



HAL
open science

Selection of soil health indicators for modelling soil functions to promote smart urban planning

Geoffroy Séré, Cécile Le Guern, Antonio Bispo, Clement Layet, Christophe Ducommun, Margaux Clesse, Christophe Schwartz, Laure Vidal Beaudet

► To cite this version:

Geoffroy Séré, Cécile Le Guern, Antonio Bispo, Clement Layet, Christophe Ducommun, et al.. Selection of soil health indicators for modelling soil functions to promote smart urban planning. *Science of the Total Environment*, 2024, 924, pp.171347. 10.1016/j.scitotenv.2024.171347 . hal-04508578

HAL Id: hal-04508578

<https://brgm.hal.science/hal-04508578v1>

Submitted on 28 Jun 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Copyright

Selection and test of soil health indicators to promote smart urban planning

Geoffroy SERE^a, Cécile LE GUERN^{b,e*}, Antonio BISPO^c, Clément LAYET^a, Christophe DUCOMMUN^{d,e}, Margaux CLESSE^a, Christophe SCHWARTZ^a, Laure VIDAL-BEAUDET^{d,e}

^a Université de Lorraine, INRAE, LSE, F-54000 Nancy, France

^b BRGM, 44000, Nantes, France

^c INRAE, Info&Sols, 45000, Orléans, France

^d Institut Agro, EPHOR, 49000, Angers, France

^e IRSTV, Nantes, France

*corresponding author: c.leguern@brgm.fr

KEYWORDS

soil functions, soil indicators, ecosystem services, urban soils

1 ABSTRACT

2 The contribution of soil health to global health receives a growing interest, especially in urban
3 environment. Therefore, there is a true need to develop methods to evaluate soil functioning and
4 assess the ecosystem services that could be provided by urban soils in order to promote smart urban
5 planning. This work first aims at identifying relevant soil indicators based either on in situ description,
6 in situ measurement or lab analysis. Then, 9 soil functions and sub-functions were selected to meet
7 the main expectations regarding soil health in urban contexts. A crucial step of the present research
8 was then to select adequate indicators for each soil function and then to create adapted reference
9 frameworks - in the form of 4 classes, i.e. scores ranging from 0 to 3 - to score soil functions. All the
10 reference frameworks were developed to evaluate soil indicators in order to score soil functions either
11 by using existing scientific or technical standards or references or based on the expertise of the co-
12 authors. Our model was later tested on an original database of 109 contrasted urban soils located in 7
13 cities of Western Europe and under various actual land uses. The scores calculated for 9 soil functions
14 of 109 soils followed a Gaussian distribution. The scoring successfully expressed the strong contrasts
15 between the various soils; the lowest scores were calculated for sealed soils and soils located in urban

16 brownfields whereas the highest were found for soils located in city parks or urban agriculture. Despite
17 requiring a soil expertise, the proposed approach is easy to implement and could help reveal their true
18 potential of urban soils in order to promote smart urban planning and enhance their contribution to
19 global health.

20 **1. Introduction**

21 What is soil health? Is it just a good way to communicate about the importance of considering soil or
22 is it a useful concept that can be used for assessing soils (Powlson, 2020)? Several definitions of soil
23 health were proposed as exposed by Janzen et al. (2021). As an example, Lehmann et al. (2020) saw
24 soil health as being an overarching concept including soil fertility and soil quality, encompassing a
25 broad range of ecosystem functions, services and actors. Faber et al. (2022) proposed soil health to be
26 seen as the current condition of the soil compared to its potential (called soil quality) depending on its
27 composition, climate and land use. In this latter definition, soil health is measured and compared to a
28 potential as for Human beings where illness will reduce your well-being. Finally, the recent EU proposal
29 for a directive on soil monitoring and resilience (EC, 2023) proposed to define soil health as the
30 physical, chemical and biological condition of the soil determining its capacity to function as a vital
31 living system and to provide ecosystem services. They also propose to use soil descriptors *i.e.*
32 parameters describing a physical, chemical, or biological characteristic of soil health. In fact, whatever
33 the definition, due to soil complexity a panel of descriptors or indicators are needed to understand soil
34 functioning and assess all ecosystem services delivered.

35 Soil health indicators have multiple aims (Jaenicke, 1998; Herrick, 2000): (1) establishing relationships
36 between the actual state of a soil and its soil functions; (2) expressing changes in soil state, as a function
37 of environmental changes and management; (3) assessing the potential resistance and resilience of a
38 soil in response to disturbance regimes; (4) for land managers, optimizing the choice of actual and
39 future land use as a function of soil health; (5) evaluating the contribution of a soil to ecosystem
40 functions at a wider level. Apart from meeting the previous aims, their ease of measurement and cost-
41 effectiveness are also expected (Dale and Beyeler, 2001).

42 The essential soil properties that express the state of the soil are: (1) physical (*e.g.*, solid density, soil
43 structure), (2) chemical (*e.g.*, cation exchange capacity, pH), and (3) biological (*e.g.*, soil enzymes,
44 respiration) (Lal, 2016). A distinction can be performed between inherent (*e.g.* soil depth) and
45 manageable (*e.g.*, bulk density, nitrogen content) properties but also considering their evolution
46 kinetics, from static (*e.g.*, soil texture) to dynamic or rapidly changing (*e.g.*, soil temperature)
47 properties; however, such considerations are not absolute and strongly context-dependent (Schwilch
48 et al., 2016).

49 In reviews about soil health or soil quality indicators, Zornoza et al. (2015), Bünemann et al. (2018),
50 Faber et al. (2022) and Gatica-Saavedra et al. (2023) found that the most used properties were
51 chemical (soil organic carbon content, pH, available P and K, total N, electrical conductivity, cation
52 exchange capacity, and mineral N, in order of occurrence), followed by physical (water storage, bulk
53 density, soil texture, structural stability and soil depth, in order of occurrence) whereas biological are
54 less common (soil respiration, microbial biomass, invertebrate diversity and/or abundance, in order of
55 occurrence). The number and nature of soil health indicators is correlated with the cost and time
56 required to perform the diagnosis, but can also increase collinearity as well as the complexity of the
57 relationships between indicators (O'Sullivan et al., 2017; Bünemann et al., 2018). As a consequence,
58 the standard approach is to seek for a minimum dataset that can still enable policy-making and policy
59 implementation (Stone et al., 2016). However, it is highly difficult to reach a small set of indicators due
60 to the complexity of soil biota and functions (Bispo et al., 2009, Faber et al., 2022).

61 At last, as mentioned by Bünemann et al. (2018): “An indicator is only useful if its value can be
62 unequivocally interpreted and reference values are available”. It is essential to associate a reference
63 framework to each soil property considering each soil function (Séré et al., *under review*). Indeed, a
64 given soil property (*e.g.*, soil texture) could be interpreted differently considering one soil function –
65 water infiltration – or the other – water retention -.

66 As highlighted by recent regulations in Europe and worldwide, the multifunctionality of soils and their
67 capacity to deliver ecosystem services to societies are of increasing importance to land planners and
68 decision-makers. These services need to be estimated and visualised at relevant scales in order to
69 improve their consideration in land planning decisions. Whereas there is increasing evidence that the
70 improvement of ecosystem services increases the quality of life in cities (Tardieu et al., 2021), the
71 contribution of urban soils remains strongly underestimated. Urban soils exhibit a large diversity of
72 properties but are dominantly perceived as degraded by stakeholders (Blanchart et al., 2018b). As a
73 consequence, their potentials are not taken into account in urban planning even though they can
74 deliver a range of ecosystem services (Blanchart et al., 2018a). Hyun et al. (2022) notably developed a
75 set of indicators to express the soil quality of metropolitan cities and develop a novel urban soil quality
76 index.

77 Our goal is to develop a method to reveal the true and poorly known potential of urban soils in order
78 to promote smart urban planning and enhance their contribution to global health. Such a method relies
79 on the creation of an integrated model to assess soil functions provided by urban soils. This paper
80 starts with the identification and then the selection of bio-physico-chemical soil properties that meet
81 the expected criteria: easy to implement, cost-effective and adequate to fulfil the expectations related
82 to urban planning and regarding soil health. Then, an architecture was developed that connects soil
83 indicators to expert-based reference frameworks that lead to an evaluation of the relevant soil
84 functions. R code (R Core Team, 2023) was created to score and compare the soils in order to enlighten
85 their actual and future potential in terms of land use and management. At last, it was tested on a
86 variety of 109 urban soils across Western Europe.

87 **2. Materials & Methods**

88 *2.1. Urban soils' database*

89 Our urban soils' database consists of 109 soil pits. They are all located in urban or peri-urban areas in
90 the following cities of France (FR) Switzerland (SW) and Spain (SP): FR-Angers (4 soils), SW-Lausanne
91 (5 soils), FR-Marseille (16 soils), FR-Nancy (25 soils), FR-Nantes (21 soils), FR-Paris and peri-urban area

92 (23 soils), FR-Rennes (2 soils), SP-Santiago de Compostela (13 soils). The corresponding climates of all
93 locations are: i) Angers, Nantes, Rennes, Santiago de Compostela: Temperate oceanic climate; ii)
94 Lausanne, Nancy, Paris: Temperate semi-continental climate; iii) Marseille: Temperate Mediterranean
95 climate.

96 The 109 soils that were observed, described, sampled and analysed had different land uses that were
97 classified into 5 contrasted classes: city parks (20 soils), sealed soils (12 soils), sites under development
98 (38 soils), urban agriculture (16 soils), and urban brownfields (23 soils).

99 To create such a large and original database, some data were acquired in the frame of the Ademe-
100 SUPRA project but were also gathered from other research projects. As a consequence, not all the
101 parameters that are required in our model were available. Overall, there was 21% of missing data that
102 did not limit the scoring of soil functions but still influenced the quality of the evaluation. Most of the
103 missing data concerned soil contamination (81% of missing data). On the opposite, there was only 2%
104 of missing data regarding water retention and nutrient retention.

