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1 **Soil mapping, digital soil mapping and soil monitoring over large areas and the dimensions of soil**
2 **security – A review**

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9 **Abstract**

10 Soil Security includes dimensions, soil capability, soil condition, soil capital, soil connectivity and soil
11 codification (the “five C’s”). This article provides a short review on how soil mapping, digital soil
12 mapping and soil monitoring systems (SM, DSM and SMS) over large areas contribute to these five
13 C’s at scales ranging from country to globe. Changes and the evolution in aims of SM, DSM and SMS
14 were driven both by main issues related to policy priorities and associated advances in science and
15 technology. This review shows that SM, DSM and SMS can provide the basis for assessing soil
16 capability and condition over large areas, especially if we assume that capability mainly depends on
17 rather stable soil attributes. Repeated DSM or SMS are appropriated tool to monitor changes in soil
18 condition at these scales. They may even allow mapping changes in soil capability. However, broad-
19 scale SM, DSM and SMS have not yet fully achieved the provision of information concerning the
20 delivery of some soil functions and soil-based ecosystem services. Although significant progress in
21 estimating the capital dimension of soil security has been achieved, there is need to progress
22 monitoring changes in soil capital. Broad-scale SM, DSM and SMS has great potential to increase soil
23 connectivity. The main challenge is adapting our language and our communication to the target
24 audience. There are encouraging initiatives to enhance soil codification. Codification issues are

25 largely driven by the political agenda, there is still an urgent need to increase soil connectivity,
26 especially towards citizens, NGOs and policy-makers.

27 **Keywords:** Soil Security; Soil mapping; Soil monitoring; Large areas.

28

29

30 **1. Introduction**

31 Unprecedented demands are being placed on the world's soil resources (Hartemink and McBratney,
32 2008; Koch et al., 2013; Amundson et al., 2015; FAO-ITPS, 2015). At the same time, there is an
33 increased evidence that world's soil are under threat (Montanarella et al., 2016) and there is an
34 urgent need to put the soil at the crossroad of the sustainable development goals (SDGs) (e.g. Bouma
35 and Montanarella, 2016; Keesstra et al., 2016; Bouma, 2019); putting soils and their governance in
36 the global agenda is more urgent than ever (Koch et al., 2012; Amundson et al., 2015; Montanarella,
37 2015). Global Soil Security provides a transparent concept for sustainable development and
38 improvements of the global soil resource.

39 The global Soil Security concept emerged from two seminal publications (Koch et al., 2013;
40 McBratney et al., 2014), followed by numerous other publications, conferences and books addressing
41 Soil Security from local to global scale (e.g. McBratney and Field, 2015; Kidd et al., 2015, 2018; Koch
42 et al., 2015; Field et al., 2017; Huang et al., 2018; Allan, 2019; Bennett et al., 2019; McBratney et al.,
43 2019; Murphy and Fogarty, 2019; Richer-de-Forges et al., 2019a; Bouma, 2020; Field, 2020). The
44 emergence of this concept has been strengthened by three international conferences on Global Soil
45 Security held in Texas A&M, USA, 2014, in Paris, France, 2016, in Sydney, Australia, 2018, and by the
46 launching of the scientific journal "Soil Security" in 2020 (Morgan and McBratney, 2020). The main
47 difference between Soil Security and previous concepts such as *soil care* (Yaalon, 1996; McBratney et
48 al., 2017; Leonhardt et al., 2019), *soil quality* (Karlen et al., 1997, 2001), *soil health* (Doran et al.,

49 1996; Doran and Ziess, 2000; Doran, 2002), among others, is that the other concepts mainly consider
50 biophysical soil parameters and their changes. Soil Security considers this to be the *soil condition* and
51 *capability*. Soil Security further adds three new dimensions to the framework namely the *soil capital*,
52 *connectivity*, and *codification* (McBratney et al., 2014). These three additional dimensions add new
53 essential criteria to assess Soil Security. The *soil capital* refers to the “production of human-
54 demanded function and the attendant ecosystem services” (McBratney et al., 2019a). This way, it
55 adds a value to soils (Costanza et al., 1997). *Soil condition* and *capacity* are mainly driven by the
56 assessment of what soil can, or could, do; last three soil C’s (*soil capital*, *connectivity*, and
57 *codification*) are taking into account the actions (at social, economic and policy levels) that are put in
58 place guarantying the improvement of Soil Security. As stated in the Global Soil Security website
59 (<https://globalsoilsecurity.com/>): “Yet an overarching concept that brings together these biophysical
60 and socio-economic perspectives of soil is still lacking and this has led to the launch of the Soil
61 Security concept”.

