al. (2020) for Berlin parks (μBerlin = 70.2 t/ha), meadows (μBerlin = 74.8 t/ha) and forests (μBerlin = 72.7 t/ha). Klingenfuß et al. (2019) also reported similar values for parks in Berlin (μBerlin = 75 t/ha) but noted lower values for forest soils (μBerlin = 58 t/ha). This range of SOC values is not unique to Zurich, Lausanne and Berlin, as research in Atlanta also found city park topsoil and forest topsoil to have similar mean SOC values (μAtlantapark = 71 t/ha, μAtlantaforest= 77t/ha) (Pouyat et al., 2006). Comparatively, on average, Lausanne and Zurich's public urban SOC stocks are slightly lower compared to those of 24 monitoring grassland sites managed by farmers throughout Switzerland at equivalent soil depth ($\mu_{grasslands}$ = 81.7 t/ha) (Moll-Mielewczik et al., 2023). The grassland's SOC stocks show a notably narrower range of 63 to 131 t/ha (Moll-Mielewczik et al., 2023) compared to Zurich's and especially Lausanne's urban sites, a pattern consistent with findings from multiple studies, including Vasenev et al. (2013). However, when compared to Berlin and Swiss agriculture field soils dominated by crop production, Lausanne and Zurich's urban soils exhibit considerably higher SOC stock values ($\mu_{Berlin}^{cropland}$= 44 ± 9 t/ha; $\mu_{Switzerland}^{cropland}$= 40.6±8.9) (Klingenfuß et al., 2019; Leifeld et al., 2005). This observation matches with findings of Edmondson et al. (2012), which states that SOC storage in arable soils is significantly lower than that in urban soils.

As one important caveat, we would like to stress that although SOC is incredibly important for vegetation growth and a significant storage of carbon, our analysis is limited in that it is focused on only the topsoil. In arable areas, topsoil data did not capture variations in vegetation cover accurately but could be measured in subsoil (Johannes, Matter et al., 2017; Richter et al., 2020). Olson & Al-Kaisi (2015) recommended that the depth of soil sampling include the entire root zone to accurately report SOC stock and the effect of management practices. In grassland, 0–5 cm of the soil contains 59% of root-biomass (Don et al., 2009), and in forests, where deeper roots are more prominent, a large part of SOC can be stored well below 30 cm up to a depth of 1 m (Harrison et al., 2011; Jackson et al., 1996; Wiesmeier et al., 2013). Furthermore, a large portion of urban SOC likely resides in the aboveground biomass of the vegetation itself (Golubiewski, 2006; Klingenfuß et al., 2019; Richter et al., 2020). Therefore, while our analysis accurately describes the trends we found in the topsoil, acquiring a full picture of urban SOC requires that Swiss urban subsoils and urban aboveground vegetation be analyzed to create a more complete and holistic estimation of urban SOC potential.

In summary, the most important results of our study were that urban spaces contained relatively high levels of SOC (public green spaces overall had lower SOC than rural grassland areas but more than cropland areas) and therefore should not be underestimated or written off. Private spaces had considerably more SOC (whether due to fertilization or higher quality/less compacted soil) and thus should be considered when planning for carbon sequestration in cities. It is essential to recognize that both public and private urban soils (in the upper range we found) possess significant stocks of SOC. This will be especially crucial as urban densification intensifies, potentially impacting urban soils with high SOC. During construction work, for instance, topsoil is typically removed and replaced with gravel and concrete before sealing. This process results in the loss of the soil's C sequestration capacity, as well as around 19% of its original SOC (Ding et al., 2022).

Location	Vegetation	Mean SOC content %	SOC % variation	SOC stocks (t/ha)	Stock variation	Citation
Lausanne	Forest	2.5	0.65	46.4	23.5	-
Lausanne	Vegatable garden	3.3	1.43	61.6	29.3	-
Lausanne	Meadows	2.7	1.02	62.4	16.9	-
Lausanne	Lawn	3.59	1.31	74.9	22.2	-
Zurich	Forests	3.82	1.42	80.49	44.3	-
Zurich	(Private) P-garden	4.85	2.47	NA	-	Tresch et al. 2018
Zurich	Meadow	3.7	1.45	76.6	27.6	-
Zurich	Lawn	3.31	0.38	70.3	14.9	-
Zurich	(Private) P-lawn	4.38	1.98	NA	-	Tresch et al. 2018
Atlanta	Forest	-	-	77	-	Pouyat et al. 2006
Atlanta	Park	-	-	71	-	Pouyat et al. 2006
Berlin	Forest	-	-	72.7	-	Richter et al. 2020
Berlin	Forest	-	-	58	-	Klingenfuß et al. 2019
Berlin	Meadow	-	-	74.8	-	Richter et al. 2020
Berlin	Park	-	-	70.2	-	Richter et al. 2020
Berlin	Park	-	-	75	-	Klingenfuß et al. 2019
Switzerland	Grassland	-	-	81.7	-	Moll-Mielewczik et al. 2023
Switzerland	Cropland	-	-	40.6	8.9	Leifeld et al. 2005
Berlin	Cropland	-	-	44	9	Klingenfuß et al. 2019
Canton Vaud	Cropland	1.45	-	-	-	Dupla et al. 2021
Canton Jura	Cropland	2.3	-	-	-	Johannes et al. 2023
Canton Zurich	Cropland	2.7	-	-	-	Kanton Zurich, 2022

Table 4: Summary table of SOC percentage and SOC stock (t/ha) as well as the variation (given as the interquartile range) for each of the vegetation types and cities. Additionally, results found in the literature were included as a point of comparison.

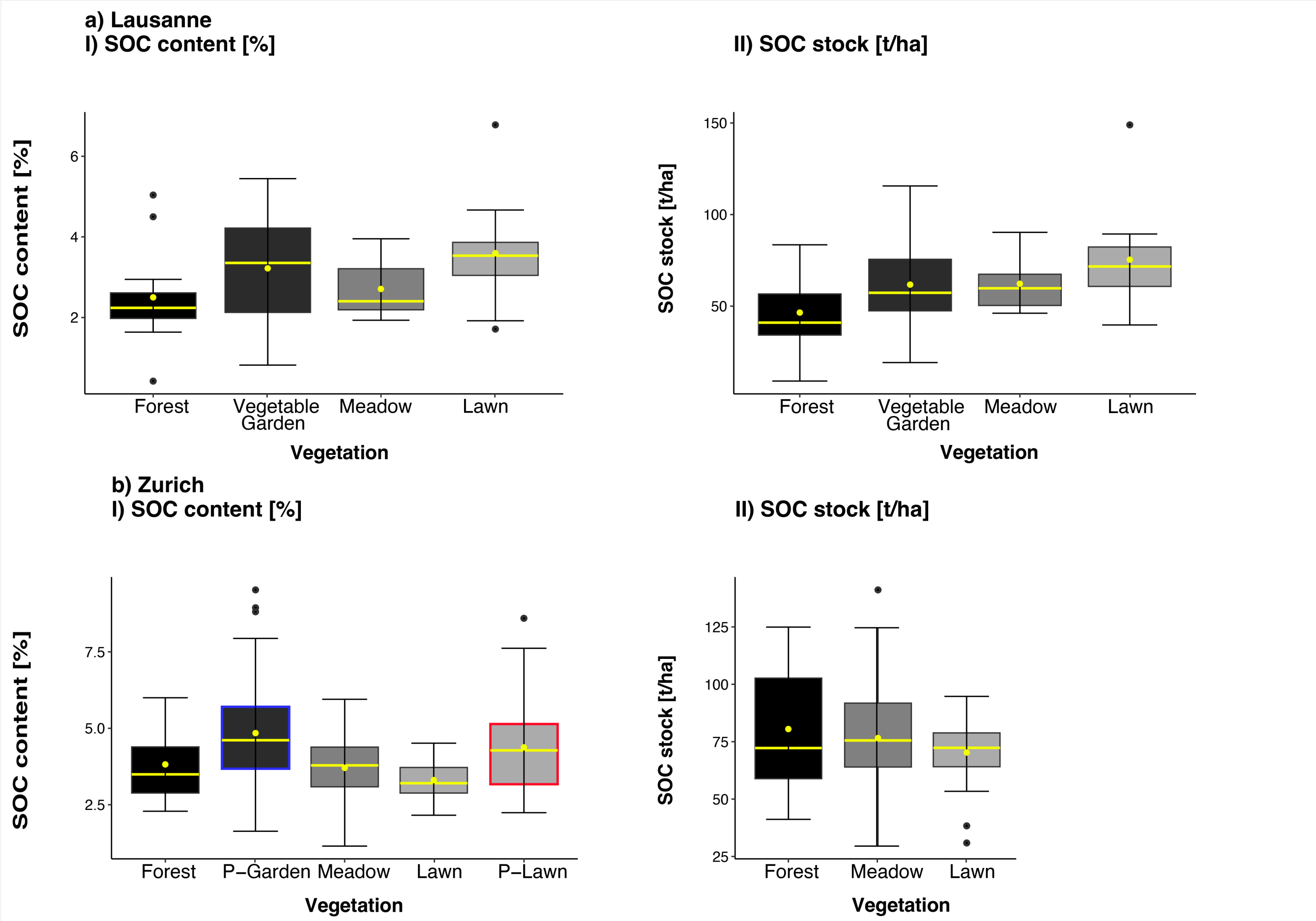


Fig. 11: Boxplots showing the distribution of I) the SOC percentage [%] and II) the SOC stock [ton/ha] for each vegetation type. Graphs display median (horizontal yellow line), mean (yellow circles), the 25% and 75% quartiles and the range of the C (minimum non-outlier, maximum non-outlier), displayed by the whiskers. Data beyond the end of the whiskers (outliers) are plotted individually as black circles. For Zurich Panel I) includes significance comparisons with the annotation of the corresponding (private) p-value (outlined in blue and red).

1.2.5 Drivers of SOC

All model fittings were conducted with the general linear modeling (GLM) package. The GLM analyses aimed to explore the individual or combined contribution of predictor variables (texture, bulk density, geomorphology and vegetation) on the SOC content in percentage (%). This choice was informed by previous research indicating the linearity of relationships between porosity and SOC (Jeffrey, 1970; Johannes, Matter et al., 2017; Saini, 1966), clay/silt content and SOC (Dexter et al., 2008; Matus, 2021; Oades, 1988) and vegetation and SOC (Richter et al., 2020; Young et al., 2005). While the best model fit (as indicated by the lowest Akaike Information Criterion (AIC) and the lowest Bayesian Information Criterion (BIC)) was obtained by only combining the individual predictors bulk density and texture, a linear model that incorporated the vegetation variable was chosen additionally to understand the effects played by vegetation (Zurich: $R^2_{adjusted} = 0.2$, Zurich public only: $R^2_{adjusted} = 0.15$, R Lausanne: $R^2_{adjusted} = 0.3$). This model was considered more suitable for addressing the specific research questions at hand.

Figures 12 and 13, and the regression diagrams reproduced in the appendixes, illustrate the two key linear relationships in the data: a positive correlation between SOC and clay content for Zurich public soils (Fig. 13 and Appendix 2 – Panel I), SOC and silt content for Lausanne (Fig. 12 and Appendix 1 – Panel I) and a negative relationship between SOC and bulk density for both cities (Appendixes 1 and 2 – Panels II), as evident across all soil vegetation types with no significant differences between them. In fact, when texture and bulk density are included in the model, neither vegetation type nor any interactions between them influence SOC in public soils, although this is not the case when including private gardens. While bulk density may affect SOC in private garden soils, neither is affected by soil texture to a significant degree. Texture and bulk density are most strongly correlated with SOC in both Zurich and Lausanne's soils public soils; however, private vegetation management can override these effects when acute enough.

The outcome of the statistical analysis reaffirms these relationships. In Lausanne, the silt content has a significant minor positive effect, with a coefficient of 0.03. This implies that a 1% increase in silt content corresponds to a 0.03% increase in SOC. Conversely, bulk density has a significant negative effect with a coefficient of -3.3. Interestingly clay had little effect on Lausanne's SOC content, likely due to how little clay was found in Lausanne's soils. Carbon is most often bound to clay and (to a lesser degree silt); and thus, in place of the absent clay, Lausanne's carbon was mostly determined by the amount of silt in its soils (Matus, 2021). In Zurich's public green spaces, the clay content has a significant positive effect, with a coefficient of 0.01 ($p < 0.01$). As in Lausanne, bulk density has a negative effect of with a coefficient of -1.13, although it is nonsignificant ($p < 0.1$). This suggests that while bulk density negatively impacts Zurich's public soils other factors also interactions may influence the relationship.

Finally, an analysis of all of Zurich's soils highlighted the importance of management. Both private green spaces had different relationships with these physical soil properties. This was largely driven by private gardens and lawn's high SOC levels being completely unaffected by soil texture and high bulk density only reducing SOC in gardens. Indeed, (private) P-Gardens had significantly more SOC than any other vegetation type when accounting for both clay and bulk density. Thus, clay had little effect on private gardens or lawn SOC content and bulk density only affected garden's SOC. This suggests that the high levels of SOC in private green spaces is driven by either the vegetation present or the management through humus supplementation and compaction mitigation in gardens (perhaps through tillage).

Results suggested that public soils with higher clay or silt content and lower bulk density tend to have an increased capacity for carbon sequestration. Findings of the clay to SOC relationship align with previous studies explained by the stabilizing effect of SOC-clay binding (Johannes, Matter et al., 2017; Leifeld et al., 2005), and the formation of micropores (Six et al., 2000), protecting SOC from decomposition. In addition, soils have slower root growth in coarser texture than in finer texture (Högberg & Högberg, 2002). This leads to a greater extent of root litter decomposition in clay and fine silt due to higher rhizospheric microbial respiration, which is essential to organic carbon storage into soils (Silver et al., 2005).

Focusing on the relationship between SOC and bulk density is more complicated to draw causative direction. Findings of the SOC-bulk density relationship is comparable to research from Saini (1966), who indicated a proportional increase between porosity (equivalent to 1/ bulk density) and SOC. However, in Saini's study (1966), the significance is ten-fold higher than in this study. This difference could be attributed to overriding management practices. Because bulk density is a secondary soil property, it is determined by a combination of factors, including soil texture, the degree of aggregation influenced by SOC and soil management practices (Lützow et al., 2006; Parton et al., 1987). Therefore, while bulk density may significantly influence SOC, this is because of a combination of multiple mechanisms, including human activities. Furthermore, the relationship between bulk density and SOC is bidirectional, adding to this complexity. Since the density of organic matter is typically about twice as low as the density of minerals, soils high in organic matter (higher SOC) will automatically have a lower bulk density than soils containing almost exclusively mineral matter. Nevertheless, there are ways that the bulk density itself can impact SOC. Soils with higher bulk density are highly compacted, restricting root growth and limiting the ability of vegetation to sequester carbon. This reduces the ability of highly compacted and continually compressed soils to increase their SOC through the carbon cycle. The hypothesis of a two-way causal relation between bulk density and SOC is even more plausible in the context of urban soils, which are very often characterized by relatively recent anthropogenic substrate, strongly influenced by post-disturbance pedogenetic developments. In this context, recent carbon sequestrations dynamics, which are likely to be impacted by potential compaction, may have a significant impact on SOC.