105 2.2. *Workshop organization*

106 A group of 5 urban and agricultural soil experts gathered a dozen times over 2 years in a workshop
107 format to work on the architecture of the model. As proposed by Faber et al. (2022), we developed a
108 top-down approach in order to: i) select the main ecosystem services to be delivered by urban soil, ii)
109 identify the underlying soil functions, ii) review the parameters and indicators linked to each function
110 and iv) then discuss and agree on the reference frameworks to establish and interpret each result
111 (Table 1). The indicators linked to the different functions were first listed collectively. For each
112 function, a pair of experts was then appointed as responsible for providing, for each indicator linked
113 to the targeted function, the selection criteria and its reference framework. The pairs' proposals were
114 then discussed during workshops. The selection was made iteratively as the model was constructed.

115 2.3. *List of soil functions and indicators based on literature survey*

116 To define a minimum set of indicators to be studied, the selection work was based on three elements:
117 (1) the experience of the scientists involved in the research program, (2) the work of three PhDs
118 associated with the project (Blanchart 2018; Cambou 2018; Sauvaget 2019), and (3) the search for
119 state indicators or assessment tools available in the literature for urban soils. In three studies (Urban
120 SMS, Vrščaj et al., 2008; UQualisol-ZU, 2012; ENVASSO¹), the indicator classification categories
121 concerned general soil information and parameters of physical, chemical and biological soil properties.
122 Contamination elements were treated separately. For our program/research project, the selected
123 indicators had to satisfy three ecosystem services retained: biomass provisioning, global climate
124 regulation (via carbon storage) and anthropic stress regulation. To inform these services, several
125 functions have been identified, along with an initial list of the principal indicators required to
126 adequately reflect the functions. Thus, six main functions have been selected to reflect soil quality and
127 inform on the 3 ecosystem services. Certain functions have been divided into sub-functions in order to
128 take into account the different possibilities associated with a given function.

- 129 • Function “1 - Storage, recycling and transformation of organic matter” named “Organic matter
130 cycle” reflects the soil's capacity to store carbon, based mainly on physical parameters. A good
131 storage capacity will enable the development of the organic matter recycling function, which
132 will depend mainly on biological activity (see function 5 - Biodiversity support) and
133 environmental conditions (e.g. presence of water, temperature).
- 134 • Function “2 - Retention and supply of nutrients (decomposition of organic matter)” named
135 “Nutrient cycle” provides information on the soil's capacity to supply plants, via their root
136 systems, as well as soil organisms, with the nutrients required for their metabolic activity and
137 development. Three sub-functions were listed: “2.1 Nutrient storage”, “2.2 Nutrient retention
138 capacity” and “2.3 Nutrient recycling”.

¹ <https://esdac.jrc.ec.europa.eu/projects/envasso>

- 139 • Function “3 - Physical support – habitat” named “vegetation support” reflects the soil's
140 capacity to provide physical support for vegetation, as well as a habitat for biodiversity. For
141 plants, the soil must anchor their roots and enable them to develop harmoniously without
142 mechanical or physical constraints.
- 143 • Function “4 - Water retention, circulation and infiltration” named “Water cycle” reflects, on
144 the one hand, the soil's capacity to retain useful water within its porosity (notion of useful
145 reserve) and, on the other, the soil's contribution to water infiltration (particularly rainwater),
146 as opposed to runoff. This function is therefore linked to the ecosystem services of biomass
147 supply (via physical fertility) and flood regulation. Two sub-functions were listed: “4.1 Water
148 retention capacity” and “4.2 Water infiltration” in surface and along the profile.
- 149 • Function “5 - Biodiversity support” reflects the soil's capacity to support biodiversity. The
150 indicators selected aim to qualify the presence and activity of different biological groups.
- 151 • Function “6 - Contaminant retention, filtration and degradation” named “Contaminant cycle”
152 reflects the soil's capacity to cope with contaminants. The indicators selected aim to qualify
153 the presence or stock of contaminants, bearing in mind that their subsequent fate (infiltration,
154 transfer, sorption, degradation, etc.) will depend in particular on biological activity (see
155 function 5 - Biodiversity) and environmental conditions (e.g. flow properties, presence of
156 water, vegetation, temperature). These elements have not been developed here, because if
157 contaminants are found to be present, specific studies will have to be carried out to verify their
158 compatibility with use. Thus, for this function, only stocks have been considered.

159

160 The set of indicators has been exhaustively listed to describe the selected functions of the soil (Table
161 1). As we wanted our approach to be used directly on the field, when doing the investigations, we also
162 defined not only indicators measured with laboratory equipment but also *in situ* ones, using sensitive
163 observations as for colour, texture, structure.

164

Table 1: Links between the services, the functions associated and the indicators considered essential to reflect soil health. Indicators are separated between *in situ* determination or measurement and laboratory measurement or analysis.

Service	Functions	<i>In situ</i> indicators	Laboratory indicators
Global climate regulation	Organic matter cycle	Soil depth	Horizon organic matter / total organic carbon Horizon textural class Horizon Bulk density
		Horizon color Horizon structure Horizon texture Horizon coarse element content	
Biomass provisioning	Nutrient cycle		Horizon organic matter / total organic carbon Horizon organic matter fractions Horizon Electrical conductivity, Horizon CEC, C _{tot} , N _{tot} , C/N, pH, CaCO ₃ , P _{Olsen} , Ca, K, Mg, Mn, Na, Al, Fe, Horizon active limestone Horizon microbial / fungal biomass Horizon enzymatic activities
		Vegetation support Biodiversity support	Soil depth Topography Horizon structure Horizon texture Horizon Hydromorphy Surface condition: % sealing, % vegetation cover Root depth Presence of engineering fauna Earthworm density
	Water cycle		Soil depth Hydromorphy depth Horizon coarse element content Horizon texture Surface condition: % sealing, % vegetation cover, % slope Presence of engineering fauna Earthworm density
		Water cycle	See above
Anthropic stress regulation	Contaminant cycle		Horizon diversity of biological communities Ecotoxicological effects
		Land use history Total traces elements	Horizon Traces elements (TE = Sb, As, Ba, Cd, Cr, Co, Cu, Hg, Mo, Ni, Pb, Se, Ti, Zn), Horizon Total organic pollutants (TOP = 16 PAH, 7 PCB _i , hydrocarbons C10-C40, VOP), Horizon clay content Horizon TOC Horizon Electrical conductivity, CEC, C _{tot} , N _{tot} , pH, CaCO ₃ , P _{Olsen} , Ca, K, Mg, Mn, Na, Al, Fe, Horizon microbial/fungal biomass Horizon enzymatic activities

CEC = Cation Exchange Capacity ; TOP = Total Organic Pollutants ; PAH = polycyclic aromatic hydrocarbons ; PCB_i = polychlorobiphenyls indicators; VOP = Volatil Organic Pollutants ; TOC = Total Organic Carbon

165 2.4. Method for indicators selection and soil functions scoring

166 The set of indicators to be selected must make it possible to define a list that combines both rapid,
167 reliable and operational field observations/measurements and laboratory measurements or analyses.

168 To define the set of indicators, the method used consisted in selecting the most relevant indicators
169 based on various criteria: (1) usefulness of the indicators for assessing the functions and services
170 selected, (2) complexity of assessment or measurement, and cost of acquisition, (3) significance of
171 selected indicators vs. operability for planners and stakeholders and (4) interactions between
172 indicators. Moreover, as far as possible, indicators should be evaluated using value-range reference
173 systems, and their acquisition should be based on well-defined measurement standards.

174 For each indicator and each function, four value classes have been defined in order to assign it a score
175 ranging from 3 (being a favourable situation) to 0 (being the most unfavourable one). The choice of
176 value classes was based on literature data and/or expert opinion within the 5-person working group
177 (cf.§2.2). A score was given either for the surface (e.g. slope, vegetation cover), for the soil profile (e.g.
178 soil depth, earthworm density) or for a horizon. For each rated soil horizon, the notation value was
179 weighted by its thickness relative to the total soil depth. This means that some of the values assigned
180 to an indicator may be not integer values.

181 A confidence index (CI) and a relevance index (RI) have been assigned to each indicator according to
182 the concordance of the information sources used: (3) several concordances references, (2) several non-
183 concordant references and expert opinion, (1) a single reference and expert opinion and (0) no
184 reference.

185 The scoring method by function was based on the same aggregation principle as that developed in
186 Destisol (Séré *et al.*, *under review*). It involved taking an arithmetic average of the function indicators
187 and associating with it the notion of downgrading indicators. We developed the hypothesis that low
188 scores on certain indicators could strongly constrain soil functioning. This latter concept was preferred
189 to that of indicator weighting, which remained complex to establish. For example, for the "infiltration

190 (vertical vs. runoff)” function, we considered the “presence of surface crust” and “texture” indicators
191 to be “downgrading”. This means that if one of these indicators has a score of 0, whatever the values
192 of the other indicators, the function score will also be zero.

193 At the end, all 9 soil functions and sub-functions have been scored individually and their mean value
194 and sum could also be calculated to assess soil health.

195

196 *2.5. Coding of the model*

197 The set of indicators was transcribed in an R programm, via an Rstudio interface. The code aimed to
198 make the indicator evaluation as accessible as possible for non R users, and to make easier any
199 modification of valuation rules. Information on the different physicochemical properties came from a
200 single Excel file, filled in by the different users. Output Excel files included scores of different indicators
201 for each soil, and an indication of the quality of the scores obtained, according to the status of the
202 various values given in the database: measured, estimated, or missing. The given proportion of missing
203 values was essential to moderate the quality of the information, and possibly consider the need for
204 new measurements to enrich the database. The current R program and input files will be later
205 published.

206 **3. Results**

207 *3.1. Selection of indicators in relation to soil functions*

208 Table 2 shows the list of 29 indicators - evaluated or measured *in situ* or in the laboratory - that were
209 selected among the 60 previously listed in Table 1. The selection was based on: their relevancy towards
210 soil functions, the availability of stabilized methods (standardized if possible) and an existing reference
211 framework. Operational and economical issues were also considered. Table 2 also shows the level of
212 expertise required for data acquisition and the average cost.