62 Parallel to these developments, two emerging requisites were raised from the broader soil science
63 community over the past few decades to answer to society’s demand for high-resolution soil
64 information:

- 65 1. Large-area digital soil maps of soil attributes that can be produced either by a top-down
66 approach (from country to globe, e.g. Sanchez et al. 2009; Arrouays et al. 2014, 2017b) or a
67 top-down approach (Hengl et al., 2014, 2017a; Poggio et al., 2021), or by various
68 combinations of both approaches (e.g. Caubet et al., 2019; Chen et al., 2021). The
69 complementarity of both approaches was underlined (Arrouays et al., 2017a; 2020a) and
70 ways to collaborate without sharing data were proposed as another bottom-up option
71 (Padarian et al., 2019; Padarian and McBratney, 2020).
- 72 2. Establishing long-term soil monitoring systems (SMS) and methods to harmonize them
73 between countries (Morvan et al., 2008; Arrouays et al., 2012; Brus, 2014; Louis et al., 2014).

74 These needs are explicitly outlined in the roadmap of the European Joint Programme SOIL
75 “Towards climate-smart sustainable management of agricultural soils” (Keesstra et al., 2021).

76 These requisites were pushed by recent advances in digital soil mapping (DSM, McBratney et al.,
77 2003; Grunwald et al., 2011; Minasny and McBratney, 2016) and by striking evidences that large
78 changes in some soil properties were detected by some SMS (e.g., Bellamy et al., 2005; Kirk et al.,
79 2010). Now, we have reached the point where we have global soil information available which can
80 potentially be used for assessing all five C’s of Soil Security. In this paper we will make a stock take
81 and review our current position.

82 We focus on the main inputs from soil mapping (SM), DSM and SMS over large areas (further
83 referred to as broad-scale SM, DSM or SMS) and connect it with local to global end users for
84 assessing the five C’s of Soil Security (*Capability, Condition, Capital, Connectivity, Codification*, as
85 defined by McBratney et al. (2014)). The main questions raised in this paper are:

- 86 1. How do broad-scale SM, DSM and SMS contribute to the 1st and 2nd C’s of Soil Security, the
87 soil *capability* and *condition*?
- 88 2. How has spatial soil information progressed valuing soil services and evaluating the *capital*
89 dimension of soil security, i.e. the 3rd C of Soil Security?
- 90 3. How may the development of broad-scale SM, DSM and SMS be used to contribute to the 4th
91 C of Soil Security, the *soil connectivity*? Does it enable a large increase in soil *connectivity* and
92 awareness, and to which target audiences? If not, what could be done to improve the
93 situation?
- 94 4. How much have we progressed on using spatial soil information for *soil codification* and what
95 should be improved to further advance the 5th C of Soil Security?

96 We first take as an example the country France and revisit their main aims and drivers of SM, DSM,
97 SMS and the main evolutions in their objectives, progress, and settlement. We choose this country
98 because it is a good illustration of some drastic changes that took place in SM, DSM and SMS

99 strategies over time. Then, we make up the balance to which extent we have achieved assessing the
100 five C's using existing examples from country to global scale, and identify pathways on how to
101 improve Soil Security.