It is important to acknowledge the heterogeneity of the soils encountered in urban areas. Some lawns are fertilized on rich soils while others are unfertilized on thin layers above construction materials. The same can be said for meadows. This is most clearly seen in private gardens where management (tillage, which may decrease or increase bulk density depending on the method and inputs, which directly drive humus and fauna/flora growth) drives SOC levels. These practices have been shown to induce changes in microbial community structure and enzyme activity, reducing heterotrophic soil respiration and increasing soil carbon residence time (Grandy et al., 2008; Janssens et al., 2010; Sinsabaugh et al., 2005). Klingenfuß et al. (2019) hypothesized that in highly urbanized land-use types, including settlement areas and parks, an undetermined part of the determined C storage is artificial. Plastic, which was found in two of Zurich's lawn sites, contains C that has not been created by humus formation and are not part of the natural C-cycle in the soil. Macro- and micro-plastics were also found in previously analyzed Lausanne garden soils. Such soils are not C reservoirs worthy of protection in terms of climate protection (Klingenfuß et al., 2019).

Such variance throughout the different vegetations makes the estimation and the pattern finding of SOC in cities difficult. As Canedoli et al. (2020) put it, some soils may have experienced mechanical disturbance and the positive effect of vegetation on SOC may not yet be significant. In other words, while vegetation could significantly influence soil properties, past and present human activities such as construction can lead to soil compaction and SOC loss. This heterogeneity requires that future studies expand their sampling to hundreds of sample sites if they are to push beyond our analysis to understand more of the SOC drivers in Swiss cities. Nevertheless, while it is difficult to fully identify a directional relationship across both cities and all vegetation types, some things are clear. There is an obvious importance in reducing soil compaction wherever possible and conserving soils with high clay and silt levels as the primary stores of urban SOC. Private green spaces again show a different pattern to public spaces, highlighting that the heterogenous management and input practices of gardeners are likely deeply affecting the SOC content of these potentially rich soils decoupling them from other processes.

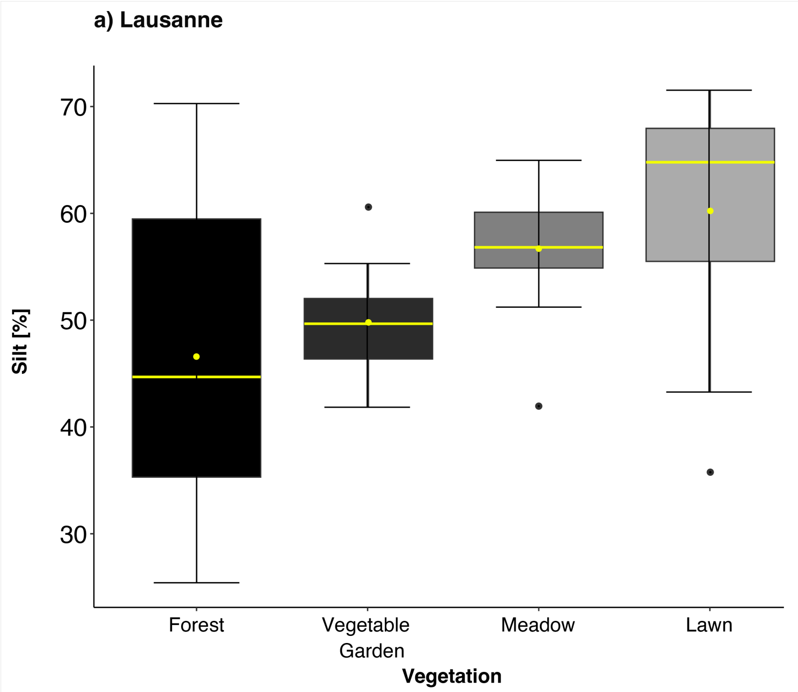


Fig. 12: Boxplots showing the distribution of the soil silt content [%] by vegetation type in Lausanne. The graph displays median (horizontal yellow line), mean (yellow circles), the 25% and 75% quartiles and the range of the C (minimum non-outlier, maximum non-outlier), displayed by the whiskers. Data beyond the end of the whiskers (outliers) are plotted individually as black circles.

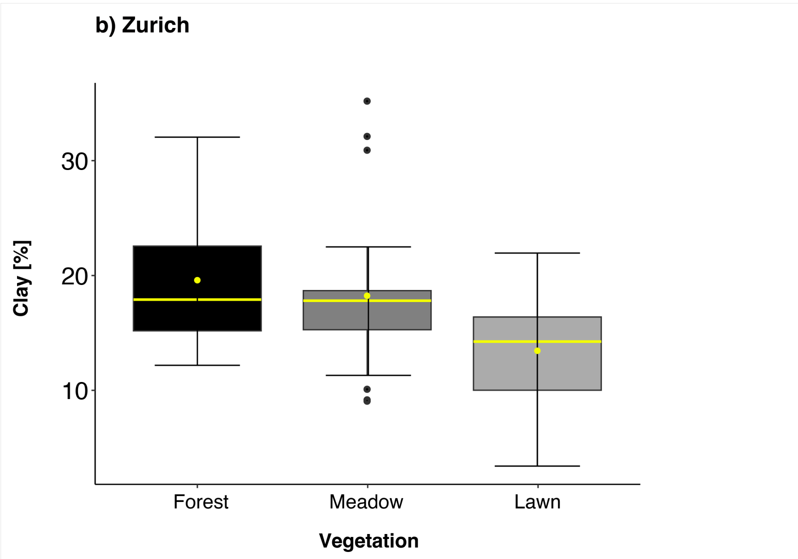


Fig. 13: Boxplots showing the distribution of the soil clay content [%] by vegetation type in Zurich (public green spaces). The graph displays median (horizontal yellow line), mean (yellow circles), the 25% and 75% quartiles and the range of the C (minimum non- outlier, maximum non-outlier), displayed by the whiskers. Data beyond the end of the whiskers (outliers) are plotted individually as black circles.

1.2.6 SOC/clay ratio

The linearity in the SOC to clay relationship and the importance of clay in binding to SOC allows for the comparisons of the SOC/clay ratio between soils in the literature, as one approximation of soil quality and the extent to which a soil's clay is saturated with SOC. Unfortunately, the lack of a SOC/clay relationship in the soils of Lausanne (which are driven by a SOC/silt relationship rather than a SOC/clay relationship) and the management-driven soils of Zurich's private green spaces suggest that such a comparative analysis would be less useful with these samples. Nevertheless, we examined this relationship in Zurich's public soils to still allow a comparison with the literature. Moreover, as silt can often be an important binder to carbon, especially in absence of clay, we hope that additional research well be conducted on SOC/silt ratios and how they reflect soil quality.

As summarized in Table 5 and shown in Figure 14, in public green spaces of Zurich, the SOC/clay ratio significantly surpassed the threshold ratio of 1/8 (0.125), denoting very well-structured soil as defined by Johannes, Matter et al. (2017) (denoted by the red dashed line in Fig. 14). Surprisingly, lawns in Zurich exhibit the highest SOC/clay ratio across vegetations, which contradicts a study by Prout et al. (2021), where woodlands had the highest SOC/clay ratio, and ley grass and permanent grass had lower values. This discrepancy may be attributed to historical land use choices driven by soil quality. It is possible that well-textured soil was preferred for settlements and residential lawns, while forests and meadows were left on poorer soils, introducing bias arising from settlement patterns. This assumption is supported by the fact that professionals conduct soil tests before construction to assess its properties, including bulk density, swelling, compaction and potential for settling (Lucian, 2008). The boxplots reveal that the mean SOC/clay ratio in lawns is higher (μ = 0.30) than in meadows (μ = 0.22) and forests (μ = 0.20). Nevertheless, SOC/clay ratios were highly variable in all three tested vegetation types with both high and low outliers potentially compromising a confident conclusion on these soils. The different histories and managements likely contribute to this variability with some lawns on previous pastureland, others on what were once gardens and still others only being planted in the last decades. Such complex heterogeneity makes unpacking the specific cause of this variability difficult without additional research with many more samples. Still, the relatively high of SOC/clay ratios within the entire study indicate the potential quality of these soils.

From the ratio it follows that for soils with a large clay content, the SOC must be very high to achieve the best soil structure quality. A recent study by Johannes et al. (2023) argues that reaching an acceptable SOC/clay ratio is less dependent on clay contents and is more influenced by farming practices, regardless of the clay content. This study specifically highlights the limited influence of clay on the formation of coarse porosity, which is crucial for soil quality. These findings underscore the impact of organic matter input from vegetation and management practices on the quality of

Zurich's soils. All soils indicate good to very good overall structural quality, in accordance with the categorization provided by Johannes, Weisskopf et al. (2017), but no significant differences were found among VESS scores (which were a visual means of assessing structural quality).

Location	**Vegetation**	**SOC/clay ratio**	**SOC/clay ratio variation**	**Citation**
Zurich	Forest	0.2	0.09	-
Zurich	Meadow	0.22	0.1	-
Zurich	Lawn	0.3	0.12	-
Jura	Good structured arable soil	>0.125		Johannes, Matter et al. (2017)
Jura	Medium structured arable soil	0.125>0.1> 0.08		Johannes, Matter et al. (2017)
Jura	Poor structured arable soil	<0.08		Johannes, Matter et al. (2017)

Table 5: Summary table of SOC/clay ratio as well as the variation (given as the interquartile range) for each vegetation type in Zurich. Additionally, baseline results found in the literature were included as a point of comparison.

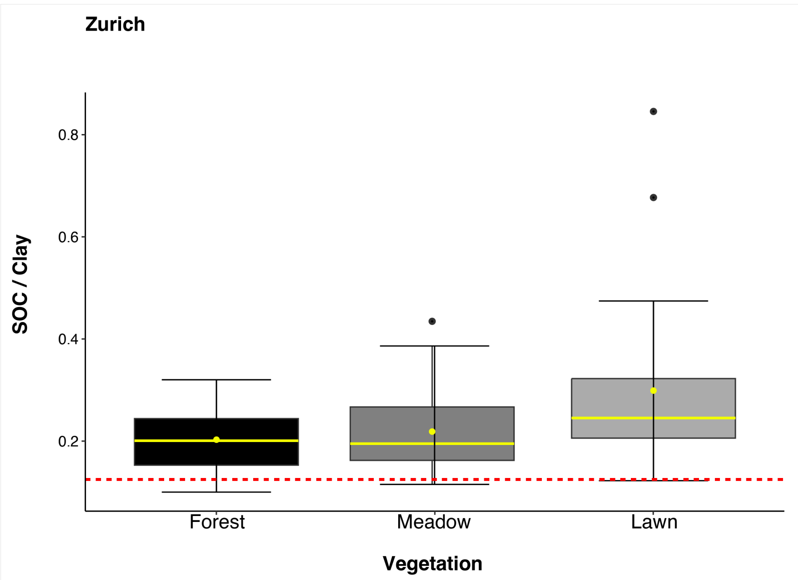


Fig. 14: Boxplots showing the distribution of SOC/clay ratio in Zurich (public green spaces). The graph displays median (horizontal yellow line), mean (yellow circles), the 25% and 75% quartiles and the range of the C (minimum non-outlier, maximum non-outlier), displayed by the whiskers. Data beyond the end of the whiskers (outliers) are plotted individually as black circles. The threshold ratio of 1/8 (0.125) indicating a very well-structured soil is denoted as the dashed red line.

1.3 Conclusions of Part I

1.3.1 Outlook on studied urban SOC content and drivers

Topsoil SOC values of Zurich and Lausanne's green spaces are relatively typical when compared to other global cities, slightly lower compared to Swiss grasslands and considerably higher than Swiss croplands. Findings showed that the **texture (clay content in Zurich and silt in Lausanne) and bulk density in public urban soils drive and establish the SOC content**, but it can be further enhanced through different vegetation covers. **In Zurich, lawns tended to have reduced SOC stocks compared to meadows, whereas forest soils contain the highest SOC**. The comparison of private and public green spaces showed that **privately owned gardens exhibit significantly higher SOC levels than public green spaces in either city, likely due to differing management practices**. When comparing lawns, meadows and forests, the lack of significance of the influence of vegetation on SOC was attributed to the overriding factors like highly variable human soil disturbance and management practices. Lastly, **the study underlined Zurich's extremely high SOC/clay ratios, suggesting Zurich public green spaces harbors well-structured soils**. **These high SOC/clay ratios confirm the need to consider the potential impact of vegetation and management practices (OC input through roots and other OC input) on urban SOC and soil quality**.

Overall, because of their heterogeneity and varied SOC values, urban soils are challenging to assess without thorough investigation. **Soil assessment should therefore be recognized as an indispensable component of urban soil management**. Further research should focus on the measurement of SOC under impervious surfaces, as well as subsoil and soil on ruderal areas to allow for a more precise estimation of the cities' total SOC stock. To assess the influence of vegetation cover types and other anthropogenic influences on subsoil, deeper sampling should be considered. The data on SOC stocks, soil bulk density and soil textures recorded through this study could contribute to the NABO database and enhance the accuracy of soil mapping efforts in Switzerland and provide insights that can shape future land management strategies.

1.3.2 Addressing the potential for organic carbon sequestration in urban soils: the objective of holistic soil functionality in the perspective of territorial resistance and resilience

In the scientific literature, there is no real numerical indicator for estimating a soil's potential to sequester organic carbon. However, the SOC/clay ratio is usually used to understand this complex matter (Johannes et al., 2023; Johannes, Matter et al., 2017). This indicator is used in agronomy to indirectly assess the structural quality of the soil, and therefore its physical fertility. A high SOC/clay ratio generally indicates better soil quality, as organic matter helps to improve soil structure, increase its water and nutrient retention capacity and promote beneficial biological activity. A threshold of 1/8 is proposed to set the limit below which soil fertility is compromised. In agronomy, as this threshold is considered a target to be reached, the delta between the actual SOC/clay ratio and the 1/8 target is generally used to define a potential for increasing soil organic carbon sequestration.

However, the SOC/clay ratio of the samples taken in this study is already well over 1/8 (see above, section 1.2.6). Consequently, this result, which shows that the urban soils studied have a very good structural quality, is in itself interesting but not very useful for understanding the potential for increasing organic carbon sequestration in urban soils.