213 Some soil indicators are used for estimating several functions or subfunctions. For example, soil texture
214 is used in 6 functions or subfunctions, and bulk density in 4 of them. Some indicators are used in two
215 functions or subfunctions like organic C. The other ones are used in only one function or subfunction.
216 This is the case for instance of the diversity of soil biological communities.

Horizon TOC	measurement/	medium	++	x		x		
Horizon total nitrogen	analysis	medium	++		x			
Horizon C/N ratio		medium	++				x	
Horizon CEC		medium	++			x		x
Horizon P _{0lsen}		medium	++		x			x
Horizon total and active CaCO ₃		easy	++			x		x
Horizon microbial DNA		expert	+++				x	x
Horizon enzymatic activity		expert	+++				x	x

TOC = Total Organic Carbon ; CEC = Cation Exchange Capacity ; DNA = deoxyribonucleic acid

217 3.2. *Creation of reference frameworks for soil indicators to score soil functions*

218 Indicators were described in different tables according to the type of acquisition: *in situ* (table 3), *in*
219 *situ* and/or in the laboratory (table 4) and only in the laboratory (table 5). For each indicator, the
220 function(s) concerned were specified. The observation type or sampling zone were then indicated: on
221 the soil surface, on the entire soil profile or in each horizon. A unit of qualification or quantification
222 was associated with each indicator. Then, the construction of reference frameworks had been
223 performed. It consisted in the definition of upper and lower boundaries in 4 distinct classes for all soil
224 indicators in all functions and sub-functions. It has to be noted that, for the same soil indicator,
225 different reference frameworks could have been developed, depending on the functions or sub-
226 functions considered. For example, "Coarse element content" (table 4) was used to score 6 functions
227 or sub-functions, and required 3 different reference frameworks to score them. This indicator could
228 have opposite scores for the same reference: "lower bound >40" = 0 or 3 for functions 1 - 4.1 and
229 function 4.2 respectively.

230 When reference frameworks for some given soil indicators were available, their origins were specified
231 in tables 3, 4 and 5. In Tables 4 and 5, which correspond to indicators measured or analysed in the
232 laboratory, standards were also indicated when available.

233 The fact that the indicator was possibly downgraded in terms of soil function was also specified. There
234 were no degrading indicators for functions 1 (Organic matter cycle), 2 (Nutrient cycle), 5 (Biodiversity
235 support). For function 3 (Vegetation support), only the "soil depth" indicator, with a value of less than
236 25 cm, was considered as downgrading. For sub-function 4.2 (Water infiltration), several indicators
237 were downgraded because they did not enable the desired function to be fulfilled: (1) "surface
238 situation" with a highly impermeable surface that favours runoff and not vertical infiltration, (2)
239 "Horizon texture" for which the high clay content limits macroporosity and water infiltration and (3)
240 "Coarse element content" with a volume value of less than 5% does not favour water penetration into
241 the soil. And finally, for function 6 (Contaminant cycle), several indicators were considered prohibitive

242 for the use of a site: (1) "Land use history", which may reveal a past that is certain to induce pollution
243 *in situ*, (2) "Smell", which is a characteristic indicator of the presence of certain pollutants, (3) "Horizon
244 trace element" when values exceed authorized thresholds and (4) "Horizon trace organic pollutants"
245 when values exceed authorized thresholds.

246 For each soil indicator, the confidence and relevance indexes were estimated (Tables 3, 4 and 5). The
247 confidence index (CI) values of all the indicators were good and all between 2 and 3. For the relevance
248 index (RI), the values were also between 2 and 3 except for the "Barber pot" indicator which had a
249 value of 1 (Table 3). Indeed, this indicator required specific skills for soil macro and mesofauna
250 identification. There is a strong operator effect in the determination of species which makes this
251 indicator more sensitive to use and more variable.

252

Table 3: List of indicators to be described or measured directly in situ for the concerned functions (function 1 = organic carbon cycle; function 2.1 = nutrient storage, function 2.2 = nutrient retention capacity, function 2.3 = nutrient recycling; function 3 = Vegetation support; function 4.1 = water retention capacity, function 4.2 = water infiltration; function 5 = biodiversity support; function 6 = contaminant support). The rules of notation are defined between 0 and 3 (0 = bad value and 3 = good value). For each indicator, confidence index (CI) and relevance index (RI) are defined between 0 and 3 (0 = bad value and 3 = good value). References are given when available, if not expertise is required.

Indicator	Function ID	Situation	Unit	Score	Rule	Lower Boundary	Upper Boundary	Down-grading factor	CI	RI	Reference	
Land use history	6	surface	Description	0	or	Potential source of pollution with high impact	Confirmed pollution	YES	2	3	Le Guern et al. 2018b	
				1	or	Residual pollution not compatible with sensitive use	Potential source of pollution with medium impact					
				2	or	Residual pollution compatible with sensitive use	Potential source of pollution with low impact					
				3	or	No source of potential contamination	No pollution verified					
Slope	4.2	surface	%	0	>	15		NO	3	3	Laubier 2001 ; Auroousseau et al. 1998	
				1	between	5	15					
				2	between	2	5					
				3	between	0	2					
Surface Situation % sealing % vegetation cover	3, 4.2	surface	Description	0	=	Battance crust or sedimentary crust		YES function 4.2	3	3	Le Bissonnais et al. 2003	
				1	=	Massive clay or structural crust >70%						
				2	=	Equilibrate texture and medium structure and structural crust < 70%						
	5	surface	Description	3	=	Sandy or no crust		NO	2	3	Expertise	
				0	or	Bare soil	Sealed soil					
				1	=	Spare vegetation						
Soil depth	1	pit	cm	2	or	Cultivation	Meadow	NO	2	3	Expertise	
				1	=	Dense vegetation						
				3	=							
	2.1, 3, 4.1	pit	cm	0	<		10	NO	3	3	Expertise: carbon storage hypothesis down to 50 cm	
				1	between	10	50					
				2	between	50	100					
Hydromorphy depth	2.3, 4.2	pit or auger	Description	0	<	25		NO	2	2	Expertise	
				1	between	25	60					
				2	>	60						
	3	=	Absence		0	=	light grey/white/white	1	NO	3	3	Munsell code read vertically
					1	=	brown to light red brown	2				
					2	=	brown to dark red brown	3 or 4				
3	=	very dark/blackish		3	=		6 or 8					

Horizon structure	1, 2.2, 2.3, 3, 4.1	pit	Description	0	or	compact or lamellar or columnar (5-15 cm) or columnar/prismatic (>15cm)	NO	3	3	Schoeneberger et al, 2012 Expertise	
				1	=	structureless					
				2	or	coarse crumbly or polyhedral (2-5 cm)					
				3	or	fine crumbly or polyhedral (< 2 cm)					
Horizon structure	5	pit	Description	0	or	compact or lamellar (5-15 cm)	NO	3	2	Schoeneberger et al, 2012 Expertise	
				1	=	structureless (<0.2 cm) or columnar/prismatic (>15cm)					
				2	or	fine polyhedral (< 2 cm)					coarse polyhedral (2-5 cm)
				3	or	fine crumbly (< 2 cm)					coarse crumbly (<2 cm)
Presence of artefacts	6	pit or auger	Description	0	=	T4 = asphalt, bitumen, tar, coal	NO	3	3	Le Guern et al, 2016, 2017, 2018a	
				1	=	T0.5 = Micaschists and other rocks susceptible to natural trace element anomalies					T4a = wood coal
				2	=	T3 = rubble, bricks, concrete, plaster, paving stones, blocks, building demolition					T3 = slate, ceramics, glass
				3	=	pedological materials					low geochemical background rock
Color of artefacts	6	pit or auger	Description	0	=	violet, burgundy, blue (Prussian blue)	NO	3	3	Le Guern et al, 2016, 2017, 2018a Expertise	
				1	=	black (not peat)					
				2	=	orange, rust, grey dark					
				3	=	other					
Smell	6	pit or auger	Description	0	or	Strong hydrocarbon or bitter almond or solvent	YES	2	3	Expertise	
				1	or	Moderate hydrocarbon or bitter almond or solvent					
				2	or	Light hydrocarbons or bitter almond or solvent or sulfur or H ₂ S					
				3	or	No or mud or peat or organic matter or iron					
Root depth	2.3	pit	cm	0	<	25	NO	2	3	Expertise	
				1	between	25					50
				2	between	50					100
				3	>	100					
Presence of engineering fauna	2.3, 5	pit	Description	0	=	no	NO	3	3	Expertise	
				1	=	low					
				2	=	medium					
				3	=	high					
Barber pot	5	surface	group number	0	=	0	NO	3	1	Expertise	
				1	between	0					2
				2	between	2					10
				3	>	10					
Earthworm density	5	surface	number m ⁻²	0	<	25	NO	3	2	French national observatory of biodiversity	
				1	between	50					150
				2	between	150					300
				3	>	300					

Table 4: List of indicators to be described or measured in situ and measured or analysed in laboratory for the concerned functions (function 1 = organic carbon cycle; function 2.1 = nutrient storage, function 2.2 = nutrient retention capacity, function 2.3 = nutrient recycling; function 3 = Vegetation support; function 4.1 = water retention capacity, function 4.2 = water infiltration; function 5 = biodiversity support; function 6 = contaminant support). The rules of notation are defined between 0 and 3 (0 = bad value and 3 = good value). For each indicator, confidence index (CI) and relevance index (RI) are defined between 0 and 3 (0 = bad value and 3 = good value). Standards and references are given when available, if not expertise is required.