102

103

104 **2. The evolution of the main aims and drivers of soil mapping and monitoring over large areas in** 105 **France**

106 At the birth of pedology, soil science and large areas soil mapping were obviously linked. The
107 scientist considered to be the father of pedology (Vassili Dokuchaev) was originally a geographer and
108 cartographer. It was by traveling through Russia and making thousands of observations that he
109 demonstrated the climatic zonality of Russia's soils. Vassili Dokuchaev was the first who produced
110 soil maps at continental scales (Boulaine, 1983). Seventy-three years later, it was by exploring and
111 mapping the soils of northern France that Marcel Jamagne highlighted one of the most famous
112 chrono-sequences of the evolution of silty soils in temperate climates (Jamagne, 1973, 1978;
113 Jamagne et al., 1984). Undoubtedly, the study of the spatial distribution of soils and their properties
114 is a major tool for understanding their pedogenesis. However, recent developments in this field were
115 rarely driven by the concern for the study of pedogenesis. The two main drivers of methodological
116 changes in broad-scale SM, DSM and SMS were related both to pressing societal issues that countries
117 and policy-makers had to solve, and to scientific and technological advancements with time. We take
118 here as an example the main changes that have been taking place in France since the 1960s. As some
119 of these changes were obviously linked to EU policy and to worldwide scientific advances, we argue
120 that the example of France may be representative for what happened in many other countries.

121 In the early 1960s, the challenge was to feed the growing post-war population and produce sufficient
122 crop for human consumption and fodder. This was the early years of the Common Agricultural Policy
123 (CAP) launched in 1962 (The European common policy at a glance:

124 farming-fisheries/key-policies/common-agricultural-policy/cap-glance-en). The objective was mainly
125 tailored towards agricultural production rates. It was to develop new agricultural areas and to aim for
126 maximum yields. The new agricultural areas that were developed, were mainly to the detriment of
127 the forest and other natural areas which were cleared for this purpose only. It was the era of the
128 development of large land-use planning companies, involving many soil mapping activities.
129 Consequently, it also involved deforestation, drainage, liming, fertilization and cultivation of large
130 areas (see, for example, Legros, 1996). This tendency was amplified both by technology
131 (mechanization, fertilizers and pesticides use and progress in plant breeding) and by war conflicts
132 (the need for new arable lands due to the massive return from Algeria of French colonial farmers,
133 Journal officiel de la République française, 1961). This period clearly focused on improving *soil*
134 *capability* and *soil condition* with the aim of increasing agricultural production. In other words, it
135 mainly focused on only one soil ecosystem services – food security.

136 From a soil science and pedometric point of view, the 1960s and the 1980s were characterized by so-
137 called “conventional mapping”. At the end of the 1960s, the first detailed manuals appeared, such as
138 Marcel Jamagne's “Bases et techniques d'une cartographie des sols” (in English: Fundamentals and
139 techniques of soil mapping, Jamagne, 1967) and the collective work of the commission on soil
140 science and soil classification (CPCS, 1967). These harmonization efforts helped to increase the
141 *connectivity* with end-users who no longer had to struggle with different soil classifications. France
142 also pursued conventional soil mapping in numerous countries of the world, mainly in Africa. Note
143 that a large amount of these data have been rescued and incorporated by ISRIC into the AfSiS and
144 Wosis databases (Leenaars, 2014; Leenaars et al., 2014a, 2014b; Hengl et al., 2015). Thus, indirectly,
145 the French efforts during this period helped the achievement of continental and global DSM,
146 contributing to continental assessments of soil *capability* (Leenaars et al., 2018) and *condition* (Hengl
147 et al., 2017b).

148 Around the 1980s, space became constrained due to urbanization and the development of
149 infrastructure. New challenges appeared, the question of managing this space for land-use, but also
150 preserving the most productive soils. Consequently, the French departments agricultural land maps
151 program was initiated. This program aimed at covering France entirely with maps of “agricultural
152 lands” at 1:50,000 scale (Jamagne et al., 1989). It failed, not only because of lack of funding, but
153 because it was a mix of mapping soil “capacity”, “suitability”, “agricultural incomes” and land
154 “economic prices”, without clearly defining the rules for mapping these altogether. In other words, it
155 was a mix of agricultural suitability, soil *capability* and land market value maps, without clear
156 guidelines how to produce them. This resulted in large discrepancies between maps and endless
157 discussions about their usage. Although this program failed, in some way it already tried to take into
158 account three *C*'s (*capability*, *condition* and *capital*), unfortunately not in a successful manner. In
159 parallel, at the end of the 1970s, computerization, digitization and mathematical processing of data
160 became operational (Legros and Bonneric, 1979). This would bring major changes to the aims and
161 drivers of soil mapping and monitoring over large areas, not only in France but to the entire world.