In the fields of spatial and urban planning, the emerging notion of *territorial adaptation* includes both the notions of *resistance* – i.e., the ability of territories to continue to function despite disturbances induced by climate change (flooding, heat waves, etc.), and *resilience* – i.e., the ability of territories to back to function following major disturbances induced by factors such as climate change. Such approach of *territorial adaptation* leads to consider the holistic functionality of soils, beyond the objective of fertility sought in agronomy. In this context, the SOC/clay ratio can be used as an indicator of holistic soil functionality. By holistic soil functionality, we mean an approach taking into consideration the soil functions as defined in the Swiss National Soil Strategy, adopted by the Federal Council in 2020 (FOEN, 2020), in particular the regulation functions:

- Regulation function: infiltrate and filter rainwater, then retain it for vegetation growth and evapotranspiration (climate regulation)
- Regulation function: immobilize contaminants and therefore contribute to cleaning air
- Production function: support biomass production (leisure and food)
- Habitat function: maintain specific habitats for below and aboveground organisms' diversity (plants, soil organisms, etc.)
- Etc.

As SOC plays a role in the abovementioned functions, and beyond the 1/8 threshold generally used in agronomy, **the present study therefore supports the use of the SOC/clay ratio in the perspective of holistic soil functionality, so that it can become an exploitable indicator setting targets for improving carbon sequestration in urban environments**. In future research developments, **different thresholds could then be defined, with regard to the different soil functions desired from the perspective of territorial adaptation (resistance and resilience). This should foster the development of soil management approaches considering various forms of organic matter inputs, in relation to given or modified soil textural conditions.**

PART II. Soil management: guidelines for the improvement of carbon sequestration in urban soils through urban planning policies

2.1 Spatial planning, urban redevelopment and carbon sequestration

2.1.1 Methods

The second part of this report deals with the phenomena of urbanization and the disciplinary field of urbanism, i.e., all the planning, design and management practices of the designers and stakeholders involved in urban redevelopment operations, focusing in particular on the case of the Lausanne-Morges agglomeration. It pursues a twofold objective: (a) relating the typical SOC distribution in urban soils (as characterized in Part I) to soil management, as well as urban planning and design policies, and (b) elaborating guidelines for the improvement of carbon sequestration in urban soils through urban planning policies, especially in the context of urban redevelopment operations. Urban redevelopment does not comprise developing new portions of city on agricultural land or natural areas, but redeveloping existing neighborhoods, spaces or infrastructures, in particular to adapt them to climate change. Such urban redevelopment operations are considered crucial opportunities to improve the carbon balance through soil preservation and regeneration best practices.

In terms of the content of urban redevelopment operations, the aim is to identify the various aspects that are related to soils and their capacity to sequester organic carbon. In particular, we seek to understand how these different aspects pertain in more or less specific ways to the strategic challenges of contemporary urbanism – densification, mobility, landscape and environment, and to identify opportunities for improvement. In terms of the planning, design and management practices, the aim is to identify, at each stage of the project life cycle, the questions, original information (quantitative, qualitative) and approaches that are necessary to integrate the soil- and carbon-sequestration-related aspects.

The results presented in Part I of this report, together with three case studies carried out as part of a parallel mandate for the Direction Générale du Territoire et du Logement (DGTL) of the Canton of Vaud (Vialle & Poyat, 2024) – the agro-urban-park Espace Blécherette, the University Campus of Dorigny and the soft mobility infrastructure known as Voie verte d'agglomération have led to the development of a comprehensive approach to the preservation and regeneration/reconstitution of urban soils. This approach took the form of an overall process aiming to increase the organic carbon sequestration capacity of urban soils, by improving the surfaces (land uses, soil covers) and the substrates (soil profiles). The overall process was then broken down into eight guidelines, which were presented for discussion at a workshop with the Lausanne-Morges Agglomeration Project (PALM 2025) team on July 11, 2023, as part of the DGTL parallel mandate. Finally, the eight guidelines were used to elaborate three urban redevelopment scenarios for the Agglomeration Lausanne-Morges developed by the Chair of Transitioning Urban Ecosystems (Fachgebiet Klimaorientierter Städtebau und urbane Systeme) at the Technische Universität Berlin under the direction of Prof. Dr. Vialle, some elements of which are used to illustrate the present report.

2.1.2 Preservation and regeneration of urban soils

In view of the results presented in Part I of this report, urban soils can rightly be considered as a carbon sink. Therefore, in first place, existing stocks of organic carbon need to be maintained, by preserving urban soils and improving open space management practices that clearly contribute to raising the SOC content of urban soils. This approach, which is essentially qualitative, thus aims to improve the health of soil as a resource, with the main levers of action being, on the one hand, the legal tools of soil protection and, on the other, soil management practices. The aim is to transpose, to the urban environment, an approach to soil carbon sequestration already well mastered in the agricultural context.

However, unlike the agricultural environment, the urban environment is also characterized by a high proportion of artificialized surfaces (Camenzind & Sfar, 2014). Increasing carbon sequestration in urban soils should therefore also include regeneration, understood here as reconstitution and re-functionalization, of currently sealed surfaces. This approach, which is essentially quantitative, aims to increase the stock or capital of soil available for carbon sequestration. Beyond the usual agronomic paradigm based on soil management practices, urban redevelopment operations thus represent an opportunity and an important lever for action.

In practical terms, maintaining existing organic carbon stocks, improving open space management practices and regenerating urban soils are achieved by implementing planning and design solutions (ecological planning and urbanism) and technical solutions (soil engineering).

Explore more thoroughly in the following sections of this report, these solutions are embodied in the concept of ecological infrastructure and can be classified into two categories:

- **In situ soil preservation and regeneration**. This category covers a range of planning, design and technical protocols for reworking the soil profile without exporting any material. A soil regeneration protocol, for example, can be implemented at the foot of trees. In terms of tools, these practices can be based in particular on the definition of brown and green networks (Cormier, 2011).

- **Soil regeneration using exogenous materials**. This category covers a range of planning, design and technical protocols for recreating a soil profile using earth materials from outside the site. This solution is considered when the site's resources do not allow for in situ regeneration (e.g., surfaces that are currently sealed, with a need to reconstitute soils). In terms of tools, in addition to brown and green networks, these practices rely in particular on the implementation of a metabolic approach to urban soils (Damas & Coulon, 2016) involving the circular management of waste/resources through a soil bank and the creation of soil nurseries.

2.1.3 Overall process to increase the organic carbon sequestration capacity of urban soils

In urban environments, and particularly in Swiss agglomerations, increasing the organic carbon sequestration capacity of soils requires three types of action that are complementary and interrelated within urban redevelopment projects:

- **Preserving** existing functional soils, and therefore the stock of organic carbon they currently contain
- **Regenerating** soils on currently artificialized surfaces, and therefore reconstituting the stock of organic carbon they should contain
- **Improving and diversifying** the vegetation cover and related management practices of both preserved and regenerated soils, and therefore enabling these soils to sequestrate more/better more organic carbon, and to increase their SOC stock in the future

These three types of action define **an overall three-stage process** shown in Figure 15. While it is important to emphasize the logical sequence that underlies these three complementary types of action, this does not mean that they must be carried out in strict chronological order: on the contrary, several actions can be carried out in parallel.

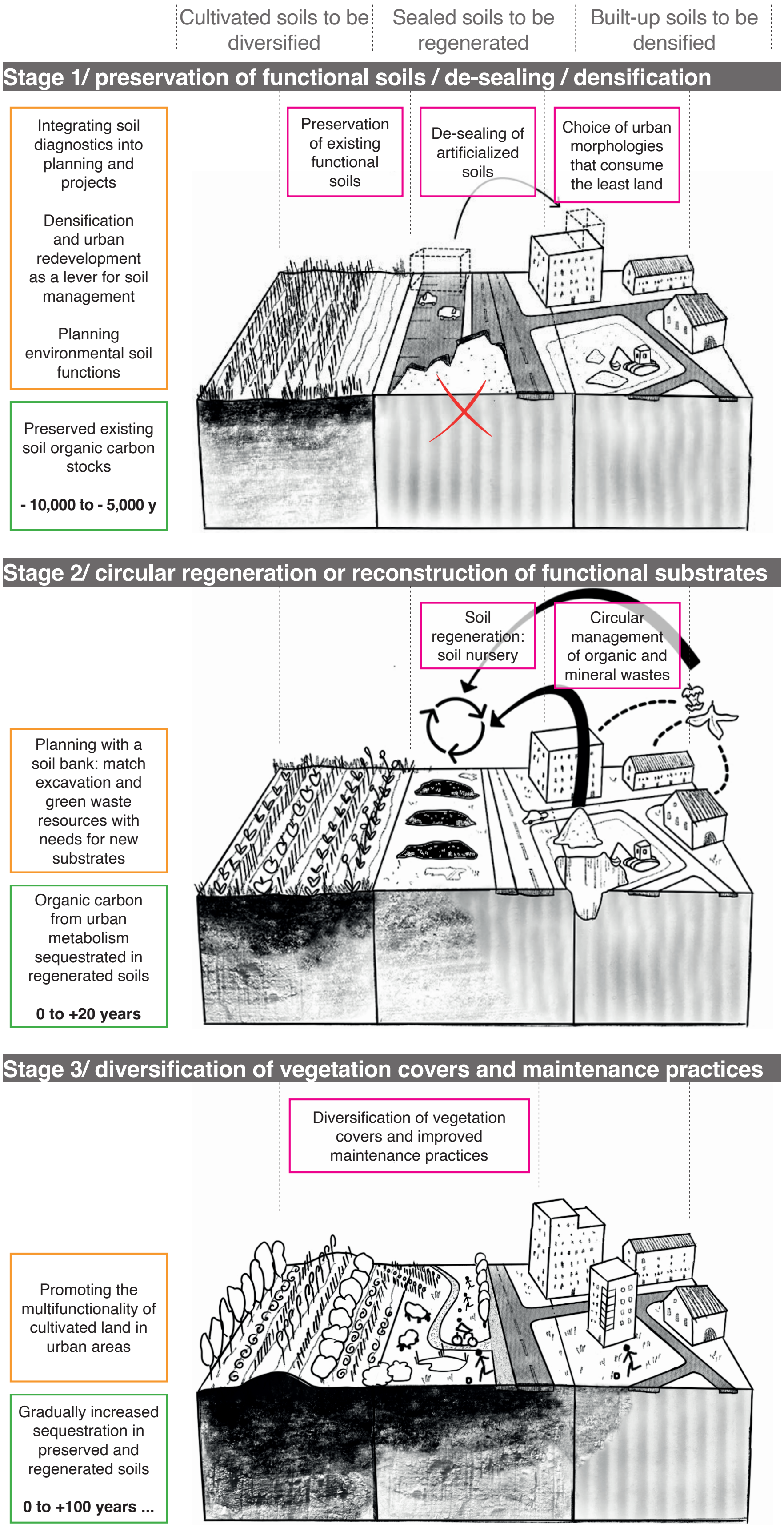


Fig. 15: The three stages of the overall process aiming to increase the organic carbon sequestration capacity of urban soils. Evolving triptych diagram, showing schematically for each stage: how the implementation of the two main objectives of current urban policies – densification and urban redevelopment projects – offers opportunities to improve the health and functionality of urban soils (in pink); the main methodological challenges for the urban planners (in orange); the impact on carbon sequestration at different timescales (in green).

2.2 Guidelines to increase the organic carbon sequestration potential and other environmental functions of urban soils through urban redevelopment

As illustrated in Figure 16, the overall process outlined above is broken down here into eight guidelines that can be translated into a series of operational measures and/or needs for research and action, as part of future federal and local policies and strategies. To different extents, these guidelines concern all sector-based land-use and urban planning strategies.

Four of these guidelines concern the content of urban redevelopment projects and open space management practices. They are complemented by four other guidelines focusing on the methodological approaches and tools required for their implementation. All these guidelines are presented here in the form of a summary diagram distinguishing between the two types of guideline, how they relate to each other and how they contribute to the overall objective of carbon sequestration.

It is important to note that these guidelines should not be seen as a series of additional constraints to be considered in planners' practices and projects, but rather as an incentive to evolve the project approach, in order to gradually integrate what might be called a soil culture into the building culture (*Baukultur*) and the culture of urban development/management.

Finally, it is important to specify that these guidelines must be seen as complementary to the objective of protecting natural and agricultural soils and landscapes. *Under no circumstances* should the guidelines formulated here and the proposed support for urban soil reconstitution be considered as an argument to increase or compensate more natural and agricultural soil degradation.

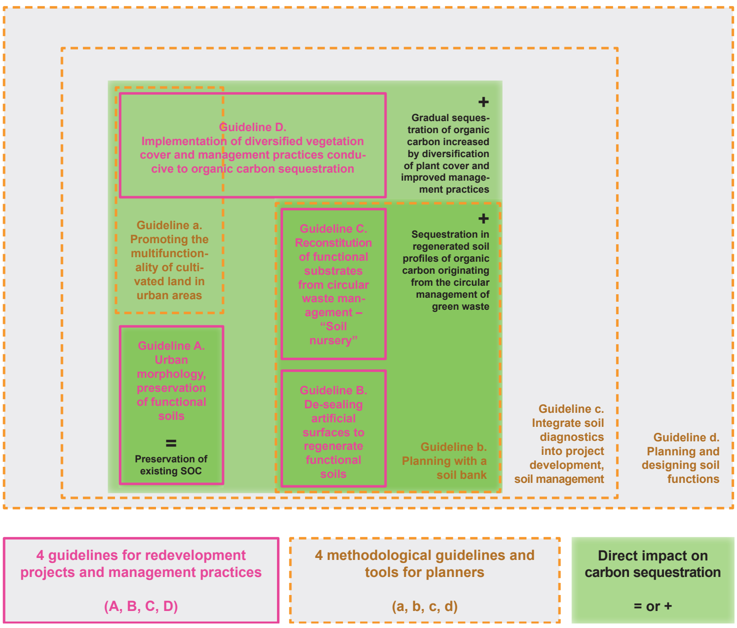


Fig. 16: Eight guidelines to increase the organic carbon sequestration capacity of urban soils. Summary diagram showing the interactions between the two types of guidelines (practices- and project-oriented in pink; methodological in orange) and their impact on carbon sequestration (in green).

2.2.1 Guidelines for urban redevelopment projects and management practices

The four guidelines presented below explain how the content of urban redevelopment projects and associated management practices can contribute to the objective of increased organic carbon sequestration in urban soils.

Each guideline is described as follows:

- Justification of the guideline based on case studies carried out as part of the parallel mandate for the Direction Générale du Territoire et du Logement (DGTL) of the Canton of Vaud (Vialle & Poyat, 2024)
- Definition of the guideline
- Challenges in terms of urban/environmental planning and design at different scales, and possible solutions

Each guideline is illustrated by a scenario developed by the Chair of Transitioning Urban Ecosystems (Fachgebiet Klimaorientierter Städtebau und urbane Systeme) at the Technische Universität Berlin under the direction of Prof. Dr. Vialle. The scenario consists of a prospective vision of the Lausanne-Morges agglomeration (map) and possible urban redevelopment project proposals for sites identified as representative in terms of the project challenges they raise.