Indicator	Function ID	Situation	Unit	Score	Rule	Lower Boundary	Upper Boundary	Down-grading factor	CI	RI	Standard	Reference							
Horizon texture Horizon textural class	1	Pit	Description or $g\ kg^{-1}$	0	=	sandy			NO	3	3	NF EN ISO 17892-4	Duchaufour 1997 Expertise						
				1	=	loamy													
				2	=	balanced													
	2.2, 2.3, 3			0	=	sandy			NO										
				1	=	loamy													
				2	=	clayey													
	4.1			0	=	sandy			NO										
				1	=	clayey													
				2	=	loamy													
	4.2			0	=	clayey			YES										
				1	=	loamy													
				2	=	balanced													
	Coarse element content			1, 4.1	Pit	Description or % vol	0	>	40						NO	3	3	NF EN ISO 17892-4	GEPPA 1981
							1	between	20					40					
							2	between	10					20					
2.1, 2.2, 3		0	<	10				NO											
		1	<	50															
		1	between	30			50												
4.2		2	between	15			30	YES											
		3	>	15															
		0	<	0			5												
2.1		1	between	5			10	3											
		2	between	10			20												
		3	>	40															
Horizon electrical conductivity		2.1	pit or auger	$\mu S\ cm^{-1}$			0	>	2000		NO	3	3	NF ISO 11265	Durand 1983				
							1	between	1000	2000									
							2	between	500	1000									
	3				<	500													
Horizon water pH	2.1, 2.2,	pit or		0	< or >	5.5	8.5	NO	3	3	NF ISO	GEPPA 1981							

Horizon total organic carbon (COT)	1, 2.2	pit or auger	g 100g ⁻¹	0	<	1.2	NO	3	3	NF ISO 10694	Expertise	
				1	between	1.2						3.5
				2	between	3.5						5.8
				3	>	5.8						
Horizon total Nitrogen (N _{tot})	2.1	pit or auger	g kg ⁻¹	0	<		NO	3	3	NF ISO 11261	Expertise	
				1	between	2						10
				2	>							20
				3	between	10						20
Horizon C/N (COT/ N _{tot})	2.3	pit or auger		0	>	20	NO	3	3		Expertise	
				1	<	8						
				2	between	12						20
				3	between	8						12
Horizon Cationic exchange capacity (CEC)	2.2	pit or auger	cmol kg ⁻¹	0	<	8	NO	3	3	NF X31-130	Expertise	
				1	between	8						15
				2	between	15						25
				3	>	25						
Horizon P _{0.25m}	2.1	pit or auger	g kg ⁻¹	0	<	0.04	NO	2	2	NF ISO 11263	Expertise	
				1	between	0.04						0.06
				2	>	0.10						
				3	between	0.06						0.10
Horizon active CaCO ₃	2.2	pit or auger	g kg ⁻¹	0	>	250	NO	3	3	NF X31-106	GEPPA 1981	
				1	between	150						250
				2	between	70						150
				3	<	70						
Horizon microbial DNA	5	pit or auger	µg g ⁻¹	0	<	10	NO	3	2	NF EN ISO 11063	Horrigue et al., 2016 Dequiedt et al., 2011 Terrat et al., 2017 Karimi et al., 2018	
				1	between	10						50
				2	between	50						100
				3	>	100						
Horizon enzymatic activity Arylamidase	5	pit or auger	nmol min ⁻¹ g ⁻¹	0	<	3.1	NO	3	2	NF EN ISO 20130	Arvalis et al., 2022	
				1	between	3.1						5.2
				2	between	5.2						7.1
				3	between	7.1						13.7
Horizon enzymatic activity β-D-Glucosidase	5	pit or auger	nmol min ⁻¹ g ⁻¹	0	<	12.6	NO	3	2	NF EN ISO 20130	Arvalis et al., 2022	
				1	between	12.6						18.6
				2	between	18.6						23.4
				3	between	23.4						54.5

253 The total number of indicators used to assess the functions or sub-functions ranged from 5 (Function
254 4.1 Water retention capacity) to 13 (Function 6 Contaminant cycle) (Table 2). Six functions (Function 1
255 Organic matter cycle, Function 2.1 Nutrient storage, Function 2.3 Nutrient recycling, Function 3
256 Vegetation support, Function 4.1 Water retention capacity, Function 4.2 Water infiltration) would
257 require a low number of indicators - 5 to 7 - which are often indicators that are easy to describe or
258 measure (Table 2). Functions linked to biomass provisioning (*i.e.* sub-functions 2 that express nutrients
259 storage, retention capacity and recycling, function 3 that expresses roots anchorage and sub-function
260 4.1 that expresses water retention for plants) integrated all soil indicators linked to plant growth
261 including the soil structure and depth for roots development, the access to water and nutrients and
262 the presence of soil organisms and their activity. Function 2.2 (Nutrient retention capacity) required
263 the determination of 9 indicators, 7 of which were determined in the laboratory. However, these
264 indicators are measured or analysed routinely and do not require specialist expertise.

265 Function 5 “Biodiversity support” was assessed by 8 indicators, 5 of which were determined solely with
266 field observations and determinations as the depth of plant roots, abundance of soil invertebrates
267 (through Barber pot or earthworms counting) and/or the presence of soil engineering fauna through
268 its activity (*e.g.* burrow, casts) were included. At laboratory step, measurements of bacterial amount
269 and activity through respectively DNA quantity assessment and enzymatic activities were also
270 included. Doing so, several groups of organisms were included in our evaluation process that included
271 abundance, diversity and activity and required considerable skill in terms of species identification. Note
272 that all references come from agricultural situations.

273 Function 6 “Contaminant cycle” was the most demanding in terms of the number of indicators (13) to
274 be determined in order to satisfy an appropriate interpretation. This function focused on the stock of
275 contaminants because modelling retention was considered too complex to achieve with a reduced
276 dataset. The potential of degradation was not considered either because it could be derived from the
277 biodiversity index and may be interesting only when organic contaminants are present. Contaminant

278 infiltration was linked to the infiltration capacity of soils which is already considered in the water
279 function.

280 The soil retention capacity of contaminant depended on the contaminant itself and on the presence
281 of organic and mineral bearing phases (like SOM, clay, iron or manganese oxi(hydro)xides), as well as
282 on the physico-chemical properties of soil (pH, Eh, temperature) and humidity. The indicators
283 considered to feed to the soil contaminant stock function help verify if there is a contamination issue
284 or not. Most of them were considered as downgrading factor (Table 3 and Table 4). Land use history
285 must be studied first in the office to verify the presence of any former activity that may have led to
286 point source contamination (e.g. industrial or service activity, mining). Field observation were essential
287 to find out traces of such activity. In case of a contamination issue, a verification of the compatibility
288 between soil quality and the future use is first necessary. In case of incompatibility, either a change of
289 use or the management of the pollution is mandatory. Because anthropogenic deposits are numerous
290 in the urban area, and may be intrinsically contaminated (Le Guern et al, 2018a), attention must be
291 paid to the presence of artefacts. They were classified according to their intrinsic potential of pollution
292 and to their colour (Table 3). Some materials of natural origin may be enriched in trace elements: a
293 special class (T0.5) was set to take this into account. Natural materials in place with a potential natural
294 enrichment in trace element may be described together with this type of anthropogenic deposits.
295 Smell was also an easy parameter to detect some contamination issue (like fuel, solvent or benzene).
296 Finally, the content of trace organic pollutants (TOP) and trace elements (TE) were necessary to verify
297 the level of contamination. Table 6 shows the threshold values selected, based on French references
298 for excavated material management et pedo-geochemical national reference values. The '2xNPGB'
299 threshold value (Table 4) was expected to be replaced as soon as available by LPGB (local pedo-
300 geochemical background) values. Some organic volatile substances were integrated in the list.
301 Attention must be paid to the sampling procedure for such substances.

302

Table 6: Threshold values for contaminants (selected from Coussy et al, 2020; Ademe, 2018; *other sources or expert say), **NPGB: natural pedo-geochemical background, France example). A and C refer to threshold values for each substance, QL for quantification limit.

Total organic pollutant	A	C	QL	Trace elements	NPGB**
C10-40	50	500	15	As	25
Benzene	0,05	0,05	0,05	Ba	150
TEX	1,5	6	0,05	Cd	0.4
Sum16HAP	10	100*	1	Co	20
Sum7PCBi	0,1	1	0,01	Cr	90
COHV_PCE	0,2	1	0,05	Cu	40
COHV_TCE	0,1	1	0,05	Hg	0.1
COHV_DCE	0,1	0,3	0,1	Mo	1.5
COHV_CV	0,1	0,2	0,02	Ni	60
Dioxines_Furannes	2	5*	0,5*	Pb	50
Pesticides	0,1*	2*	0,01*	Sb	1
				Se	1
				Tl	1.2*
				Zn	150

303 3.3. Scores of soil functions

304 Scores have been calculated for 9 soil functions and sub-functions based on the data from the 109 soil
305 pits. Overall, considering all soil functions and all soils, scores were ranging from 0 to 3, the average
306 score being 1.76 ± 0.3 . The distribution of the scores of all functions (981 scores) was of Gaussian-type
307 (Figure 1). The most frequent scores were between 1.5 and 2 (335; 34%), then between 2 and 2.5 (226;
308 23) and between 1 and 1.5 (181; 18.5%). The rarest scores were between 0 and 0.5 (9; 1%), 0 (46; 5%),
309 between 0.5 and 1 (50; 5%), 3 (66; 7%) and between 2.5 and 3 (68; 7%).