162 In the mid-1980s, the EU faced agricultural overproduction. To guarantee prices, policies were put in
163 place. These were the policies of quotas and those of set-aside, falsely called fallows and which for
164 some, like bare fallows, were environmental aberrations (Balesdent and Arrouays, 1999; Tonitto et
165 al., 2006), nevertheless imposed because they were easier to control. Thus, the French priority
166 changed from maximizing yields to maximizing farmer's incomes, by a better assessment of soil
167 *capability* and *condition* and a better reasoning of agricultural inputs. Some soil mapping programs at
168 1:50,000 scale were put in place by agricultural development bodies to accompany these changes
169 (Richer-de-Forges et al., 2014). These maps clearly increased soil *connectivity* (the 4th Soil C) with
170 farmers who better adapted their practices to their soils. Note, however, that these maps were
171 rather detailed and were not “broad-scale” maps (each map covering about 600 km²) which
172 facilitated the *connectivity* with local farmers.

173 At the EU level, the need to monitor and predict yields led to the implementation of the MARS
174 (Monitoring Agricultural ResourceS) project in 1988. MARS was initially designed to apply emerging
175 space technologies for providing independent and timely information on crop areas and yields (see
176 <https://ec.europa.eu/jrc/en/mars>). The models used by MARS needed EU soil data. Indirectly, this
177 led to the creation of the Joint Research Centre European Soils Bureau, who developed the first
178 harmonized soil map and geographical database of Europe (King et al., 1994). This was also a major
179 challenge for France, who had to convert its 1:1,000,000 map in a GIS database. From a technological
180 point of view, the end of the 1980s, were characterized by the appearance of geographic information
181 systems that truly revolutionized the cartographic approach. France went from paper maps to
182 operational soil databases, creating relational database models for France and Europe. This was a big
183 step towards *connectivity* with end-users and towards the feasibility of mapping soil *capability* over
184 broad areas.

185 After 30 years of pushing towards increasing yields and optimizing farmers income, changes were
186 imminent. An increased awareness for natural declines and environmental concerns took over in the
187 1990s, with the Kyoto protocol (UNFCCC, 1997) and the other Rio conventions (United Nations, 1992;
188 UNCED, 1994). These began to give insight into the global aspect towards the problems of the global
189 soil resource: carbon storage and climate change, biodiversity conservation, protection against
190 erosion and desertification. In Europe and in France, this resulted in agri-environmental policies and
191 the emergence of the concept of eco-conditionality of CAP aid (European Parliament, 2003). Slowly,
192 but progressively, this led France to adopt some agro-environmental legal constraints for soil
193 management, and to develop guidelines for the delineation of erosion risk areas (Cerdan et al., 2006)
194 and of wetlands to be protected (MEDDE and Gis Sol, 2013). At the end of the 1990s, a review of the
195 national soil monitoring system was conducted by the European Environmental Agency. Among the
196 main results, were the large discrepancies between EU countries, and the need for a transboundary
197 harmonization (Arrouays et al., 1998). For France, it was concluded that it performed very poorly in
198 comparison to other EU countries in terms of soil monitoring development. This outcome, together