Guideline A. Urban morphology and preservation of functional soils. This guideline is motivated by two observations:

- First, work package I of the present study highlighted the fact that, compared with soils under intensive agriculture, urban soils in parks and other vegetated areas in the heart of the city are subject to mixed-uses and varied management practices that seems to promote better and higher carbon sequestration. At least from this perspective, urban soils appear healthier and more functional than agricultural soils.
- Second, case studies carried out in the canton of Vaud (Vialle & Poyat, 2024) have shown that, at equal densities, different urban morphologies (i.e., the bi- and three-dimensional configuration of budlings and surface treatment of open spaces) have a greater or lesser impact on urban soils and their functions. When properly conceived and implemented, densification operations and/or urban redevelopment projects can be a lever for consolidating the status of open spaces within the urban fabric, as necessary condition for preserving existing functional soils and regenerating artificialized ones.

Integrating functional soils into the urban system therefore appears to be a way of preserving the organic carbon they contain.

This approach consists in encouraging project developers to use their leeway to implement urban forms in densification and/or urban redevelopment projects that allow

existing functional soils to be preserved, without necessarily densifying less. In other words, we need to build around the soil.

In terms of the content of urban redevelopment projects, this raises the following question: at what scale(s) and stage(s) of the project should we determine/manage the voids (i.e., the unbuilt open spaces existing in the urban fabric) and granularity of urban forms (i.e., the size of development projects and their built footprint)? The answer seems to lie in a cross-scalar approach. From the scale of the agglomeration to that of urban fabrics, it is possible to identify different types of structuring voids and their interconnections with urban forms (see Fig. 17 top). This approach is inspired by the way soil science consider that the quantity, size, form and connectivity of the voids within a soil's structure – allowing for the circulation of water, air and roots, and determining the soil's infiltration capacity – is an important determinant of its health. Likewise, defining a network of voids within the urban fabric (see Fig. 17, bottom) should lead to revealing an important network of urban open spaces and to identifying which soils of such unbuilt spaces are to be preserved and which are to be regenerated as a priority. From the scale of urban fabrics to that of architecture, the aim is to achieve the best possible control of building typo-morphologies in relation to unbuilt spaces, in order to maximize the preservation of significant surfaces of soil. The concept of differentiated densification (see, e.g., SDOL, 2019) can be interpreted in a way that make the best possible use of the quantitative density thresholds defined by cantonal master plans. Finally, from the architectural to the construction scale, attention must be paid to the choice of construction techniques and materials that are as respectful as possible of the soil, particularly with regard to the organization of construction sites, building foundations, underground structures and so on.

Guideline B. De-sealing artificial surfaces to regenerate functional soils. This guideline is motivated by two observations:

- First, work package I of the present study highlighted the fact that urban soils in parks and other vegetated areas in the heart of the city have relatively high organic carbon rates and stocks, which already exceed the carbon sequestration potentials or targets defined for agricultural soils in the same region. Therefore, in urban environments, the potential for increased carbon sequestration does not lie simply in improving management practices. Increasing the surface area of urban soils by de-sealing and regenerating currently artificialized surfaces is also a key opportunity to increase carbon sequestration.
- Second, case studies carried out in the canton of Vaud (Vialle & Poyat, 2024) have shown that, when properly managed, densification and/or urban redevelopment projects can be a lever for de-sealing artificial surfaces and regenerating soils within the urban fabric.

From this point of view, artificial but undeveloped surfaces are considered a significant resource deposit to increase carbon sequestration in soils: in the West Lausanne area, for example, artificial surfaces represent around 20% of the total surface area, i.e., twice the built-up area (Vialle, 2021). **This approach consists of de-sealing currently artificialized surfaces *and* regenerating ecologically functional soils (or substrates) in their place.** It is important to emphasize that this second step (regeneration) is essential to the objective of organic carbon sequestration: if it is not implemented, the effect of de-sealing will be limited to thermal and hydric regulation, with a serious risk of erosion and groundwater pollution (the regeneration of functional substrates enables the filtration of run-off water, to prevent it from contaminating the water table when it infiltrates the reopened soil). **De-sealing involves removing the technogenic layer covering the ground during open-space redevelopment operations. Soil regeneration requires appropriate management practices, sometimes preceded by soil engineering when the subtract must be reconstructed** (see Guideline D, below). These planning-based, designed-based and technical solutions can be divided into two categories: (I) in situ soil regeneration and (II) soil regeneration using exogenous materials (see Guideline C, below).

In terms of the content of urban redevelopment projects, this approach raises the following question: in qualitative and quantitative terms, on what scale(s) and at what stage(s) of the project should we manage the reclaiming of open spaces and artificialized surfaces within redevelopment operations? On the agglomeration scale, the aim is to identify where asphalt is located in the territory, through an in-depth diagnosis of currently impervious surfaces, to then define and map a brown network (see Fig. 18, top). Such tool would allow stakeholders to prioritize and coordinate surface de-sealing and soil regeneration actions first at the planification level, then within urban redevelopments projects. At the urban fabric level, in continuity with the Guideline A, the aim is to redefine the materiality of road and public space typologies, which is currently characterized by a preponderance of impervious surfaces, based on diversified vegetation cover and the uses it enables (see Fig. 18, bottom). This can be achieved by highlighting good examples of urban redevelopment. It is important to emphasize that such a redefinition of public spaces implies a paradigm shift in several areas of urban planning and design: supported by a shift toward collective and soft mobility, the reduction of space devoted to individual motorized transport is a sine qua non condition; the evolution of recreational uses in public spaces, the adjustment of management techniques (surface cleaning) and the adaptation of run-off water management (on-site infiltration) are also prerequisites. Finally, it should be noted that the leeway for surface de-sealing and soil regeneration on private land is currently very limited, and it is necessary to identify what incentives might be appropriate. Similarly, sustainable solutions must be found for the recycling of polluted substrates and impervious surfaces removed from public spaces during de-sealing operations.

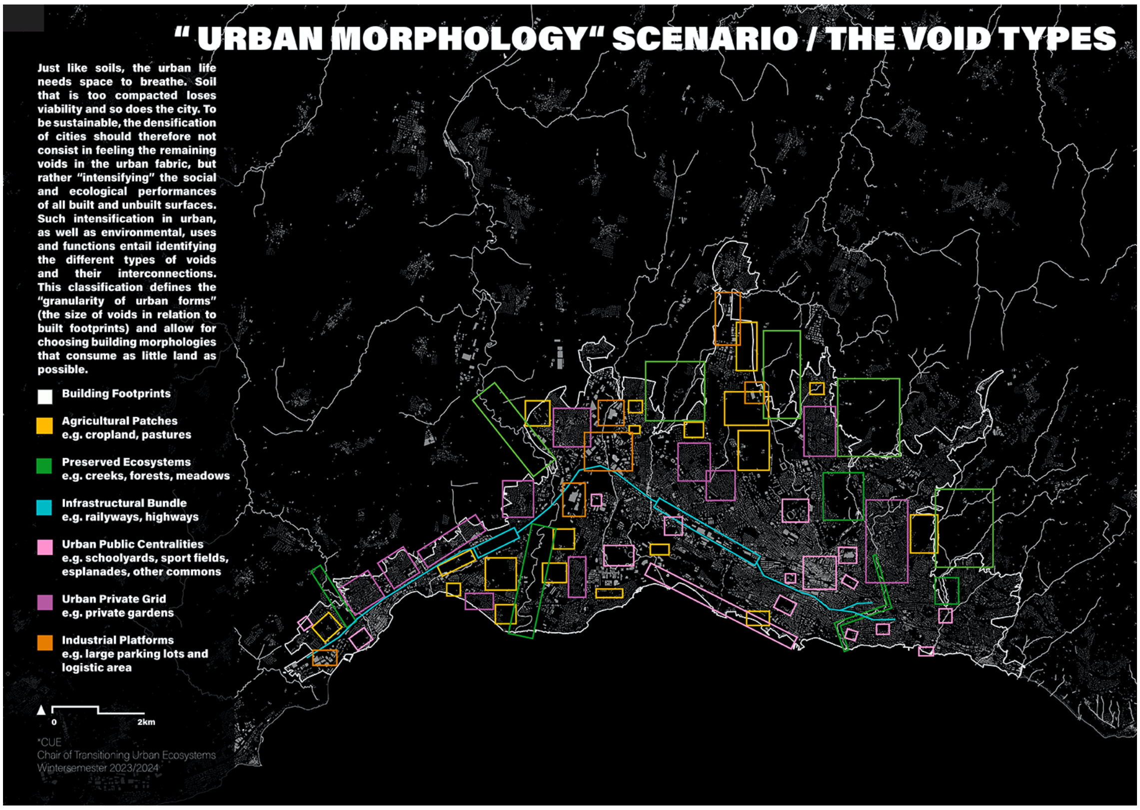
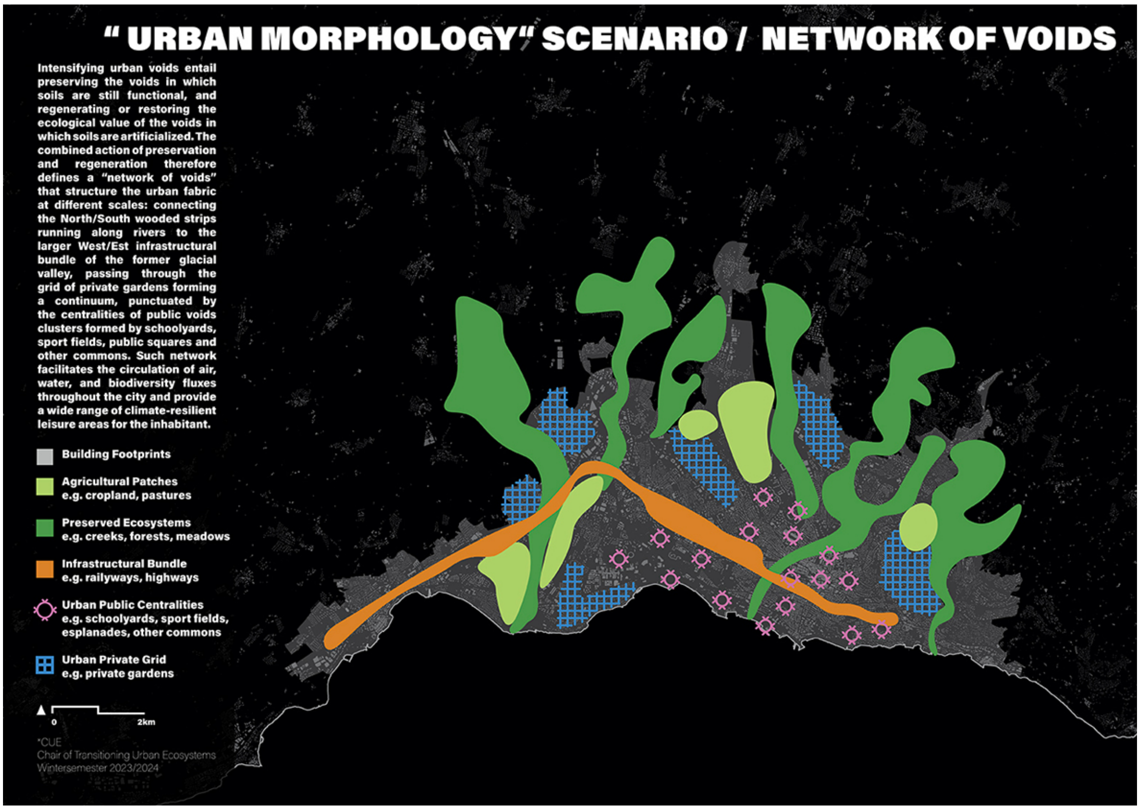


Fig. 17: Urban morphology-1 scenario illustrating Guideline A. This scenario identifies and maps various typologies of urban voids (top). The choice of appropriate urban morphologies in densification and/or redevelopment projects will allow to be preserved and/or regenerated the functional soils of those voids.



The scenario defines a network of voids (bottom) as structural backbone for the urban redevelopment of the Lausanne-Morges agglomeration.