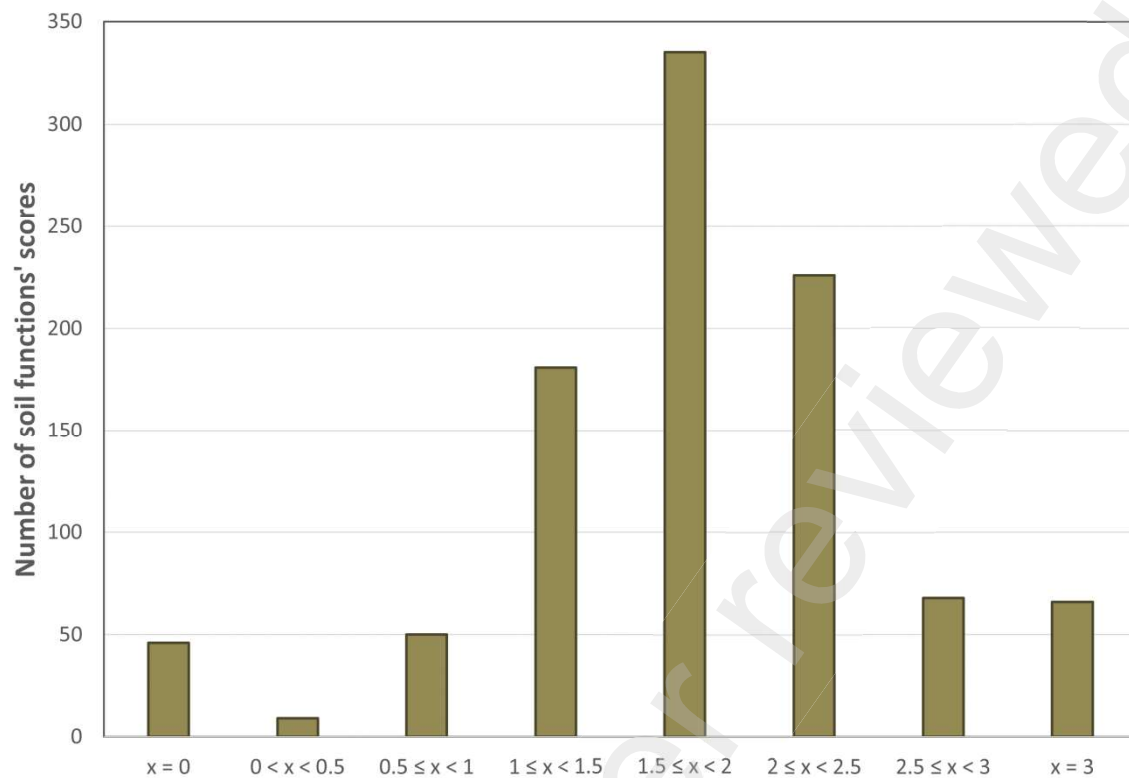


Figure 1. Distribution of the scores of soil functions calculated by SUPRA for the 109 studied soils

310 The function with the highest medium score was “Contaminants cycle” (2.67 ± 0.6) expressing the fact
 311 that a limited number of the studied urban soils exhibited significant contamination. “Nutrient
 312 retention capacity”, “Vegetation support”, “Water retention”, “OM cycle” and “Water infiltration”
 313 were relatively high and almost similar (respectively 1.79 ± 0.39 , 1.78 ± 0.55 , 1.77 ± 0.46 , 1.74 ± 0.28
 314 & 1.68 ± 1.00) (Figure 2). “Nutrient storage” and “Nutrient recycling” scores were slightly above the
 315 average score (respectively 1.56 ± 0.57 & 1.52 ± 0.40). The lowest scores are the one for “Biodiversity”
 316 (1.43 ± 0.61). The highest variations were noted for “Water infiltration”, “Biodiversity”, “Nutrient
 317 storage” and “Vegetation support” (respectively 1, 0.61, 0.57 and 0.51) and the smallest for “Nutrient
 318 retention capacity” (0.39). There were 46 “0” scores, mostly for “Water infiltration” (27 soils) - due to
 319 the presence of multiple sealed soils, “Roots anchorage” and “Nutrient storage” (7 soils each),
 320 “Contaminants cycle” (4 soils) and “Nutrient retention capacity” (1 soils). Almost all the 3 scores were
 321 accounted for “Contaminants cycle” (65) and one for “Water infiltration”.

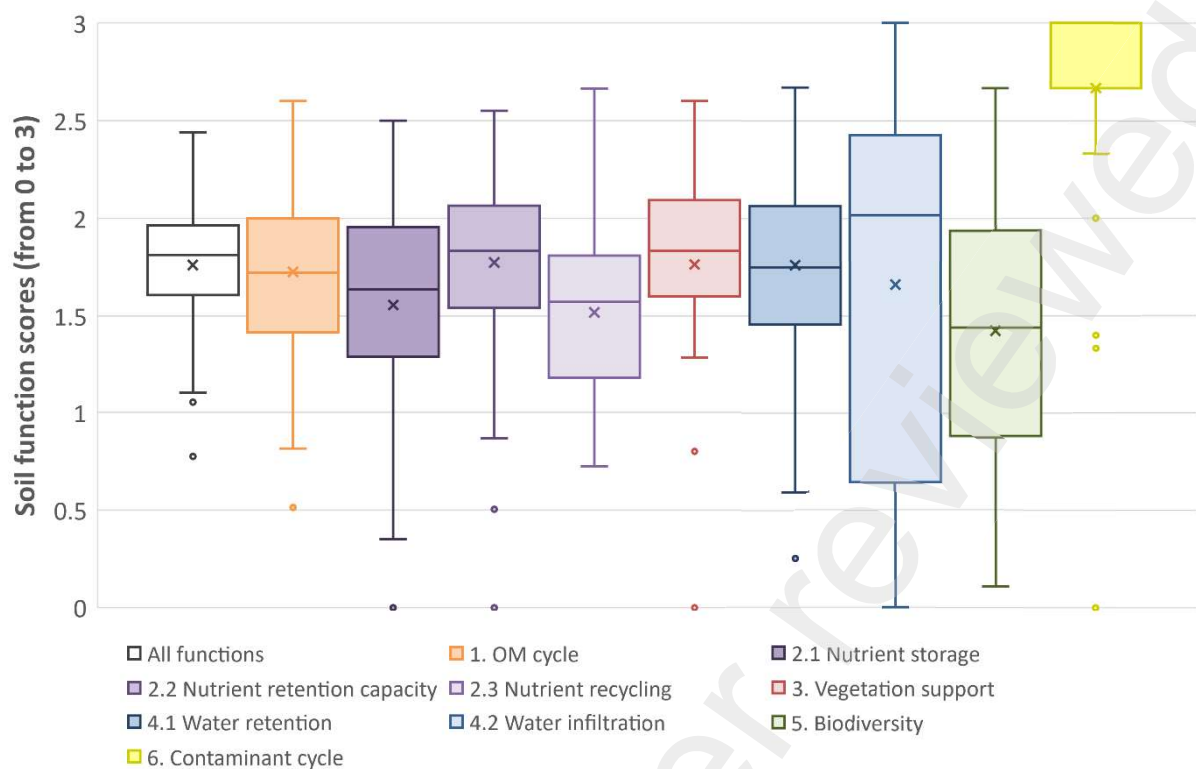


Figure 2. Scores of soil functions calculated by SUPRA for the 109 studied soils sorted by soil functions

322 Considering the mean values and sum of all soil functions' scores (Figure 3), only one soil had a mean
 323 value lower than 1 and a sum of 7/27; this soil appeared to be a very shallow Constructed Technosol
 324 in small wooden boxes dedicated to rooftop urban agriculture (Grard et al., 2017). Seventeen soils had
 325 mean between 1 and 1.5 and sums of soil functions between 10 and 13/27; there were mainly sealed
 326 soils and urban brownfields. Sixty-eight soils had mean scores between 1.5 and 2 and sums of soil
 327 functions between 14 and 17/27; they were very various soils but with a dominance of soils sampled
 328 during urban development projects. Twenty-three soils had mean scores between 2 and 2.5 and sums
 329 of soil functions between 18 and 22/27; they were all located in city parks. Surprisingly, the soil with
 330 the higher score (mean value of 2.44 and sum of 22/27) is a spontaneously revegetated urban
 331 brownfield located in Marseille that was left over for many years.

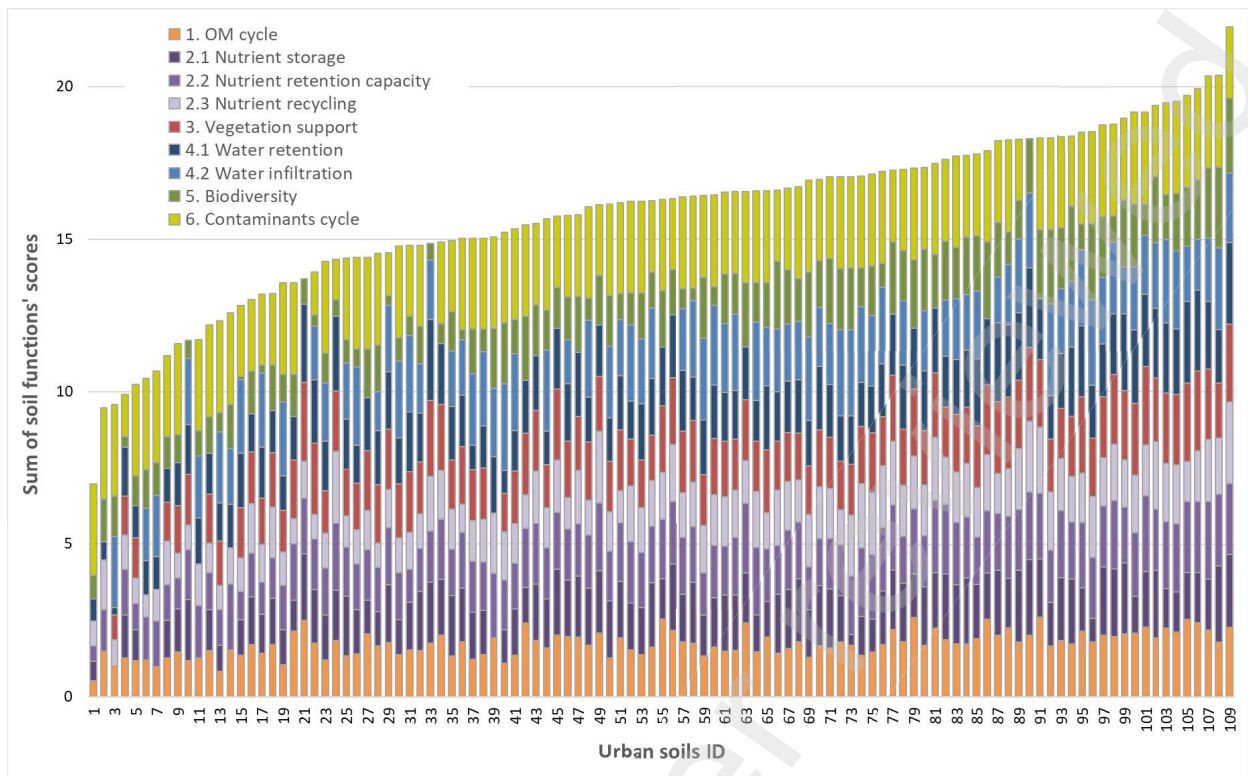


Figure 3. Soil health evaluation based on sum of scores of soil functions calculated by SUPRA for the 109 studied soils sorted by soils ID

332 4. Discussion

333 4.1. Adapting the scores to urban soils

334 As stressed for the indicators used to assess Biodiversity, the main existing reference frameworks come
 335 from agricultural context since only limited operational researches have been conducted on urban
 336 soils. The situation is different for the concentration of contaminants in soils as several references
 337 already exist (see Table 6) for urban soils since trace elements and organic contaminants are currently
 338 measured in urban situations. For all other indicators, references in agricultural soils compared to
 339 urban ones may be quite different. As an example, Joimel et al. (2017) showed that agricultural soils
 340 exhibited lower abundance and diversity of soil microarthropod than urban soils - being strongly
 341 diverse - that were similar to forest soils. This point should be improved by investigating more urban
 342 sites to develop proper references.