199 with the increasing need of monitoring the soil *condition*, led to the launch of the French soil
200 monitoring network in 2001. This clearly added a new priority that was to monitor the 2nd C
201 (*condition*). During the 1990s, the available digital data drastically increased (digital terrain models,
202 satellite data, digitized map data of climate, vegetation, geology, etc.). Meanwhile, the computing
203 power of the computers increased rapidly. Therefore, French research in soil mapping gradually
204 moved from a model of tacit knowledge of the soil expert (conventional soil mapping) to formalized
205 and quantified models (pedometrics and DSM). In the 1990s, some French papers already dealt with
206 DSM, although they most often focused on local applications (e.g. Lagacherie and Depraetere, 1991;
207 Lagacherie et al., 1995; Arrouays et al., 1995, 1998; Bourennane et al., 1996; Voltz et al., 1997). At
208 the end of the 1990s, five main technical decisions influenced SM, DSM and SMS in France:

- 209 i) all the points and areal data gathered in regional and national SM programs should be rescued and
210 stored in a national database,
- 211 ii) the highest SM priority will be given to the achievement of a 1:250,000 soil geographical database,
- 212 iii) more detailed maps and data will be gathered to provide soil data to environmental and
213 agronomical purposes and calibration areas for DSM,
- 214 iv) soil analysis ordered by farmers will be centralized in a common database, and
- 215 v) a soil monitoring network will be implemented for the entire mainland territory of France.

216 All these technical and policy changes clearly increased the possibility of monitoring soil *condition*, to
217 build national databases enabling SM and DSM of soil *capability* at the national scale, and to increase
218 soil *connectivity* with farmers.

219 In the 2000s, the notion of ecosystem services emerged, particularly due to the Millennium
220 Ecosystem Assessment (MEA, 2005). Though the need for soil maps became more and more evident,
221 France was still among the less advanced EU countries concerning its national soil mapping program.
222 Finally, during the mid-2010s, France was asked by the EU to contribute to the delineation of

223 agricultural areas subject to natural constraints, i.e. 'Agricultural Areas with Natural Handicaps'
224 (Jones et al., 2014), by making use of existing soil maps to assess the biophysical criteria for this
225 delineation. The French policy-makers suddenly realized that data was still missing in some critical
226 regions. Consequently, it could imply they may lose an enormous amount of agricultural EU
227 subsidies. This resulted in a fantastic boosting of the French program of soil mapping at 1:250,000
228 scale, the funding quadrupled in only few years.

229 In the 2000s, France organized the First Global Workshop on DSM in Montpellier in 2004 (Lagacherie
230 et al., 2006) following the publication of a seminal paper on DSM (McBratney et al., 2003). Ever since,
231 France took a growing importance in international initiatives devoted to DSM (Lagacherie et al.,
232 2006; Sanchez et al., 2009; Arrouays et al., 2014, 2017b, 2020a). The national decisions taken at the
233 end of the 1990s proved fruitful and led, among others, to a large production of national DSM
234 products contributing to the assessment of national soil *capability* and *condition*. The impacts of
235 some of them are detailed in Arrouays et al. (2020b).

236 Last, but not least, some of the latest changes in the French soil mapping strategy are linked to the
237 urgent need to give access to more detailed maps of soil and soil properties, so as more local actions
238 about soil multi-functionality and soil-based ecosystem services can be implemented. This includes
239 soil protection against degradation, but also the integration of the five C's and their impact on agro-
240 ecosystems management and land-use planning. The future of SM and DSM in France is secured; the
241 main aims are focused on the development of DSM for detailed maps of soil types and soil properties
242 (Voltz et al., 2020), driven by the user's need (Richer-de-Forges et al., 2019b). The objective is clearly
243 increase the understanding of the five C's , enabling the improvement of Soil Security by everybody.

244 **3. The contribution of broad-scale SM, DSM and SMS to the 1st and 2nd C's: soil *capability* and** 245 ***condition*.**

246 As defined by McBratney et al. (2014) and Field (2017) soil *capability* "asks what this soil can do?".
247 This dimension implies that under a given climate and landscape, different types of soil,