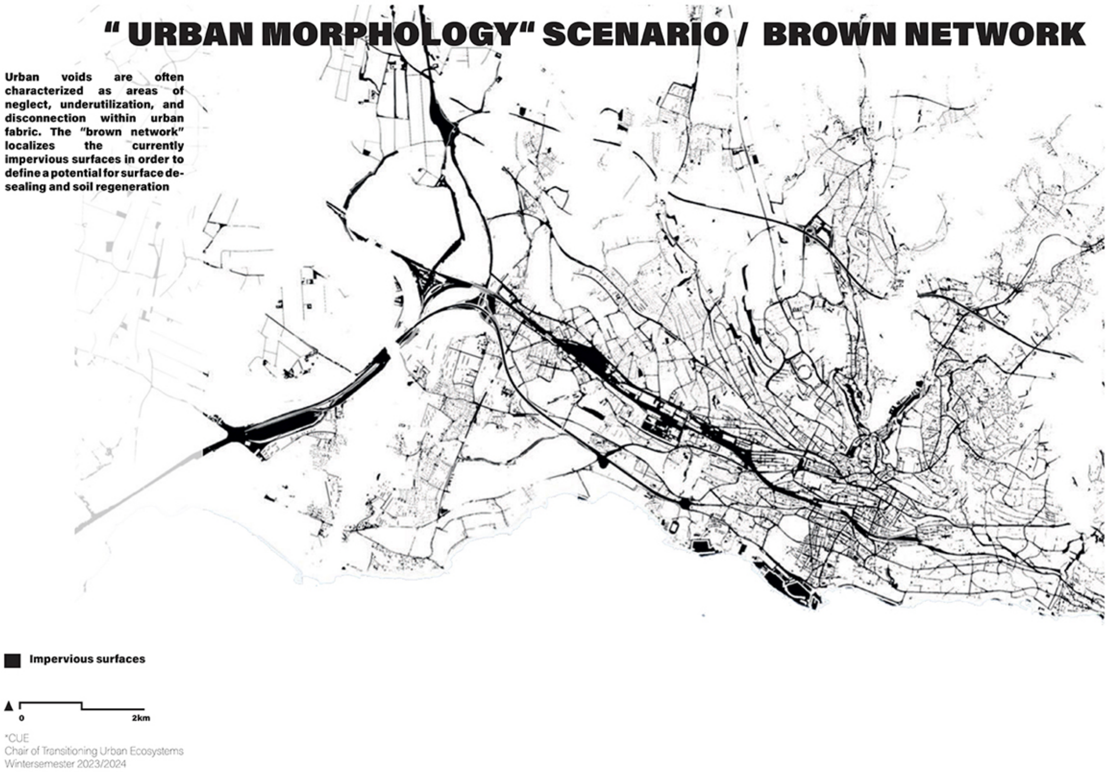
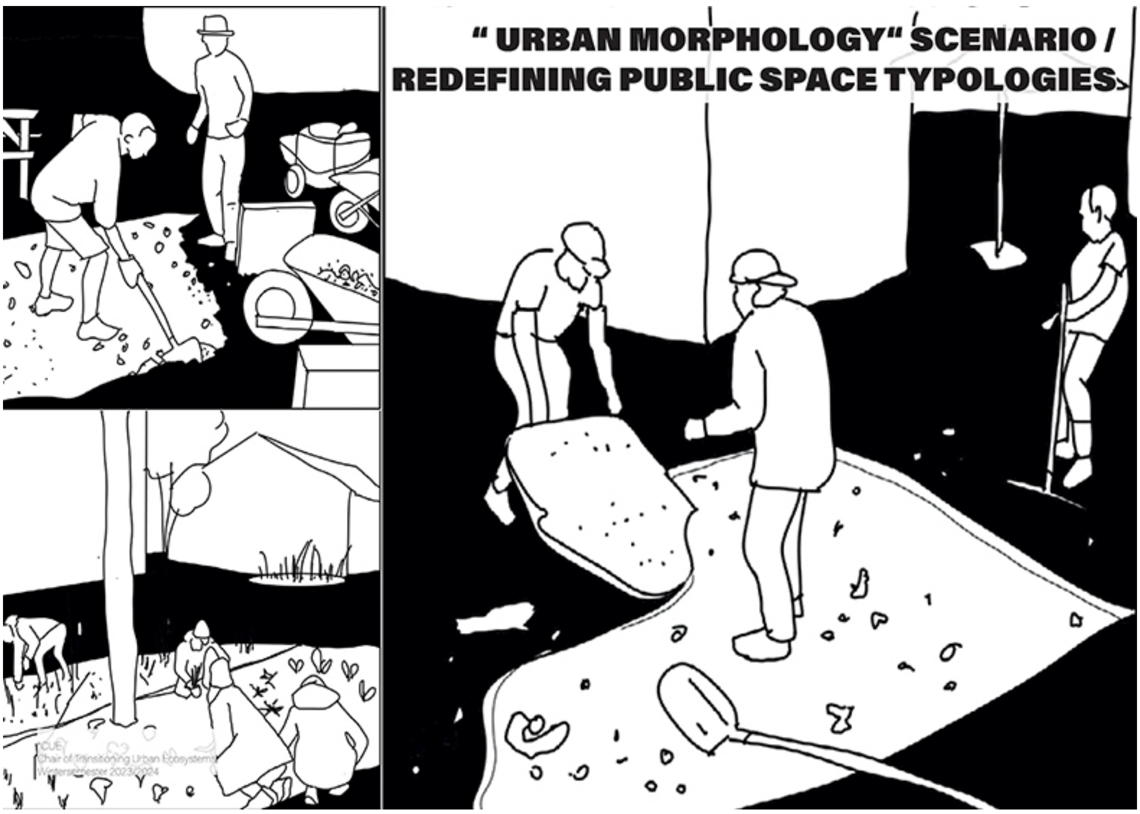


Fig. 18: Urban morphology-2 scenario illustrating Guideline B. This scenario identifies and maps a (top) as structural backbone for the urban redevelopment of the Lausanne-Morges agglomeration. The brown network localizes the currently impervious surfaces that have a potential for surface de-sealing and soil regeneration.



The scenario then redefines the materiality of road and public space typologies currently characterized by a preponderance of impervious surfaces (bottom). This process is illustrated here as a potentially collective, low-tech takeover of public space by local players.

Guideline C. Reconstitution of functional substrates from circular management of urban waste or resources – soil nursery. This guideline is motivated by the observation that, in current urban planning practice, the greening of cities and the regeneration of artificialized surfaces generally involves the use of topsoil taken from excavation sites in the agricultural environment. By itself, however, this practice has no effect on increasing soil organic carbon sequestration, as it simply displaces existing soil and the organic carbon it contains. In fact, it has a number of negative effects including energy costs associated with the displacement of large volumes of soil and possible degradation of the substrate during displacement. The reconstitution of soils in de-sealed areas (see Guideline B, above) can increase organic carbon sequestration if the regeneration of artificialized surfaces does not involve soils from natural and agricultural environments. From this point of view, excavation materials (B and C horizons), or mineral waste, from building sites, as well as organic matter, or green waste, from the management of green spaces and the domestic environment (composting of kitchen residues or, theoretically, human waste) can be considered as resources to be exploited through the implementation of a circular economy value chain, leveraging urban metabolism. In the Canton of Vaud, for instance, 1,700,000 m^3 of excavated materials (horizon C) are produced annually, equivalent to over 140,000 truckloads. The cantonal waste management plan makes no provision for the agronomic recovery of these earth materials, most of which are sent to quarries and landfill sites. However, some of this earthy material can be transformed into a planting substrate through the application of soil engineering. The substrates thus created can then be used as a substitute for topsoil in the regeneration of soils in urban areas (with a view to prioritizing the use of A and B horizons for the regeneration of agricultural land).

This approach consists of systematically collecting excavated materials and organic matter from urban metabolism, then treating them appropriately, using soil engineering, to produce functional substrates to be placed on previously de-sealed surfaces. It should be stressed that the physical qualities and functional properties of the substrates produced in this way, which can also be described as pseudo-soils or Technosols, are incomparably less developed and resistant/resilient than those of natural soils. This practice therefore only makes sense in urban environments, as a replacement for artificial surfaces, and can under no circumstances be considered in agricultural or natural environments. The implementation of circular management of excavated materials benefits from a favorable legal framework, with the notable exception of polluted materials, which must be reclaimed on site or landfilled, according to pollution levels set by law. Similarly, the circular management of green waste is benefiting from a rapid and favorable evolution in practices. In both cases, however, circular management requires the involvement of local actors (see Fig. 20, bottom). Figure 19 describes the main stages in the treatment of waste-resources through soil engineering, referred to as the concept of a soil nursery. The aim is to accelerate pedogenesis processes that take place over hundreds or even thousands of years, such as the incorporation of organic matter (humus formation). In operational terms, the treatment of waste-resources by soil engineering relies on three conditions:

- Technical knowledge: Improving the functional potential of inert excavated materials requires professional expertise based on specific technical knowledge and know-how, which is still at the experimental stage and not widely disseminated within the industry.
- Place: The storage and handling of earthy materials require a sufficiently large platform, as the maturation processes (comparable to pedogenetic processes) can only take place at a relatively shallow depth, and therefore require a large spreading surface. Maturation of earthy substrates also generates nuisances (odors, presence of insects, etc.) that are not necessarily compatible with local urban uses.
- Time: Maturation of earth materials is a process that takes place over several months – based on expert opinion (Terasol), at least twelve months depending on the targeted function (e.g., support for tree growth, lawn, etc.).

Fig. 19: Diagram of the steps involved in recycling excavated material to create fertile substrates.

If each of the steps described in Figure 19 is carried out correctly, planting substrates can be designed and produced to meet the requirements of territorial adaptation (resistance and resilience) and the objective of holistic soil functionality cited in section 1.3.2 (rainwater regulation, plant growth, carbon storage, etc.). The success of the soil regeneration process depends not only on the quality of the planting substrates, but also on their implementation (reconstitution of the soil profile) and management practices, which can be supported by the use of a soil bank as a planning support tool (see Guideline b, below).

In terms of the content of urban redevelopment projects, the regeneration of functional substrates based on circular management of mineral and green waste raises the following questions:

- What resources are available – origins and volumes of waste flows?
- At what scale(s) and in what form(s) should circular resource management be implemented – public, associative or private collection at the level of the agglomeration, district or development site and/or individual collection and treatment at the level of the housing unit (individual house, for example)?
- Where, on what scale(s), in what form(s) and according to what timeframe(s) should the platform(s) needed to process functional substrates be set up – as permanent infrastructure on one or more dedicated site(s) in the agglomeration and/or as part of temporary installations set up opportunistically on a case-by-case basis on construction sites?

Here again, the answer seems to lie in a multi-scalar approach, in order to respond in the most appropriate and sensible way possible to the multiplicity of situations.

The abovementioned fact that the accelerated reproduction of pedogenetic processes (i.e., soil-forming processes) involved the production of functional substrates requires the materials to be placed and then manipulated at a thickness comparable to that of the first soil horizons (a few decimeters at most) and over a sufficiently long period (based on expert opinion – Terasol, at least twelve months depending on the targeted function) also has consequences for urban redevelopment projects. In its temporal, spatial and material aspects, the soil nursery can thus be considered as an ecological infrastructure, also featuring a societal dimension related to raising users' awareness of soil issues and their involvement as actors in circular waste management. It is therefore advisable to avoid a strictly monofunctional approach, relegating substrates formation processes to a purely logistical space. On the contrary, in the context of urban redevelopment projects and within the limits of cohabitation taking into account nuisances, the soil nursery, or even soil farm, could take on the aspect of a proto- urban-landscape (i.e., a new urban mixed-used landscape in the making) associated with recreational and extensive park uses (see Fig. 20, bottom).

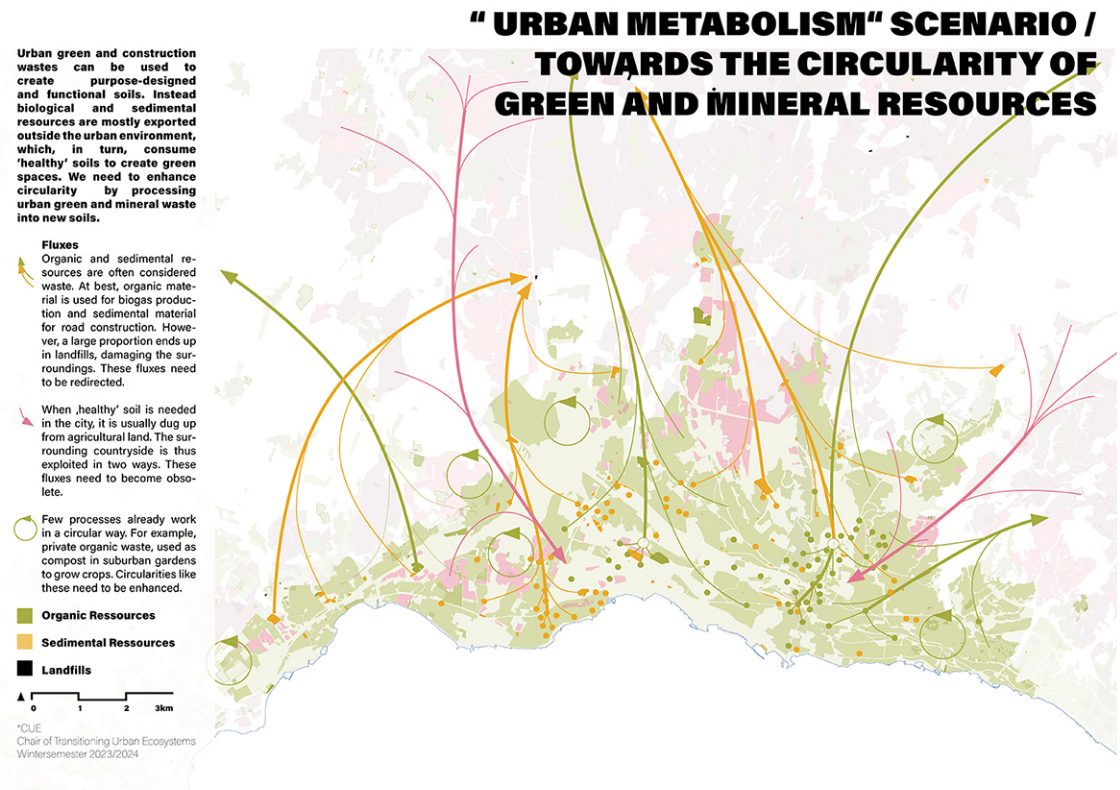
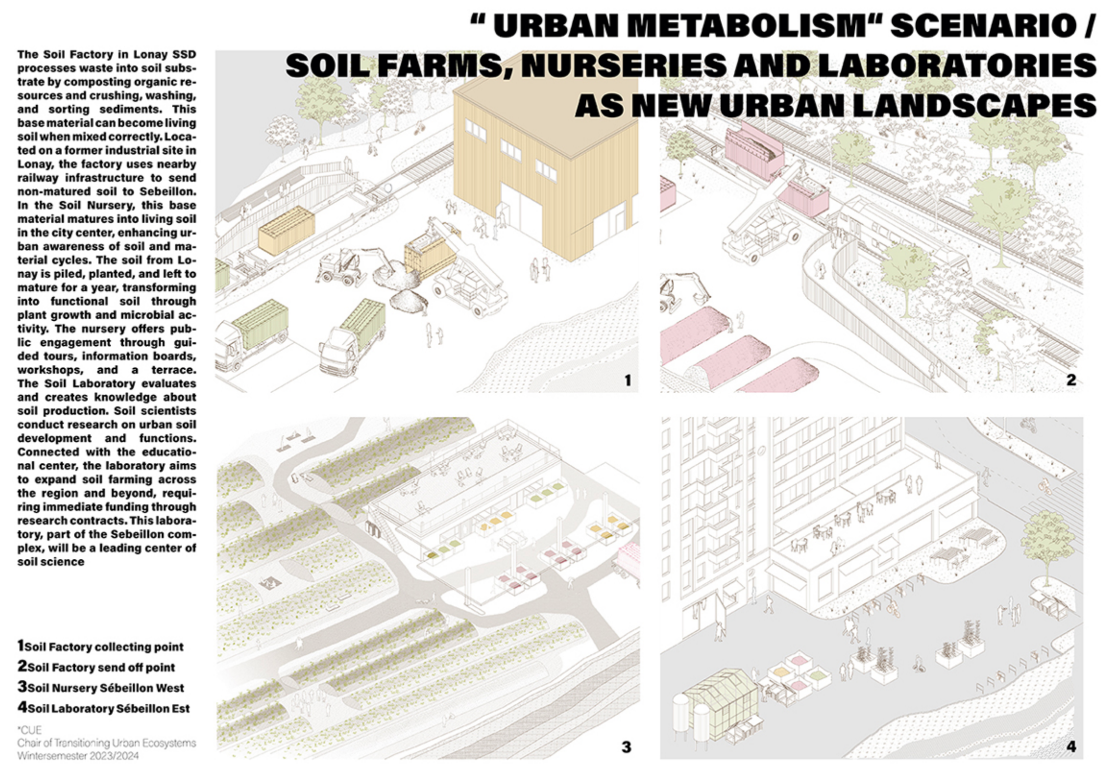


Fig. 20: Urban metabolism scenario illustrating Guideline C. This scenario identifies and maps fluxes of mineral and organic wastes (top) to implement a circular management of these resources within the Lausanne-Morges agglomeration, aiming to regenerate functional soil substrates.