343 Note that quite all reference values (e.g. NPGF, Table 6) considered in this work are relevant at French
 344 scale. Monitoring urban soils should help defining reference values at all national scales across Europe.

345 All the data should then feed open databases for further reuse as stressed by the recent EU proposal
346 for a directive on soil monitoring and resilience (EC, 2023). Such interoperable databases (local-
347 national-Europe-International) appear necessary in this frame. One challenge relies in harmonised
348 analytical protocols, knowing that different ones are used at the moment according to countries or
349 objectives (e.g. agronomical study vs pollution diagnosis).

350

351 *4.2. Promoting a use of a wider set of soil indicators*

352 None of the samples available in our database was fully informed. This comes from the fact that several
353 sites were investigated before starting the current research. Some parameters have been estimated
354 while others are missing which impacts the scoring of several functions and subfunctions. It is expected
355 that the proposed minimum dataset will be fully measured in the future, becoming sort of a reference
356 protocol for data acquisition to assess urban soils health and subsequent decision making. For instance,
357 a better description of the nature, abundancy and impacts on soil functions of artefacts should be
358 strongly promoted. The trace organic pollutants to be analysed depends on the context of each site,
359 which should be better taken into account in the function assessment. Persistent substances should
360 be systematically analysed. Volatile substances, which need particular caution during sampling, should
361 be checked only if expected.

362 Some parameters determined at lab also suffer yet from high technicity and are still costly. Bulk density
363 in particular is used in 4 subfonctions. Further research activity to ensure easy field acquisition is
364 mandatory to check variability and render its acquisition easier with less error. Microbial DNA and
365 enzymatic activities are also still costly but appear really relevant. Innovation is in progress and still
366 needed to make such analyses less costly.

367 For all parameters, sampling caution is mandatory, all the more as urban soils are heterogeneous.
368 Urban soil mapping needs further research efforts to define soil units and precise their degree of
369 heterogeneity.

370 *4.3. Architecture of the model*

371 Our method is based on the diagnosis of soils, considered as 3D ecosystems constituted of natural or
372 anthropogenic soil horizons. A selection of 29 soil indicators has to be evaluated, measured and
373 analysed by soil experts at the field or in the lab. These data are subsequently transformed into scores
374 for 9 soil functions and sub-functions.

375 A limited number of similar approaches have been conducted for now. Calzolari et al. (2020) focused
376 on 9 input parameters that are not only soil properties (land use, land capability, pH, organic carbon,
377 bulk density, soil texture, saturated hydraulic conductivity, moisture at field capacity, average shallow
378 groundwater depth) that are connected to six soil functions (potential habitat for soil organisms,
379 filtering and buffering, carbon sequestration, food provision, water regulation and water storage). This
380 early work has been expanded by Ungaro et al. (2022) by adding five new input parameters (leaf area
381 index, analysis of presence and diversity of microarthropods, cation exchange capacity, rooting soil
382 depth, coarse fragment content). Their indicators were scored from 0 to 1 with various standardization
383 methods and were successfully translated into maps of ecosystem services hotspots at the scale of
384 Carpi (Italia). Hyun et al. (2022) proposed a set of indicators to “represent the soil quality of
385 metropolitan cities and develop a novel urban soil quality index”. They selected 9 bio-physico-chemical
386 soil indicators (bulk density, saturated hydraulic conductivity, depth of litter layer, texture, cation
387 exchange capacity, fluorescein diacetate hydrolytic activity, pH, available nitrogen, total
388 concentrations in 6 trace elements) to evaluate six soil functions (physical stability and support, water
389 storage and infiltration, habitat provision, organic matter stabilization, nutrient supply and retention,
390 pollutant immobilization and decomposition). They also used these soil functions to assess 10
391 ecosystem services and applied the method on 36 soils from 2 South-Korean cities. At last, the Destisol
392 model (Séré et al., under review) selected 20 soil properties to evaluate 15 soil functions that has been
393 later associated with soil covers to assess 18 ecosystem services. This method is strongly connected to
394 our approach that aimed at improving it by considering a larger spectrum of soil indicators and
395 strengthening the construction of the reference frameworks.

396 Compared to the ones that are mentioned above, the model that has been here developed lies on the
397 larger number of soil indicators. If it promotes a wider apprehension of soil health, possible drawbacks
398 are the difficulty to acquire all of them as well as the time and budget required to apply such method.
399 Three major perspective arose. The first one would be to take into account the soil cover and/or the
400 land use as it may affect the capacity of a soil to function. For example, an actual sealed soil health
401 could strongly be improved by desealing and greening operations. Furthermore, the type of vegetation
402 (e.g. lawn or tree) could influence some specific functions (e.g. water infiltration, biodiversity). The
403 second one would be to go one step further by conducting an assessment of ecosystem services.
404 However, such additional step could be achieved only by considering not only the soil compartment
405 but also the vegetation and possibly the human infrastructure that would have a significant
406 contribution (Blanchart et al., 2018a). At last, a crucial ambition would be to be capable of mapping
407 soil functions and sub-functions and, if possible, soil health at small and larger scales. This would
408 require a sufficient density of information on soil cover which, for now, is complex to imagine
409 considering the strong spatial variability of urban soils.

410 *4.4. Towards a decision support method*

411 Soils from our cities exhibit a high diversity and heterogeneity without no equivalent in the nature
412 (Morel et al., 2005; Béchet et al., 2009). However, urban soils actually provide a wide range of
413 ecological functions and ecosystem services that appear to be essential for the viability of urban areas
414 to face multiple environmental issues (O’Riordan et al., 2021; Morel et al., 2023). From a wider
415 perspective, considering the connection between human, animal and environmental health, having
416 soils in bad health in urban areas - places with the highest concentration of population - could
417 significantly damage our living conditions (van Bruggen et al., 2019). As a consequence, there is a true
418 need of method to reveal the poorly known potential of urban soils in order to improve urban planning.
419 Our method has been tested on a database of 109 contrasted urban soils. It has led to a wide range of
420 scores that revealed their strong differences in terms of soil health that are influenced by their actual

421 land use, but not restrictively correlated to it. Such information could be truly useful to orientate urban
422 planning in order to: i) preserve the healthiest soils from artificialization; ii) promote the valorisation
423 of healthy urban soil instead of scrapping and landfilling them before replacing them by agricultural
424 top soil for urban greening; iii) anticipate the remediation of soils in poor health; iv) target the most
425 degraded soils for the most degrading anthropogenic land uses (*e.g.* sealing, excavation).

426 In order to be considered by urban planners and embedded in a smart urban planning process, the
427 urban soils need to be characterized. Apart from soil functions and soil health scoring methods - such
428 as the one that is presented in this paper - it would also require a larger network of urban soils experts
429 that could perform such a critical fieldwork and transform the acquired information into efficient and
430 transferable information, soil maps being one of the possibilities.

431 **5. Conclusion**

432 The aim of this work was to propose and test a robust and science-based method, using urban soil
433 indicators, to reflect the soil's ability to perform different functions and to reflect soil health. These
434 indicators range from bio-physico-chemical soil parameters to levels of contamination or biological
435 activity in a broadest sense.

436 The “calibration” part of the reference frameworks was an essential and complex phase to carry out
437 in order to interpret the descriptions, measurements and analyses of the urban soil indicators as
438 accurately and explicitly as possible. Our method was based on a soil functions and sub-functions
439 scoring system, itself being based on a scoring system of each selected indicator. In order to improve
440 the metrics of the scores, a comparison of the model results with the field assessment of soil health by
441 various soil experts could be valuable. The results obtained show the wide disparity of soil functions
442 and sub-functions’ scores in the contrasted urban soils that have been studied.

443 This research has led to the creation of a first version of a tool that takes into account soil potential
444 (multi-criteria evaluation integrating soil depth and volume). To go further, the tool should be tested

445 on a wider diversity of situations, including agricultural, forest or natural soils that benefit already from
446 a deep and long-time knowledge regarding their potential by soil experts; the idea here would be to
447 compare the validity of our model proposed for urban soils.

448 The semi-quantification of the soil functions selected in this research programme should promote and
449 optimize the allocation of land uses during the urban planning process by taking into account the
450 expected and potential ecosystem services. More ambitiously, the setting up (at national, european or
451 even international) soil monitoring networks in urban environments, could enhance the establishment
452 of metric for ecosystem functions and services. It would be an ambitious but decisive objective for
453 meeting the environmental challenges of sustainable cities that would perfectly fit into such decisive
454 initiative as the recent European Directive on Soil Monitoring and Resilience.

List of tables

Table 1: Links between the services, the functions associated and the indicators considered essential to reflect soil health. Indicators are separated between in situ determination or measurement and laboratory measurement or analysis.