248 characterized by some biophysical properties, may perform different functions. Soil *capability* is thus
249 mainly influenced by soil attributes that are considered as more or less stable except in case of
250 drastic changes (e.g., landslide, severe erosion, sudden and high contamination, flooding). As such,
251 *capability* is strongly linked to intrinsic soil characteristics. Most of the SM, DSM and SMS scheme
252 ensure a strong link to these intrinsic soil characteristics. Conventional SM usually delineates soil
253 classes on the basis of the succession of horizons that are supposed to have analog properties. If the
254 delineation is accurate, and if the variability of soil types is well captured by the map, then we can
255 make the hypothesis that, under the same climate, vegetation and topography, traditional soil maps
256 may help to map soil *capability*. However, when dealing with large areas most of the conventional
257 soil maps are not precise enough to characterize the variability of soil properties, or even to
258 delineate soil classes. Some noticeable exceptions may be some countries having conducted a
259 detailed systematic mapping of their soils (e.g. Belgium, The Netherlands, South Korea, USA), but
260 most of the countries do not have such detailed maps. Thus, mapping *capability* using conventional
261 soil maps over large areas may be hazardous, especially on areas characterized by a high soil
262 diversity. This is why some global maps (e.g. the Harmonized Soil World Database
263 (FAO/IIASA/ISRIC/ISS-CAS/JRC., 2008); the WISE30sec soil property database (Batjes, 2016); the S-
264 World (Stoorvogel et al., 2017) that were originally based on traditional soil class delineation at high
265 classification levels, may give a useful big picture of spatial trends in soil *capability*, but should be
266 used with caution at the local scale. This is also true for the first global DSM SoilGrids products (Hengl
267 et al., 2014, 2017a), even if soil class maps were not used as co-variates. In other words, these maps
268 may be used as inputs to run coarse modelling at the global scale, but they convey a large
269 component of uncertainty that is not quantifiable. Moreover, a recent study showed that these type
270 of global maps may exhibit large differences in predictions between them, and when also compared
271 to regional maps (Stoorvogel and Mulder, 2021; Tifafi et al., 2018).

272 The situation improved substantially with the release of the new Soilgrids2.0 product (Poggio et al.,
273 2021) for several reasons. The number of calibration points was much larger compared to the first

274 versions. This new version also provides an estimate of the uncertainty of predictions, which is
275 helpful to estimate the confidence of the predicted values and to indicate where calibration data
276 density should be improved. This therefore provides better information on some current properties
277 related to soil *capability* and *condition*. However, we still need to find ways to identify *shifts* in
278 *capability* or *condition* compared to this reference state. Indeed, this product by itself is not able to
279 inform the impact of changes in management practices. This will require the settlement of long-term
280 SMS, or coupling DSM predictions with modeling which may lead to large error propagation. As
281 suggested by Heuvelink (2014), for modelers, the ideal product would be a map providing for each
282 cell the probability distribution function (PDF) of soil properties or even the joint PDF of several soil
283 properties.

284 As stated by Arrouays et al. (2017a) DSM over large areas may be more efficient at country or
285 regional level than at global level, because the availability and the relevance of calibration and co-
286 variates may differ between countries. Most notably, “the relative importance of driving factors and
287 co-variates may strongly differ between physiographic areas”. Thus, global DSM maps are useful for
288 setting soil *capability* and *condition* at broad scales because they provide a generic product that is
289 complete and covers the globe, but utilizing all the data available at country level generally delivers
290 better quality products. This is why comparisons between global and national products sometimes
291 showed very different results. Moreover, validation of such global products remain challenging
292 (Stoorvogel and Mulder, 2021). Some of the discrepancies between national predictions are
293 obviously due to different sampling strategies in space, time and depth, and to difficulties to
294 harmonize/compare analytical protocols (Morvan et al., 2008). The same difficulties also apply when
295 comparing SMS. Moreover, in a recent review, van Leeuwen et al. (2017) underlined some important
296 gaps in collecting soil properties, especially for soil biological characterization.