The scenario comprises four urban redevelopment projects including a soil farm, a soil nursery and a soil laboratory (bottom). Within a multifunctional and mixed-uses approach, these ecological infrastructures, where mineral and organic waste are reprocessed into functional substrates, are meant to become new temporary urban landscapes.

Guideline D. Implementation of diversified vegetation cover and management practices conducive to organic carbon sequestration. This guideline is motivated by a threefold observation based on the results of work package I:

- First, in comparison with the usual food-production-related land uses (intensive agriculture), multifunctional and mixed urban uses (leisure, ornamental greenery, urban and community-based agriculture) involve varied management practices that are less invasive for soils, implying less biomass export and/or a greater organic matter input. Mixed urban uses are therefore more favorable to the progressive accumulation of organic matter in soils.
- Second, the different types of vegetation cover measured and analyzed in work package I (i.e., forests, vegetable gardens, meadows, lawns) have shown a great variability in organic carbon levels, due to the complexity of natural and anthropogenic factors involved in carbon sequestration. However, all the studied types of vegetation cover, including those subjected to intense urban use and high management practices, are significantly effective in sequestering carbon, and should therefore all be taken into account for the purposes of this study.
- Third, in the case of Zurich, a comparison of organic carbon levels in privately and publicly managed lawns and meadows showed higher levels in the privately managed areas. As it is already well known in the agricultural context, this field observation confirms the hypothesis that urban management practices have a more or less negative/positive impact on organic carbon sequestration and can therefore be improved.

In other words, three abovementioned findings underline the fact that, in the urban environment, there is no such thing as a “bad” type of vegetation cover as regard to the carbon sequestration objective, but that all vegetation cover can be improved in terms of management practices.

This diagnostic should be considered in the light of the preliminary vegetation cover mapping carried out in work package I (see Figures 3 and 4 in section 1.1.1), which showed a very strong predominance of lawns and a very strong underrepresentation of other types of vegetation cover. On that matter, it should be noted that Zurich is slightly more diversified than in Lausanne, suggesting that there is room for improvement in some agglomerations. In addition, case studies carried out in the canton of Vaud (Vialle & Poyat, 2024) have shown that many aspects of urban redevelopment projects could potentially provide an opportunity to diversify vegetation cover and related soil management practices:

- renaturation projects and the implementation of ecological networks
- the preservation of large voids in the form of agglomeration parks with appropriate treatment of urban edges
- the redevelopment of open spaces within built-up areas

- the implementation of soft mobility infrastructure accompanied by generous landscaping measures, etc.

From this point of view, the gradual diversification of vegetation cover, considered as ecological habitats, and associated management practices over the coming decades represents a lever for increased sequestration of organic carbon in the preserved or regenerated urban soils.

As an alternative to the current overrepresentation of lawns in open spaces, this approach consists in supporting and increasing the greatest possible diversity of vegetation cover in urban redevelopment projects: forests, orchards and vineyards, meadows and pastures, vegetable gardens, etc. This diversification of vegetation cover on protected soils and (for non-food-production-oriented uses) on regenerated substrates must be accompanied by an improvement in management practices consisting, for example, depending on the situation, of less soil structure disruption through the absence of ploughing, a more substantial supply of organic matter through the natural formation of litter or the addition of nature-based input (compost), as well as natural mowing by livestock.

In terms of the content of urban redevelopment projects, the diversification of vegetation cover and management practices raises the following question: beyond the traditional definition of a park, what urban uses can promote organic carbon sequestration in open spaces? On a territorial scale, on the basis of the network of voids and the brown network (soils of open spaces to be preserved and regenerated as a priority), respectively, mentioned above for guidelines A and B, the aim is to define a green network made up of a mosaic of diversified ecological habitats (see Fig. 21, top). In addition to its qualitative aspect, this network could also take on a quantitative dimension in the form of an index of greenery defining the proportion of the ground to be covered by vegetation. At the level of redevelopment projects, the typology of open spaces and related urban uses needs to be redefined as diversified ecological habitats (see Fig. 21, bottom), in order to give vegetation cover the structuring role that asphalt currently plays. For instance, several non-exhaustive options have emerged for rethinking open spaces based on a relationship with vegetation as backbone:

- Creating areas in the heart of the urban fabric with little or no access for users, dedicated to the development of pseudo-natural flora and fauna (biodiversity) defined as urban wilderness.
- Rethinking sports practices to make the most of the spontaneous uses that have increased since the coronavirus pandemic, and which do not require highly maintained or even artificial surfaces, as is generally the case with team sports.
- Increasing the surface area dedicated to participatory and community-based urban agriculture, in response to strong social demand. It should be noted, however, that community-based agriculture raises questions in terms of the management required. For instance, the maximum capacity of permanent residents to devote the time and energy

needed for urban gardening does not yet seem to have been reached, while that of other users, such as employees or students, seems more difficult to assess.

- Finally, promoting multifunctional and mixed recreational uses on cultivated land in urban areas. As observed in case studies carried out in the canton of Vaud (Vialle & Poyat, 2024), this approach comes up against legal constraints that can only be fully resolved by an evolution of federal legislation (see Guideline a, below)

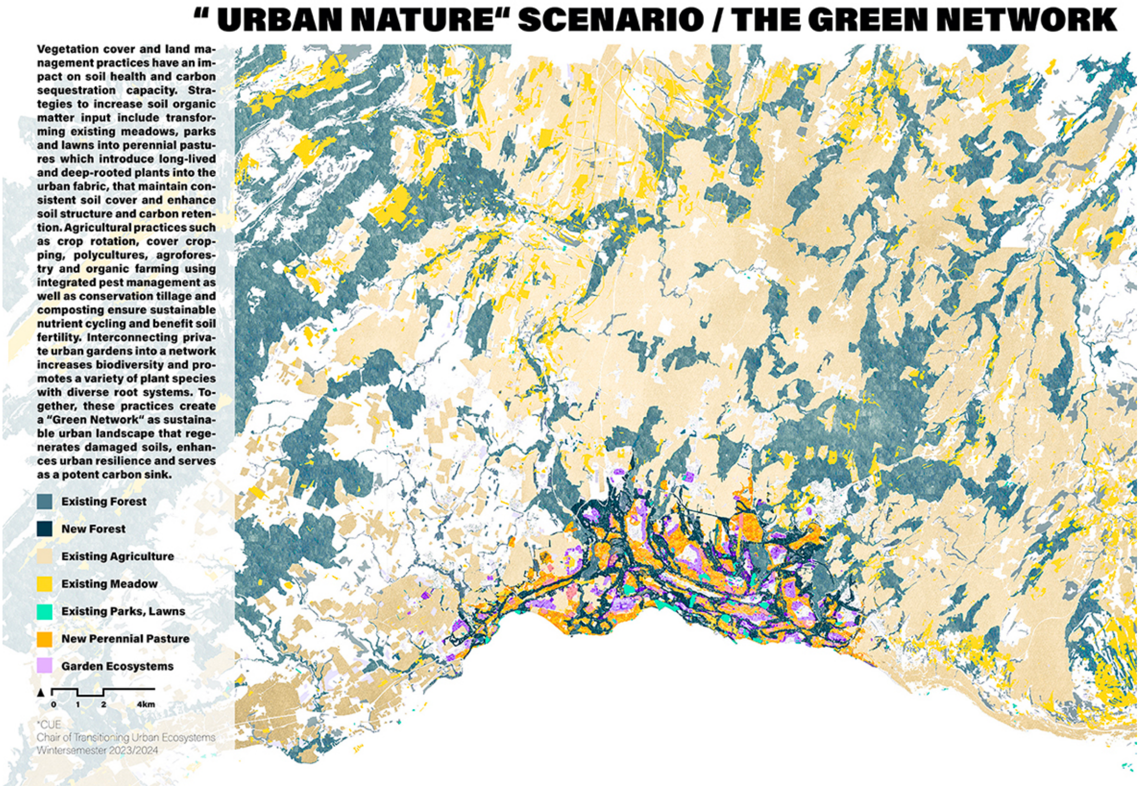
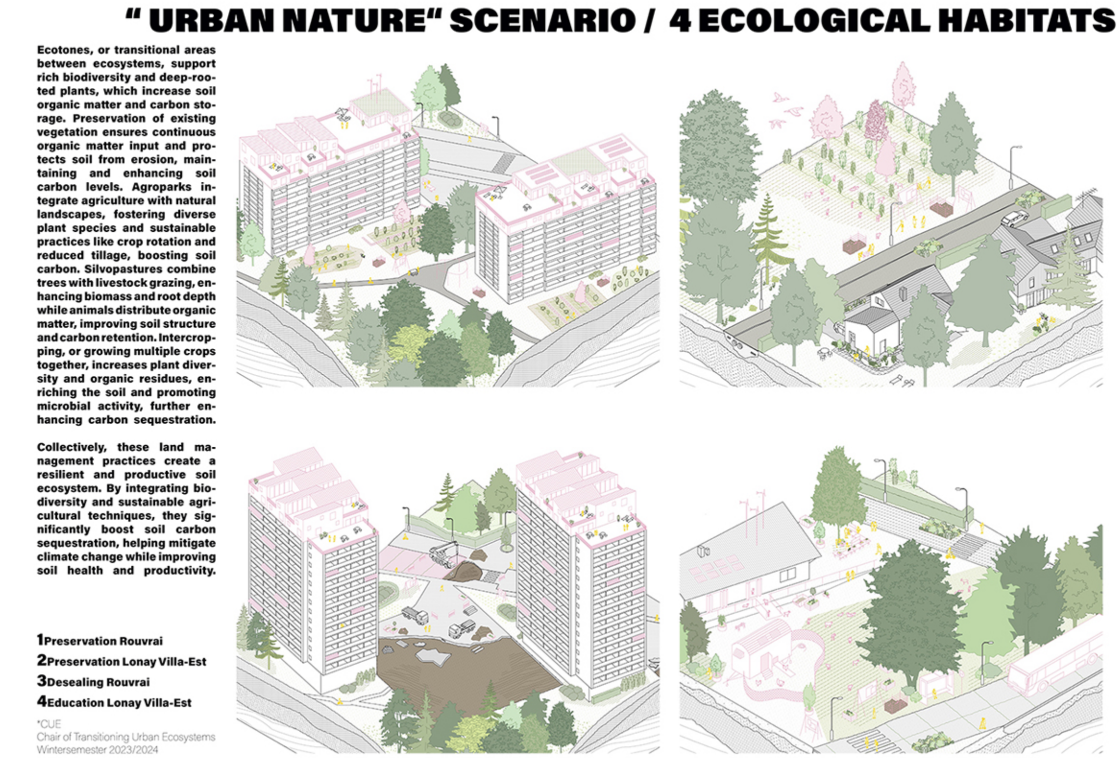


Fig. 21: Urban nature scenario illustrating Guideline D. This scenario identifies and maps a possible green network (top) as structural backbone for the urban redevelopment of the Lausanne-Morges agglomeration.



The scenario comprises four urban redevelopment projects as ecological habitats (bottom) exemplifying the implementation of diversified vegetation covers and management practices conducive to increased organic carbon sequestration.

2.2.2 Methodological guidelines and tool for urban planners and designers

The four methodological guidelines presented below explain how the specific tool for stakeholders, planners and designers can contribute to the implementation of the four abovementioned project-oriented guidelines, and therefore to the objective of increased organic carbon sequestration in urban soils.

Each guideline is described as follows:

- Justification of the guideline based on case studies carried out as part of the parallel mandate for the Direction Générale du Territoire et du Logement (DGTL) of the Canton of Vaud (Vialle & Poyat, 2024)
- Relevance and utility in implementing the four project-oriented guidelines
- Thematic and objectives of the guideline
- Possible ways of implementing the guideline at federal, cantonal/agglomeration and urban redevelopment levels
- Other potential fields of application of the guideline

Guideline a. Promoting the multifunctionality and mixed uses of cultivated land in urban areas. As observed in case studies carried out in the canton of Vaud (Vialle & Poyat, 2024), the designation of remaining cultivated patches of land in urban areas as agricultural zones, according to spatial planning law (Swiss Spatial Planning Act, 2014), is an obstacle to their integration into redevelopment projects, such as agro-urban parks, the landscaping of soft mobility infrastructures or the treatment of urban fringe areas, as the current legal framework severely limits any multifunctional mixed use. Consequently, in order to achieve the objective of increased carbon sequestration in urban soils, the implementation of guideline D. "Implementation of diversified vegetation cover and management practices conducive to organic carbon sequestration" and, to a lesser extent, guideline A. "Urban morphology and preservation of functional soils" (see above) requires a multiscalar reflection on the vocation and future of cultivated land in urban areas.

On a methodological level, with regard to conception and management tools available to urban planners and designers, the aim of this guideline is to promote reflection on the vocation of cultivated areas in the urban environment. This reflection could ultimately lead to an evolution of the legal framework defining authorized uses for agricultural zones located in the urban environment. Supporting urban redevelopment dynamics which are already underway in Swiss agglomerations, this process can be structured around two main objectives:

- The field results obtained in work package I of the present study provide arguments for rethinking the function of food production in urban environments. With the aim of increased carbon sequestration, these results highlight the relevance and efficiency of certain cultivation and management practices as an alternative to intensive agriculture, such as so-called organic and/or conservation agriculture, participatory agriculture in the form of community or allotment gardens, etc.

- In relation to demographic dynamics in the urban context, this reflection on agricultural zones should also take into account potential multifunctional or mixed uses and varied management practices beyond the food production function. In this respect, allowing multifunctional and mixed land uses targeting leisure activities, soft and active mobility, biodiversity protection/promotion and/or diversification of landscapes represents an opportunity in terms of the objective of carbon sequestration, as well as in other social co-benefits.

This reflection on the food production function in agricultural zones located in urban areas could be held at different scales and take different forms:

- In line with the Swiss National Soil Strategy for Sustainable Soil Management adopted by the Federal Council in 2020 (FOEN, 2020), a change in the legislative framework governing the use of land for agriculture at the federal level (Swiss Spatial Planning Act, 2014) could then be applied to cantonal planning.
- At the level of Swiss agglomerations and their interaction with cantonal planning, an evolution of the prerogatives attributed to agglomeration projects (led by the Federal Office for Spatial Development – ARE) could integrate an agriculture (or) food production strategy.
- Lastly, this reflection should lead to greater integration of local actors (farmers, owners of private gardens or green spaces, gardeners, etc.) in the design and implementation of urban redevelopment projects. Following the example of the Groupe des agriculteurs du Nord Lausannois (GANL) involved in the development of the Espace Blécherette agro-urban park, the integration of local actors of soil management into the management of urban redevelopment operations also requires municipal support. In terms of tools, it would be useful to identify what incentive measures could be envisaged to encourage local actors to diversify/improve/optimize soil management practices and use(s): legal obligations, subsidies, economic co-benefits, etc. For instance, it can be noted that subsidies for organic farming currently do not particularly encourage practices conducive to carbon sequestration (Boivin et al., 2021).