Table 2: List of indicators selected to contribute to the nine expected functions and subfunctions (function 1 = organic carbon cycle; function 2.1 = nutrient storage, function 2.2 = nutrient retention capacity, function 2.3 = nutrient recycling; function 3 = Vegetation support; function 4.1 = water retention capacity, function 4.2 = water infiltration; function 5 = biodiversity support; function 6 = contaminant support). Indicators are classified according to their mode of acquisition. The level of acquisition and the cost were estimated

Table 3: List of indicators to be described or measured directly in situ for the concerned functions (function 1 = organic carbon cycle; function 2.1 = nutrient storage, function 2.2 = nutrient retention capacity, function 2.3 = nutrient recycling; function 3 = Vegetation support; function 4.1 = water retention capacity, function 4.2 = water infiltration; function 5 = biodiversity support; function 6 = contaminant support). The rules of notation are defined between 0 and 3 (0 = bad value and 3 = good value). For each indicator, confidence index (CI) and relevance index (RI) are defined between 0 and 3 (0 = bad value and 3 = good value). References are given when available, if not expertise is required.

Table 4: List of indicators to be described or measured in situ and measured or analysed in laboratory for the concerned functions (function 1 = organic carbon cycle; function 2.1 = nutrient storage, function 2.2 = nutrient retention capacity, function 2.3 = nutrient recycling; function 3 = Vegetation support; function 4.1 = water retention capacity, function 4.2 = water infiltration; function 5 = biodiversity support; function 6 = contaminant support). The rules of notation are defined between 0 and 3 (0 = bad value and 3 = good value). For each indicator, confidence index (CI) and relevance index (RI) are defined between 0 and 3 (0 = bad value and 3 = good value). Standards and references are given when available, if not expertise is required.

Table 5: List of indicators to be measured or analysed only in laboratory for the concerned functions (function 1 = organic carbon cycle; function 2.1 = nutrient storage, function 2.2 = nutrient retention capacity, function 2.3 = nutrient recycling; function 3 = Vegetation support; function 4.1 = water retention capacity, function 4.2 = water infiltration; function 5 = biodiversity support; function 6 = contaminant support). The rules of notation are defined between 0 and 3 (0 = bad value and 3 = good value). For each indicator, confidence index (CI) and relevance index (RI) are defined between 0 and 3 (0 = bad value and 3 = good value). Standards and references are given when available, if not expertise is required.

Table 6: Threshold values for contaminants (selected from Coussy et al, 2020 ; Ademe, 2018 ; *other sources or expert say), **NPGB: natural pedo-geochemical background, France example). A and C refer to threshold values for each substance, QL for quantification limit.

List of figures

Figure 1. Distribution of the scores of soil functions calculated by SUPRA for the 109 studied soils

Figure 2. Scores of soil functions calculated by SUPRA for the 109 studied soils sorted by soil functions

Figure 3. Soil health evaluation based on sum of scores of soil functions calculated by SUPRA for the 109 studied soils sorted by soils ID

Acknowledgements

This research is part of the SUPRA (grant number: 1772C0035) research project which has been funded by French Environmental Agency, ADEME. The authors thank Isabelle Feix, H el ene Roussel and C ecile Grand (ADEME) for their support and fruitful discussions. The authors warmly thank Baptiste Grard (ISARA), Remigio Paradelo N u nez (Universidade de Santiago de Compostela) and Antoine Vialle (EPFL) for sharing their soils data.

References

ADEME, 2018. M ethodologie de d etermination des valeurs de fonds dans les sols : Echelle territoriale. Groupe de travail sur les valeurs de fonds. 112 p.

ARVALIS, ARVALIS, AUREA, Chambre d'agriculture de Bretagne, INRAE, ITAB, TerresInovia, UniLaSalle, Chambre d'agriculture d'Alsace, Chambre d'agriculture du Grand Est, Chambre d'agriculture de Sa one et Loire, Celesta-lab, RITTMO, SEMSE, Universit e de Lorraine, 2022. Guide d'interpr etation   l'analyse des bioindicateurs - Programme CASDAR Microbioterre, 40 p. <https://www.arvalis.fr/infos-techniques/douze-indicateurs-pour-evaluer-la-fertilit e-biologique-du-sol>

Association fran aise de normalisation, 2018. NF EN 16167 Soil, treated biowaste and sludge - Determination of polychlorinated biphenyls (PCB) by gas chromatography with mass selective detection (GC-MS) and gas chromatography with electron-capture detection (GC-ECD). Paris, France: AFNOR.

Association fran aise de normalisation, 2016. NF EN 16170 Sludge, treated biowaste and soil - Determination of elements using inductively coupled plasma optical emission spectrometry (ICP-OES). Paris, France: AFNOR.

Association française de normalisation, 2016. NF EN 16171 Sludge, treated biowaste and soil - Determination of elements using inductively coupled plasma mass spectrometry (ICP-MS). Paris, France: AFNOR.

Association française de normalisation, 2020. NF EN ISO 11063 Soil quality - Direct extraction of soil DNA. Paris, France: AFNOR.

Association française de normalisation, 2017. NF EN ISO 11272 Soil quality – Determination of dry bulk density. Paris, France: AFNOR.

Association française de normalisation, 2016. NF EN ISO 15009 Soil quality - Gas chromatographic determination of the content of volatile aromatic hydrocarbons, naphthalene and volatile halogenated hydrocarbons. Purge-and-trap method with thermal desorption. Paris, France: AFNOR.

Association française de normalisation, 2004. NF EN ISO 16703S oil quality - Determination of content of hydrocarbon in the range C10 to C40 by gas chromatography. Paris, France: AFNOR.

Association française de normalisation, 2016. NF EN ISO 17892-4 Geotechnical investigation and testing. Laboratory testing of soil. Part 4: Determination of particle size distribution. Paris, France: AFNOR.

Association française de normalisation, 2013. NF EN ISO 13196 Screening soils for selected elements by energy-dispersive X-ray fluorescence spectrometry using a handheld or portable instrument. Paris, France: AFNOR.

Association française de normalisation, 2018. NF EN ISO 20130 Soil quality - Measurement of enzyme activity patterns in soil samples using colorimetric substrates in micro-well plates. Paris, France: AFNOR.

Association française de normalisation, 1995. NF ISO 10694 Soil quality- Determination of organic and total carbon after dry combustion (elementary analysis). Paris, France: AFNOR.

Association française de normalisation, 2021. NF ISO 10390 Soil, treated biowaste and sludge – Determination of pH. Paris, France: AFNOR.

Association française de normalisation, 2021. NF ISO 11261 Soil quality - Determination of total nitrogen. Modified Kjeldahl method. Paris, France: AFNOR.

Association française de normalisation, 1994. NF ISO 11263 Soil quality - Determination of phosphorus. Spectrometric determination of phosphorus soluble in sodium hydrogen carbonate solution. Paris, France: AFNOR.

Association française de normalisation, 1994. NF ISO 11265 Soil quality - Determination of the specific electrical conductivity. Paris, France: AFNOR.

Association française de normalisation, 1999. NF X31-130 Soil quality - Chemical methods - Determination of cationic exchange capacity (CEC) and extractible cations. Paris, France: AFNOR.

Association française de normalisation, 2002. NF X31-106 Soil quality - Determination of active limestone content. Paris, France: AFNOR.

Aurousseau, P., Gascuel-Oudou, C., Squidant, H., 1998. Éléments pour une méthode d'évaluation d'un risque parcellaire de contamination des eaux superficielles par les pesticides. *Etude et Gestion des Sols* 5 (3), 143 – 156

Blanchart, A., 2018. Vers une prise en compte des potentialités des sols dans la planification territoriale et l'urbanisme opérationnel, Thèse de l'Université de Lorraine, Nancy, 354 p.

Blanchart, A., Séré, G., Cherel, J., Warot, G., Stas, M., Consalès, J.N., Schwartz, C., 2018a. Towards an operational methodology to optimize ecosystem services provided by urban soils. *Landscape Urban Plann.* 176, 1–9.

- Blanchart, A., Consales, J.N., Séré, G., Schwartz, C., 2018. Consideration of soil in urban planning documents—a French case study, *Journal of Soils and Sediments*, <https://doi.org/10.1007/s11368-018-2028-x>
- Bispo, A., Cluzeau, D., Creamer, R., Dombos, M., Graefe, U., Krogh, P.H., Sousa, J.P., Peres, G., Rutgers, M., Winding, A., Rombke, J. 2009. Indicators for monitoring soil biodiversity. *Int. Environ. Assess. Policy Manag.* 5 (4), 717–719.
- Calzolari C., Tarocco P., Lombardo N., Marchi N., Ungaro F., 2020, <https://doi.org/10.1016/j.landusepol.2020.105037>
- Cambou, A., 2018. Evaluation du stock et de la stabilité du carbone organique dans les sols urbains. Thèse AgrocampusOuest, Angers, 234 p.
- Coussy, S., Dubrac, N., Hulot, C., Billard, A., Kaabouch, S., 2020. Guide de valorisation hors site des terres excavées issues de sites et sols potentiellement pollués dans des projets d'aménagement. Ministère de la transition écologique et solidaire, 59 p.
- Dale, V.H., Beyeler, S.C., 2001. Challenges in the development and use of ecological indicators. *Ecological Indicators* 1:3–10. [https://doi.org/10.1016/S1470-160X\(01\)00003-6](https://doi.org/10.1016/S1470-160X(01)00003-6)
- Dequiedt, S., Saby, N.P.A., Lelievre, M., Jolivet, C., Thioulouse, J., et al., 2011. Biogeographical patterns of soil molecular microbial biomass as influenced by soil characteristics and management. *Global Ecology and Biogeography*, Wiley, 20 (4), pp.641-652. [10.1111/j.1466-8238.2010.00628.x](https://doi.org/10.1111/j.1466-8238.2010.00628.x)
- European Commission, 2023. Proposal for a Directive of the European Parliament and of the Council on Soil Monitoring and Resilience (Soil Monitoring Law). COM(2023) 416 final.
- Duchaufour, P., 1997. Abrégé de pédologie, 291 p. 5e éd., édition Masson.
- Durand, J.H., 1983. Les sols irrigables. Etude pédologique. ACCT-PUF, 339 p
- Faber, J. H., Hanegraaf, M. C., Gillikin, A., Hendriks, C. M. J., Kuikman, P. J., Cousin, I., Bispo, A., Obiang-Ndong, G., Montagne, D., Taylor, A., Bengtsson, J., ten Damme, L., Meurer, K. H. E., Viketoft, M. 2022. Stocktaking for Agricultural Soil Quality and Ecosystem Services Indicators and their Reference Values (SIREN): EJP SOIL Internal Project SIREN Deliverable 2. <https://edepot.wur.nl/582329>.
- Gatica-Saavedra, P., Aburto, F., Rojas, P., Echeverría, C. 2023. Soil health indicators for monitoring forest ecological restoration: a critical review. *Restor Ecol*, 31: e13836. <https://doi.org/10.1111/rec.13836>
- GEPPA, 1981. Synthèse des travaux de la commission de cartographie 1970-1981, 18 pages.
- Hanks, D., Lewandowski, A., 2003. Protecting urban soil quality: examples for landscape codes and specifications. USDA-NRCS.
- Herrick, J.E., 2000. Soil quality: an indicator of sustainable land management. *Applied Soil Ecology*. 15: 75-83. [https://doi.org/10.1016/S0929-1393\(00\)00073-1](https://doi.org/10.1016/S0929-1393(00)00073-1)
- Horrigue, W., Dequiedt, S., Chemidlin Prévost-Bouré, N., Jolivet, C., Saby, N.P.A., et al., 2016. Predictive model of soil molecular microbial biomass. *Ecological Indicators*, 64, 203 - 211. [10.1016/j.ecolind.2015.12.004](https://doi.org/10.1016/j.ecolind.2015.12.004).
- Hyun, J., Kim, Y.J., Kim, A., Plante, A.F., Yoo, G., 2022. Ecosystem services-based soil quality index tailored to the metropolitan environment for soil assessment and management. *Science of the total environment*, 820, 153301. [http://dx.doi.org/10.1016/j.scitotenv.2022.153301](https://dx.doi.org/10.1016/j.scitotenv.2022.153301)
- International Organization for Standardization, 2014. ISO 13859 Soil quality - Determination of polycyclic aromatic hydrocarbons (PAH) by gas chromatography (GC) and high performance liquid chromatography (HPLC).
- Jaenicke, E.C., 1998. From the Ground up: Exploring Soil Quality's Contribution to Environmental Health. Henry A. Wallace Institute for Alternative Agriculture, Greenbelt, MD, 42 pp. <https://doi.org/10.22004/ag.econ.134117>