297 A well-known example of a continental product is LUCAS-Soil in the EU (Orgiazzi et al., 2018). LUCAS-
298 Soil represents the largest harmonized open-access dataset of topsoil properties available for the

299 European Union at the global scale. LUCAS-Soil was created from the outset as a monitoring and
300 dynamic database, thus repetition of measurements, new locations and new properties can be added
301 during subsequent surveys. Briefly, LUCAS-Soil has two main objectives, 1) mapping the soil
302 *capability* and *condition* over the E.U. and 2) provide a basis for repeated sampling allowing to
303 monitor changes in soil *condition*. Numerous EU maps related to soil *capability* and *condition* have
304 been produced, the list of collected soil information is continuously increasing, and the data and
305 maps have been used for many integrated modelling purposes. Data, maps, reports and scientific
306 papers are available at the European Soil Data Centre (Panagos et al., 2012; ESDAC, 2021). However,
307 for the local use, the resolution is still rather coarse, so there is still a need for improving it using
308 conventional SM or DSM techniques in order to improve the five C's at more local scales.

309 Repeated soil sampling, or the collection of new soil information, is the basis of the settlement of soil
310 monitoring systems. There are a lot of literature and books dealing with sampling schemes and
311 statistical and/or mapping use of these SMS and the so-called "design-based" and "model-based"
312 sampling strategies (Brus, 2014). Those were reviewed in a recent article by Brus (2021), who stated
313 that "both approaches are valid and have their strengths and weaknesses" and that "various hybrid
314 methods have been developed that try to combine the strengths of the two approaches". Though
315 they are very important, these scientific considerations are, however, outside of the scope of this
316 paper. Basically, putting in place a SMS sampling strategy should first be guided by the questions we
317 want to answer: Do we want to estimate the magnitude of changes and on which geographical
318 support? Do we want to map where the changes occur in order to put in place more targeted actions
319 and at which resolution? Do we want both? Do we want to monitor a specific soil attribute or
320 property, or do we want to put in place a "generic" strategy that will enable to monitor future
321 changes or threats that we cannot yet anticipate or measure? Obviously, repeated sampling and
322 archiving and repeated DSM predictions is a potential solution. This strategy is already in place in
323 numerous countries of the world, especially in the EU (Morvan et al., 2008; Orgiazzi et al., 2018).
324 Moreover, targeting single properties allowing to assess mean or total changes over large areas may

325 require much less sampling effort using a SMS design-based approach. Here, SM or DSM can provide
326 a basis for stratification when optimizing a SMS design-based model.

327 Finally, the response to the question “Do the SM, DSM and SMS over large areas contribute the two
328 first C’s (*capability* and *condition*) of soil security?” is partly yes. SM, DSM and SMS can provide the
329 basis for assessing soil *capability* and *condition* over large areas, especially if we assume that
330 *capability* mainly depends on rather stable soil attributes. However, we are still missing much
331 information if we want to better map and monitor the wide variety of soil functions that are
332 connected to Soil Security (McBratney et al., 2014). Soil physico-chemical and biotic data are lacking
333 about changes in e.g. nutrient status, biota, compaction, soil structure, soil hydrological parameters.
334 Therefore, one major challenge is to enlarge the range of soil properties that we are currently
335 predicting and monitoring. McBratney et al. (2014) outlined the dimensions of soil security and
336 suggested that soil biota in the future may be a significant and broad indicator of the soil's *condition*
337 (Zak et al., 2003; Barrios, 2007). In recent years, the soil biology science has substantially increased
338 our knowledge on the synergies and tradeoffs of how the soil biological *condition* and *capability* (i.e.
339 soil organisms) contribute to sustainable land management and the delivery of ecosystem services
340 (Pulleman et al., 2012; Vazquez et al., 2021) and how soil organisms play an important role in water
341 regulation, nutrient cycling, soil fertility and biological control, among other services (Creamer et al.,
342 2016; Zwetsloot et al., 2021). Studies showed that there are strong similarities between the soil
343 biodiversity and pedodiversity (Chu et al., 2020; Martiny et al., 2006). This knowledge has
344 subsequently been used to create some of the first maps on soil biota such as bacteria, nematodes
345 and earthworms from the national to global scale (Karimi et al., 2018; Phillips et al., 2019; Rutgers et
346 al., 2019; van den Hoogen et al., 2020). One of the most limiting factors for producing accurate maps
347 on the soil’s biological *condition* is data availability. Fortunately, more and more soil biological data is
348 becoming available, e.g. through collaborations such as proposed by Smith et al. (2019), where they
349 call for a collaboration for building a global database of soil microbial biomass and function. With

350 initiatives like this, pedometricians can seek out collaborations with soil biologists in the near future
351 to create reliable digital soil maps of the soil biological *condition* and *capability*. With that, we are
352 one step closer to the suggestion of McBratney et al. (2014) that soil biota may be a significant and
353 broad indicator of the soil's *condition*.