In the context of this guideline, in addition to the proposed reflection on agricultural zones and the food production function in the urban environment, a similar approach could be applied to other land uses. For instance, an evolution of management practices could be considered for the surfaces dedicated to sports and physical activities. In this case, the legal constraints appear to be less stringent, but the evolution of management practices and the multifunctional and mixed use of land currently used as sports fields would nonetheless represent a challenge in terms of the involvement of local actors (sports associations, etc.).

Guideline b. Supporting a metabolic approach integrating waste/resource management into urban redevelopment projects – planning with a soil bank. As observed in case studies carried out in the canton of Vaud (Vialle & Poyat, 2024), there is potential for the sustainable management of organic and mineral waste/resources generated in Swiss agglomerations. For example, the Hautes Ecoles campus in West Lausanne and potentially the Espace Blécherette agro-urban park offers the possibility of circular management of organic waste/resources related to the management of green and cultivated areas. Similarly, urban redevelopment operations, such as Plaines du Loup in Lausanne, offer the potential for circular management of mineral waste/resources from excavation sites. In terms of actors, we can give the example of the Green Spaces Department of the city of Lausanne (SPADOM), which is currently developing a twofold reflection on (I) the circular management of organic and organo-mineral waste/resources related to the management practices of parks and municipal domains, and (II) its needs concerning the same resources for the regeneration of green spaces (such as consideration of the organo-mineral substrates necessary as part of the Lausanne Jardins 2024 event).

Consequently, the sustainable implementation of guideline C. "Reconstitution of functional substrates from circular management of urban waste or resources – soil nursery" requires, at all scales and at that of agglomeration in particular, to anticipate the resources available in terms of excavation materials and green waste, so as to be able to match them with the needs in terms of functional substrates to be produced for urban redevelopment operations and for the regeneration of open spaces and urban soils. In addition, we must consider that the implementation of guidelines A. "Urban morphology and preservation of functional soils," B. "De-sealing artificial surfaces to regenerate functional soils" and D. "Implementation of diversified vegetation cover and management practices conducive to organic carbon sequestration" will influence available organic and organo-mineral resources. In addition, implementation of guideline B. "De-sealing artificial surfaces to regenerate functional soils" will help define the need for functional substrates to be regenerated/produced.

On a methodological level, with regard to conception and management tools available to urban planners and designers, the aim of this guideline is to promote a reflection on urban metabolism. This reflection could ultimately lead to the development of a tool for monitoring and decision-making support. Supporting urban redevelopment dynamics which are already underway in Swiss agglomerations, this process can be structured around two main objectives:

- With the aim of increased carbon sequestration and taking into account the challenges and legal framework regarding pollution of excavation materials, the field results obtained in work package I of the present study provide arguments for considering the contribution of agglomeration projects to the circular management of waste at the cantonal level and below. For example, the cantonal waste management plan mandates the reuse of soil materials (horizons A and B) for the reconstruction of soils in urban green spaces. Indeed, this is a legal obligation under the Ordinance on Waste Limitation and Disposal, which states that "Soil materials resulting from the stripping of the top and underlying layers of soil must be fully reclaimed wherever possible" (see Art. 18 of Ordinance on Waste Limitation and Disposal, 2015). A similar reasoning can be applied to the valorization of green waste.
- In relation to demographic dynamics in the urban context, this reflection on urban metabolism should make it possible to better anticipate the needs for functional substrates related to surface de-sealing and soil regeneration, in order to bring them into line with the resources produced and available. This objective could lead to agglomerations becoming self-sufficient in functional substrates for the redevelopment of open spaces, to avoid the consumption of natural topsoil and any impact on the surrounding agricultural environment.

This reflection on urban metabolism, consisting in planning and designing urban redevelopment with the help of a soil bank, could be held at different scales and take different forms, raising various methodological challenges (obstacles and opportunities):

- In line with the Swiss National Soil Strategy for Sustainable soil Management adopted by the Federal Council in 2020 (FOEN, 2020), the creation of an inter-office working group or taskforce could support decision-making concerning the recreation of functional substrates derived from the circular management of mineral and organic waste, as significant contribution to the objective of increasing organic carbon sequestration in Swiss soils. In particular, such a taskforce should consider the federal legal framework and operational management of polluted materials and sites, which currently represents a constraint (Swiss Environmental Protection Act, 2015; Ordinance on Waste Limitation and Disposal, 2015; Contaminated Sites Ordinance, 1998; Ordinance Relating to Impacts on the Soil, 2016).
- At the level of Swiss agglomerations and their interaction with cantonal planning, the urban metabolism approach offers an opportunity to strengthen the various strategies that make up agglomeration projects (led by the Federal Office for Spatial Development – ARE), and to generate synergies in their implementation at the intermediate level (urban redevelopment operations). However, this raises the need for action and research to gather or produce specific knowledge. For example, the organic and organo-mineral resources available (origin, volume, qualities, etc.) are only partially identified, and most often only at the construction

stage, i.e., very late in value chain and urban metabolism cycle. The need to produce and/or share knowledge concerns in particular: the geological context, the location of recyclable geological and pedological materials, sites available on a temporary or permanent basis for the recycling of waste/resources, etc.

- Lastly, planning with a soil bank therefore requires information feedback from local actors to the agglomeration level. Planning with a soil bank is inherently an iterative process, involving a feedback loop between needs and resources. The circular metabolic approach should thus lead to greater integration of local actors in the design and implementation of agglomeration projects – producers of waste and consumers-users of resources. In this respect, it is worth noting that planning with a soil bank (comprising in a careful way both excavated earth material – soils, and recreated subtracts) would make it possible to avoid landfill procedures and the purchase of topsoil (a precious resource subject to increasingly competitive needs and uses), and would therefore have a positive effect on the economic cost of urban redevelopment operations.

In the context of this guideline, in addition to the proposed reflection on circular management of waste/resources related to excavation sites and the management of green spaces, the objective of regenerating urban soils could also incorporate the valorization of other sources of organic matter: the food chain on the one hand (domestic waste), and sanitary infrastructures treating human and nonhuman waste on the other (feces). However, while domestic waste is currently mostly use for renewable energy production (methanization), the use of feces is deemed as utopian given current ecotoxicological and socio-technical constraints.

Guideline c. Integrating soil diagnostics into project development and soil management. As observed in case studies carried out in the canton of Vaud (Vialle & Poyat, 2024), the quality of existing soils and future substrates is, today, generally not directly and explicitly taken into account in planning and project practices on the agglomeration scale. When considered, information on soil quality only comes into play much later in the project design and implementation process, generally at the plot level. However, we have observed that this parameter is indirectly linked to many aspects of the cases studied. In order to achieve the objective of improving organic carbon sequestration in agglomeration soils, three types of diagnosis are available, or could be made available in the future:

- Predictive tool: Soil Quality Index (SQI) (*Sanu Durabilitas, Soil Quality Index (IQS)*, n.d.). Like other comparable European examples, this tool is currently under development in Switzerland (first experiment by scientist and stakeholders on a selection of soil properties and functions). The main predicted information on soils' physical and functional properties is accompanied by an assessment of its variable degree of reliability. Such type of diagnostic is useful for both soil preservation and regeneration measures.

- Field-based tool: soil surveys (field surveys). Such highly reliable information on the physical properties of existing soils is available on a case-by-case basis, at a moderate cost. Surveys are carried out for both soil preservation and regeneration measures.
- Field-based tool: geological surveys (boreholes). Such information does not concern the soil itself but the underlying geological environment. Included in the geological cadaster at the cantonal level, this information is not necessarily up to date (data sometimes old not reflecting recent earthworks and/or pollution). Such information about the geological and subsoil background is mostly useful to inform the measures related to the reconstruction of substrates, in order to define the target physical properties of the new substrate in coherence with the surrounding subsoil.

In line with the second overarching objective of the Swiss National Soil Strategy, the approach proposed in this guideline is therefore to systematically collect and interpret available soil information, as a prerequisite to urban planning, and then to support the development and implementation of urban redevelopment operations and management practices. In particular, guidelines A. "Urban morphology and preservation of functional soils" and D. "Implementation of diversified vegetation cover and management practices conducive to organic carbon sequestration" could be based on a diagnosis of preexisting soils. Similarly, guidelines B. "De-sealing artificial surfaces to regenerate functional soils" and C. "Reconstitution of functional substrates from circular management of urban waste or resources – soil nursery" could be based on a diagnosis of the surrounding and underlying environment (geological context).

On a methodological level, with regard to conception and management tools available to urban planners and designers, the aim of this guideline is to integrate and use soil diagnostics in urban planning, design project and management practices at the agglomeration level. Achieving this objective raises a number of methodological challenges (obstacles and opportunities):

- The production of urban soil data and their systematic use in spatial and urban planning is in line with the second overarching objective of the Swiss National Soil Strategy for Sustainable Soil Management adopted by the Federal Council in 2020, which states that "(the management of) soil consumption (must be established) on the basis of an overall perspective: Soil functions are factored into planning, and the associated balancing of interests, so that soil consumption can be managed in the interests of sustainable development. The soil data required to do so is available" (FOEN, 2020). The production of urban soil data and support to their systematic use could therefore be coordinated at federal level with the Soil Competence Centre (CCSols/KoBo).

- As regards agglomeration projects and their interaction with cantonal planning, it should be noted that existing data are incomplete, and data production has an economic cost. The level of definition of the diagnosis must therefore be adapted to the needs of each scale/stage, from planning to management. For instance, the available soil surveys are highly localized. The degree of generality seems more easily adaptable in the case of SQIs, but with a challenge concerning data reliability: our study shows that predictive mapping is in some cases unreliable without field verification.
- Finally, the use of soil data and diagnostics as decision making support for planning, project development and management requires the acquisition of specific skills and know-how by stakeholders and actors (*Sanu Durabilitas, Soil Quality Index (IQS)*, n.d.). From soil science to urban planning and development, for instance, the use of soil data requires an understanding of basic concepts and definitions (e.g., soil, urban soil, physical soil properties, soil functions, ecosystem services, etc.). It also requires the ability to read and interpret basic data and understand their influence on the project (notion of suitability) and conversely the influence of urban planning, design and management on soils (notion of impacts). In turn, from urban planning, design and management to soil sciences, it can be noted that, due to the high spatial variability of urban soils, the very fine resolution (generally at or below the parcel level) at which data is available entails a risk of loss of coherence (fragmentation) of decisions that need to be made on a larger urban or territorial scale (for example, the design and implementation of an ecological infrastructure across a territory cannot be limited to a multitude of decisions taken on a case-by-case basis according to information available at the parcel level). Soil data users must therefore learn to spatialize these data as part of a project-based approach (coherence with planning and design goals), bringing different scales into iterative dialogue.

Guideline d. Planning and designing soil functions. As observed in case studies carried out in the canton of Vaud (Vialle & Poyat, 2024), at all levels of cantonal planning, agglomeration project and its implementation in the form of urban redevelopment operations, there is an opportunity – and even a necessity from the perspective of the present study – to integrate the functions of urban soils, in particular their capacity to sequester organic carbon (regulation function), into planning and design practices.

In this respect, planning practices today only define objectives in terms of human or spatial densification (expressed, for example, in terms of numbers of inhabitants, or built/usable surface area). Soil functionality is addressed only indirectly, for example through the preservation of landscape or biodiversity features. At best, consideration of soil functionality is limited to carrying out an impact study after (or in iteration with) project development. Similarly, at project level, control of the impact on the soil is limited to establishing a land-use coefficient. This coefficient generally sets a minimum to be respected, with the aim of densifying the built fabric rather than preserving the soil. In rare cases, a qualitative approach to soil functions is indirectly sought through measures aimed at other environmental or landscape objectives, such as biodiversity (e.g., creating or maintaining a wooded belt). However, qualitative objectives (enabling the targeted functions to be identified) and (semi-)quantitative objectives (expressed, for example, as surface area objectives, in the form of coefficients relating to soil functions, or as estimated results, e.g., in tons of Corg/ha) could be useful and desirable.

In the context of agglomeration projects, two main complementary approaches can be envisaged:

- Negative planning: an approach that could be described as negative planning (or reversed planning) is already being applied to some extent. This approach consists of harmonizing all existing landscape protection and enhancement measures, in particular as biodiversity supports, agricultural areas, forests, etc. In other words, this approach defines, among other things, where not to artificialize soils, in function of where the organic carbon stock contained in soils must not be damaged.
- Functional planning: regeneration of the urban ecosystem, and of soils in particular, requires an approach that could be described as functional planning, referring to both the environmental and human-oriented functions that soils can perform. Such approach to planning should be based on knowledge of existing resources (assessment of existing functions) and environmental needs (modeling of future post-intervention functions). Mapping would then make it possible to thematize and spatialize desirable soil functions (i.e., those to be preserved through the protection of existing soils and/or created through soil regeneration) as part of sustainable planning and urban redevelopment operations (for example: water retention, available in the soil for plant growth and atmospheric cooling via evapotranspiration, is spatially and qualitatively very compatible with carbon sequestration and can be integrated as an goal in planning and design practices).

All the guidelines presented above, oriented toward management practices and urban redevelopment projects, could be based on qualitative and/or quantitative objectives in terms of preserving and/or improving soil functionality, by integrating the constraints and opportunities offered by the latter.

On a methodological level, with regard to conception and management tools available to urban planners and designers, the aim of this guideline is to reverse the usual methodological approach, in order to define objectives regarding the environmental and

urban functions of urban soils prior to planning and project development (in other words, rather than carrying out impact studies, the aim is to rethink and design the city from its soils). Achieving this objective raises a number of methodological challenges (obstacles and opportunities):

- In relation to demographic dynamics in the urban context, this functional approach only makes sense if it is not limited to the objective of organic carbon sequestration. It must be part of a holistic approach to soil functions (including water and climate regulation; heat island mitigation; habitat, i.e., biodiversity function biomass support and food production; etc.) formulated in terms of co-benefits and ecosystem services (population well-being, comprehensive strategy for climate change mitigation and adaptation, etc.). **Such holistic approach to soil functions should lead to redefine optimal SOC/clay ratio(s) in order to set targets (or potential) for improving carbon sequestration specifically adapted to urban environments (see above, section 1.3.2).**
- Soil functionality objectives are difficult to define, as they involve complex modeling based on various physical soil properties. At present, numerous tools for modeling and predicting soil functions are being developed, but their reliable use in real-life contexts has yet to be demonstrated. In terms of the tools available, the SQI could be used for prospective planning design and management as a predictive tool (and not just for diagnosing existing conditions – see Guideline c. above).
- The question arises as to whether these objectives should be binding in terms of the legal framework or encouraged by means of incentives. The verification of effective soil functionality after urban redevelopment operations also has an economic cost in any case. Besides, the definition of soil functionality targets should not be seen as yet another constraint, but rather as a necessary evolution in the planning and design culture, requiring not only political support, but also the training of stakeholders and local actors.