Janzen, H. H., Janzen, D. W., Gregorich, E. G., 2021. The 'soil health' metaphor: illuminating or illusory?. *Soil Biology and Biochemistry*, 159, 108167.

Joimel, S., Schwartz, C., Hedde, M., Kiyota, S., Krogh, P. H., Nahmani, J., Pérès, G., Vergnes, A., Cortet, J. (2017). Urban and industrial land uses have a higher soil biological quality than expected from physicochemical quality. *Science of the Total Environment*, 584, 614-621.

Lal, R. 2016 Soil health and carbon management. *Food and Energy Security* 5: 212–222. <https://doi.org/10.1002/fes3.96>

Karimi, B., Terrat, S., Dequiedt, S., Saby, NPA., Horrigue, W., et al., 2018. Biogeography of soil bacteria and archaea across France. *Science Advances*, American Association for the Advancement of Science (AAAS), 4 (7), pp.eaat1808. [10.1126/sciadv.aat1808](https://doi.org/10.1126/sciadv.aat1808)

Laubier, F., 2001 : La méthode de diagnostic parcellaire du risque de contamination des eaux superficielles et le détachement des particules des sols cultivés, Ingénieries EAT, Numéro spécial phytosanitaire, pp. 91-97

Le Bissonnais, Y., Couturier, A., Cerdan, O., Papy, F., Martin, P., Souchere, V., Bruno, JF., Lebrun, P., Dennis, F., Morschel, J. et al., 2003. Projet GESSOL-érosion Maîtrise de l'érosion hydrique des sols cultivés, phénomènes physiques et dispositifs d'action, 66 p.

Le Guern, C., Baudouin, V., Bridier, E., Cottineau, C., Delayre, M., Desse-Engrand, F., Grellier, M., Milano, E., Mouny, A., Pollett, S., Sauvaget, B., Ménoury, A., Bâlon, P. avec la collaboration de Conil, P. et Rouvreau, L., 2016. Développement d'une méthodologie de gestion des terres excavées issues de l'aménagement de l'île de Nantes - Phase 1 : Caractérisation des sols et recensement des sources de pollution potentielles. Rapport BRGM/RP-66013-FR, 122 p., 27. Ill., 7 Annexes.

Le Guern, C., Baudouin, V., Sauvaget, B., Pineau-Jamin, E., Gaubert, C., Braud, R., Desse-Engrand, F., Polett, S., Ménoury, A. avec la collaboration de Bodéré, G., Milano, E., Conil, P., Bâlon, P., 2017. Développement d'une méthodologie de gestion des terres excavées issues de l'aménagement de quartiers nantais - Phase 1 : Caractérisation des sols et recensement des sources de pollution potentielles. Rapport final. BRGM/RP-67138-FR, 116 p., 48 ill., 30 tabl., 4 ann.

Le Guern, C., Baudouin, V., Sauvaget, B., Delayre, M., Conil, P., 2018a. A typology of anthropogenic deposits as a tool for modeling urban subsoil geochemistry: example of the Ile de Nantes (France). *Journal of Soil and Sediments*. DOI 10.1007/s11368-016-1594-z.

Le Guern, C., Limasset, E., Conil, P., 2018b. Inventaire des friches de Vendée et outil d'évaluation en appui à l'aménagement, BRGM.

Lehmann, J., Bossio, D. A., Kögel-Knabner, I., Rillig, M. C., 2020. The concept and future prospects of soil health. *Nature Reviews Earth & Environment*, 1(10), 544-553.

Morel, J.L., Schwartz, C., & Florentin, L., 2005. Urban soils. *Encyclopedia of Soils in the Environment*. p. 202-208.

Morel J.L., Séré G., Vasenev V., Nehls T., 2023. Ecosystem services provided by soils in highly anthropized areas (SUITMAs), *Encyclopedia of Soils in the Environment*, Second Edition, <https://doi.org/10.1016/B978-0-12-822974-3.00207-X>

O'Sullivan, L., Bampa, F., Knights, K., Creamer, R.E., 2017. Soil protection for a sustainable future: options for a soil monitoring network for Ireland. *Soil Use & Management* 33, 346–363.

O'Riordan R., Davies J., Stevens C., Quinton J.N., Boyko C., 2021, <https://doi.org/10.1016/j.geoderma.2021.115076>

Powlson, D. S. 2020. Soil health—useful terminology for communication or meaningless concept? Or both?. *Frontiers of Agricultural Science and Engineering-FASE*.

R Core Team, 2023. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.

- Sauvaget, B. 2019. Constitution de référentiels géochimiques locaux pour les sols et proches sous-sols urbains : de la base de données à l'interprétation géostatistique. Thèse de l'Université PSL, 195 p.
- Schoeneberger, P.J., Wysocki, D.A., Benham, E.C., and Soil Survey Staff., 2012. Field book for describing and sampling soils, Version 3.0. Natural Resources Conservation Service, National Soil Survey Center, Lincoln, NE. Online: https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_052523.pdf
- Schwilch, G., Bernet, L., Fleskens, L., Giannakis, E., Leventon, J., Marañón, T., Mills, J., Short, C., Stolte, J., van Delden, H., Verzaandvoort, S., 2016. Operationalizing ecosystem services for the mitigation of soil threats: a proposed framework. *Ecological Indicators* 67, 586–597
- Séré, G., Lothode, M., Blanchart, A., Chirol, C., Tribotte, A., Schwartz, C., *Under review*, Destisol: a decision support tool to evaluate ecosystem services provided by urban soils in order to improve urban planning, submitted to *European Journal of Soil Science*
- Stone, D., Ritz, K., Griffiths, B.G., Orgiazzi, A., Creamer, R.E., 2016. Selection of biological indicators appropriate for European soil monitoring, *Applied Soil Ecology*, <https://doi.org/10.1016/j.apsoil.2015.08.005>
- Tardieu, L., Hamel, P., Viguié, V., Coste, L., Levrel, H., 2021, Are soil sealing indicators sufficient to guide urban planning? Insights from an ecosystem services assessment in the Paris metropolitan area. *Environmental Research Letters*, 2021, 16 (10), pp.104019. <https://doi.org/10.1088/1748-9326/ac24d0>
- Terrat, S., Horrigue, W., Dequiedt, S., Saby, N.P.A., Lelievre, M., et al., 2017. Mapping and predictive variations of soil bacterial richness across France. *PLoS ONE*, Public Library of Science, 12 (0190128), pp.1-19. [10.1371/journal.pone.0186766](https://doi.org/10.1371/journal.pone.0186766)
- Ungaro F., Maienza A., Ugolini F., Lanini G.M., Baronti S., Calzolari C., 2022, <https://doi.org/10.1016/j.ufug.2021.127455>
- UQUALISOL-ZU, 2012 Préconisation d'utilisation des sols et qualité des sols en zone urbaine et péri-urbaine – Application du Bassin Minier de Provence. Programme ADEME – GESSOL.
- van Bruggen A.H.C., Goss E.M., Havelaar A., van Diepeningen A.D., Finckh M.R., Morris J.G., 2019, One Health - Cycling of diverse microbial communities as a connecting force for soil, plant, animal, human and ecosystem health, *Science of The Total Environment*, Volume 664, <https://doi.org/10.1016/j.scitotenv.2019.02.091>.
- Vrščaj, B., Poggio, L., Marsan, F.A., 2008, A method for soil environmental quality evaluation for management and planning in urban areas. *Landscape and Urban Planning*, v. 88, p. 81-94.
- Zornoza, R., Acosta, J.A., Bastida, F., Domínguez, S.G., Toledo, D.M., Faz, A., 2015. Identification of sensitive indicators to assess the interrelationship between soil quality, management practices and human health. *SOIL* 1, 173–185. <https://doi.org/10.5194/soil-1-173-2015>