2.3 Summary table of guidelines: definitions, objectives, possible actions

Definition of the guideline	**Main objectives of the guideline**	**Possible actions at federal level** (in particular regarding legislative framework and the Swiss National Soil Strategy)	**Possible actions at cantonal planning and agglomeration project level** (detailed diagnoses; territorial project and sectoral strategies)	**Possible actions in urban redevelopment projects**
GUIDELINES FOR URBAN REDEVELOPMENT PROJECTS AND MANAGEMENT PRACTICES (A, B, C, D)				
Guideline A. Urban morphology and preservation of functional soils				
Encouraging stakeholders and project developers to use their leeway to implement urban forms in densification and/or urban redevelopment projects that allow existing functional soils to be preserved, without necessarily densifying less	Better characterize the different types of structuring voids (i.e., non-built spaces in the territory), their respective landscape, environmental and urban qualities and their interconnections	Initiate a critical reflection on the notion of compact built-up area and on the operational meaning of the principle of "measured use of land" provided for in the Swiss Spatial Planning Act as revised in 2014	Define a network of voids based, if possible, on existing landscape diagnostics, and identify open space soils that should be preserved and regenerated as a priority	
	Optimize the typo-morphology of built-up structures and open spaces to maximize the preservation of significant areas of land (functional soils)	Support research initiatives aiming to integrate soil protection and valorization into Switzerland's building culture	Make appropriate use of the quantitative density thresholds defined in the cantonal master plans, using concepts such as differentiated densification as used in the Lausanne-Morges Agglomeration Project and define qualitative criteria for any derogations if necessary	Choice of construction techniques and materials that respect the soil as much as possible (in particular lightweight foundations, ephemeral and reversible structures, bio-sourced materials, etc.)

Definition of the guideline	Main objectives of the guideline	Federal level	Cantonal planning and agglomeration project level	Urban redevelopment projects
Guideline B. De-sealing artificial surfaces to regenerate functional soils				
De-sealing currently artificialized surfaces AND regenerating ecologically functional soils (or substrates) in their place	Identify where asphalt is located in the landscape and territorial structure, then define and map a brown network on an agglomeration scale, in order to prioritize and coordinate surface de-sealing and soil regeneration actions	Support research initiatives aiming to integrate surface de-sealing and soil regeneration challenges into a coherent, cross-functional approach to sustainability	Accurate monitoring of trends related to soil artificialization, as well as an in-depth diagnosis of currently impervious surfaces and opportunities for de-sealing	
	Redefine (new operation, new uses, new management practices, new design) the types of roadways and public spaces currently characterized by a preponderance of impermeable surfaces	Foster the current dynamics of research on the sponge city, their practical applications and their positive effects on carbon sequestration in urban soils (co-benefits)	Identify possible incentives for surface de-sealing and soil regeneration on private land	Highlight good examples of urban redevelopment to promote de-sealing
Guideline C. Reconstitution of functional substrates from circular management of urban waste or resources – soil nursery				
Systematically collecting excavated materials and organic matter from urban metabolism, then treating those wastes appropriately as a resource, using soil engineering to produce functional substrates to be placed on previously de-sealed surfaces	Implement circular management of waste and resources	Support research initiatives and experiments aimed at producing specific knowledge and technical know-how concerning the circular reconstitution of soils, which are currently very little disseminated within the professional sectors	Identify sites available on a temporary or permanent basis for the recycling of waste/resources into soil substrates	Circular management of waste/resources requires the involvement of local actors (producers and users of waste)
	Implement soil nurseries		Soil nurseries could take the form of urban proto-landscapes (transitional landscapes) associated with extensive recreational park uses	

Definition of the guideline	Main objectives of the guideline	Federal level	Cantonal planning and agglomeration project level	Urban redevelopment projects
Guideline D. Implementation of diversified vegetation cover and management practices conducive to organic carbon sequestration				
Introducing the greatest possible diversity of vegetation cover in urban redevelopment projects, accompanied by an improvement in management practices	Define a green network made up of a mosaic of ecological habitats	Foster follow-up of the promising research objective of the present report regarding the impact of various urban vegetation covers and related management practices (continuation of empirical data collection, implementation of site experiments and modeling)	Introduction of a greening index, defining the proportion of land to be covered by vegetation, in order to define and monitor planning objective	
	Redefine (new operation, new uses, new management practices, new design) the types of roadways and public spaces currently characterized by a preponderance of impermeable surfaces to give vegetation coverings a structuring role	Foster the current dynamics of research on the sponge city, their practical applications and their positive effects on carbon sequestration in urban soils (co-benefits)	Identify possible incentives for vegetation covers diversification and improvement of related management practices on private land	Highlight good examples of urban redevelopment to promote vegetation covers diversification

Definition of the guideline	Main objectives of the guideline	Federal level	Cantonal planning and agglomeration project level	Urban redevelopment projects
METHODOLOGICAL GUIDELINES AND TOOL FOR PLANNERS AND URBAN DESIGNERS (a, b, c, d)				
Guideline a. Promoting the multifunctionality and mixed uses of cultivated land in urban areas				
Promoting a reflection on the purpose of cultivated areas in the urban environment	As an alternative to intensive agriculture, promoting certain cultivation and management practices, such as so-called organic and/or conservation agriculture	At the level of the federal offices concerned, promote better integration of urban redevelopment challenges and agricultural policy in urban areas	Include an agriculture (or) food production strategy in agglomeration projects	Strengthen the integration of local actors (farmers, owners of private gardens or green spaces, gardeners, etc.) in the definition and implementation of urban redevelopment operations
	Allowing multifunctional and mixed land uses in agricultural zones, including leisure activities, soft and active mobility, biodiversity protection/promotion and/or diversification of landscapes, participatory agriculture in the form of community or allotment gardens, etc.	A modification of the legislative framework governing the use of land for agriculture could then be reflected in cantonal planning and subsequently in urban redevelopment operations		
Guideline b. Supporting a metabolic approach integrating waste/resource management into urban redevelopment projects – planning with a soil bank				
Promoting a reflection on urban metabolism, to move toward self-sufficiency in in functional substrates for the redevelopment of open spaces on the scale of agglomerations	Introduce a decision-support tool to anticipate available resources in terms of excavation materials and green waste, so as to be able to match them with needs in terms of functional substrates to be produced for urban redevelopment and soil regeneration projects	Create an inter-office taskforce to support decision-making concerning the regeneration of functional substrates from circular management of mineral and organic waste. Consider the legal framework of polluted materials and sites (Environmental Protection Act; Ordinance Relating to Impacts on the Soil; Contaminated Sites Ordinance; Ordinance on Waste Limitation and Disposal)	Production and/or sharing of knowledge concerning in particular: the geological context (bedrock map), the location of valuable geological and pedological materials, etc.	Greater involvement of local actors (producers and users of waste) in circular waste management and soil regeneration, and information feedback to cantonal level

Definition of the guideline	Main objectives of the guideline	Federal level	Cantonal planning and agglomeration project level	Urban redevelopment projects
Guideline c. Integrating soil diagnostics into project development, management and maintenance				
Integrate and use soil diagnostics in urban planning, design project and management practices	Collect or produce, then systematically interpret available soil information, as a prerequisite to support planning, then urban redevelopment projects, as well as management practices	The production of soil data and their systematic use in urban environments could be coordinated at federal level with the Soil Competence Centre (CCSols / KoBo), in particular through systematic use of the SQI currently under development	The level of diagnostic definition must be adapted to the needs of each scale/stage, from planning to management	The use of soil data as support for a planning, project and management requires the acquisition of skills by stakeholders
Guideline d. Planning and designing soil functions				
Defining objectives regarding the environmental and urban functions of urban soils prior to planning and project development	Negative planning (already partially implemented)	Promote the protection of functional urban soils as a necessary evolution of the planning and project culture (not as just another constraint)	Harmonize all existing landscape protection and enhancement measures, in particular as biodiversity supports, agricultural areas, forests, etc. Define where not to artificialize soils, in function of where to not damaged the organic carbon stock contained in soils	Explicitly reflect soil protection objectives in special or local regulations (e.g., plans de quartier), guidelines and briefs for urban redevelopment projects
	Functional planning (referring to both the environmental and human-oriented functions)	Define and promote a holistic approach to soil functions formulated in terms of co-benefits and ecosystem services. Foster follow-up of the promising output of the present report regarding **the redefinition of optimal SOC/clay ratio(s) in order to set new targets (or potential) for improving carbon sequestration specifically adapted to urban environments (see above, section 1.3.2);** Should objectives be set that are legally binding or not?	Assess of existing resources (existing functions) and environmental needs (modeling of future post-intervention functions), and map (thematize and spatialize) desirable soil functions (i.e., those to be preserved through the protection of existing soils and/or created through soil regeneration) as a basis for planning and urban redevelopment projects; SQI could be used for prospective planning design and management as a predictive tool	Explicitly reflect soil functions objectives in special or local regulations (e.g., plans de quartier), guidelines and briefs for urban redevelopment projects

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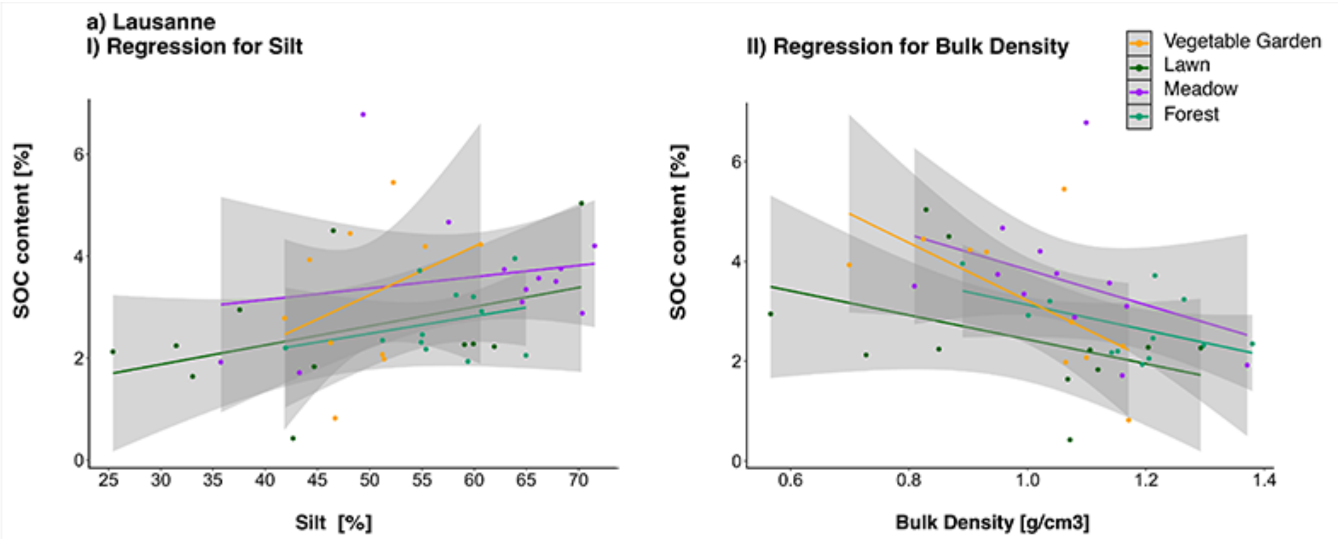
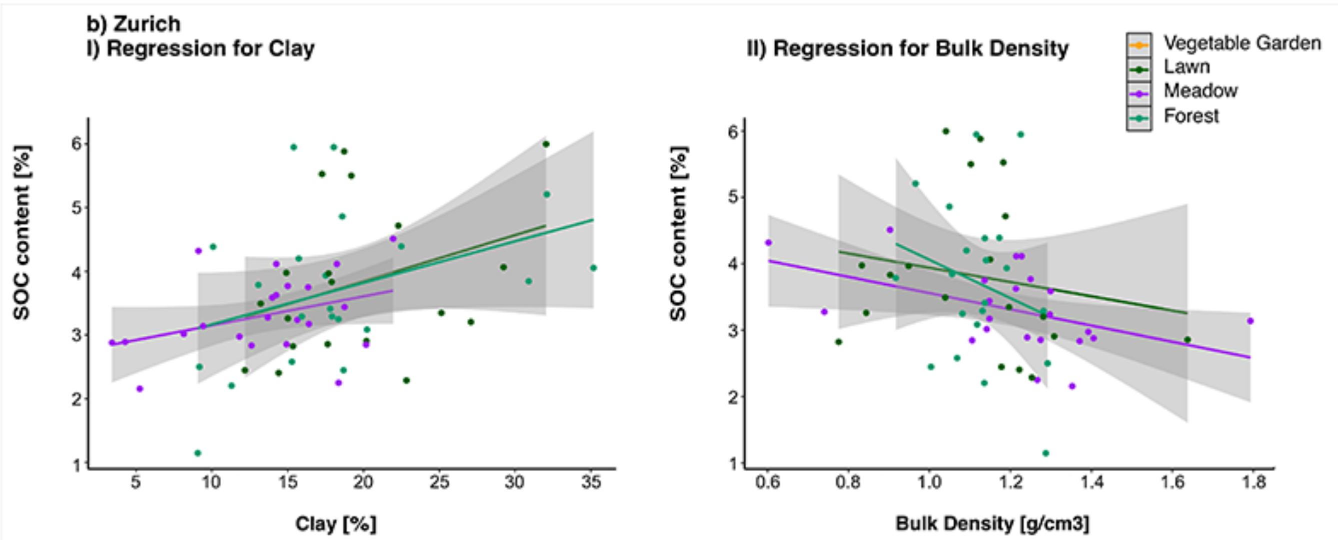
Appendixes



Appendix 1. Lausanne panel I): SOC [%] as a function of the measured silt content [%] grouped by vegetation. Panel II): SOC [%] as a function of the measured bulk density [g/cm3] grouped by vegetation. The regression line of each vegetation type is indicated in different colors. The confidence interval of 0.95 (gray area) forms predictions from a linear model.



Appendix 2. Zurich public green spaces (using a data frame including all public soil samples). Panel I): SOC [%] as a function of the measured clay content [%] grouped by vegetation. Panel II): SOC [%] as a function of the measured bulk density [g/cm3] grouped by vegetation. The regression line of each vegetation type is indicated in different colors. The confidence interval of 0.95 (gray area) forms predictions from a linear model.

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