354 Remote sensing data provide a precious source of co-variables for SMS, either because they can map
355 some controlling factors of soil properties changes, (like land-use for instance) or because they can
356 help to capture indirectly some soil properties (for instance available water capacity through
357 vegetation indexes) or be more directly related to some properties (surface SOC, thermal properties).
358 Recently, Ivushkin et al. (2019) combined soil properties maps with thermal infrared imagery and a
359 large set of field observations within a machine learning framework to produce global soil salinity
360 changes maps from 1986 to 2016. They concluded that “combining soil properties maps and thermal
361 infrared imagery allows mapping of soil salinity development in space and time on a global scale”.

362 In cases of major changes, repeated SM, or updating SM by DSM, may be able to detect some drastic
363 changes that may affect not only soil *condition*, but also soil *capability* (Kempen et al., 2012). The
364 case of peat disappearance, as shown by Kempen et al. (2012), is a typical example where drastic
365 changes in soil *condition* may lead in changes in soil *capability* and even in soil type. In a recent
366 article, Minasny et al. (2019) reviewed peatland mapping in twelve countries, and concluded that
367 DSM tools and a set of relevant co-variables could be an efficient way to monitor peatlands over the
368 world. One related question is to which extent *changes in soil condition can change soil capability*, or
369 by analogy, to which extent changes in phenoform can lead to changes in genoform (Droogers and
370 Bouma, 1997; Rossiter and Bouma, 2018)?

371 Repeated DSM, or long-term SMS are some responses to monitor changes in soil *condition* with time.
372 The oldest long-term broad-scale established SMS in England and Wales already demonstrated its
373 efficiency (Bellamy et al., 2005; Kirk et al., 2010). Preferably, repeated DSM and SMS should be able
374 not only report on mean, total changes and locations where they occur, but also to test new

375 hypothesis on the causes of these changes (Wadoux and McBratney, 2021) or to even bring new data
376 knowledge discovery in soil science (Wadoux et al., 2021). A challenge here is also to differentiate
377 between actual changes in the soil over time and uncertainty around the measured soil property.
378 Van Leeuwen et al. (2021) showed that even laboratory measurements in wet chemistry soil data can
379 be very uncertain and thus affect the monitoring of changes over time. Hence, we must keep in mind
380 though that improving soil *condition* and enhancing soils to their maximum *capability* requires local
381 actions. Supporting these local actions will require more detailed-scale assessment of soil *capacity*
382 and *condition*. For example, Soil Navigator DSS, a the decision Support System for Assessment and
383 Management of Soil Functions (Debeljak et al., 2019) was developed for assessing soil functions in
384 the delivery of various ecosystem services. This DSS works well at the field-scale and can be a great
385 tool for farmers to improve the soil *condition* and *capability*. Moreover, if DSS like the Soil Navigator
386 can be coupled with DSM and land management information, it may become a great tool for large
387 farm holders having diverse abiotic conditions and crops on their farms, or even regional or national
388 stakeholders may use the toolkit for assessing soil functions at larger scales. Thus, supporting these
389 local actions will also largely depend on some aspects of the 4th C, the *connectivity* dimension of soil
390 security, e.g. how to raise soil awareness, education, and the adoption of good soil management
391 practices of local actors (farmers, farmers' advisers, land-use planners, local decision makers, etc.).
392 Finally, the main question related to this section was 'How do broad-scale SM, DSM and SMS
393 contribute to the 1st and 2nd C's of Soil Security, the soil *capability* and *condition*?

- 394 • With respect to soil *capability* it can be concluded that broad-scale SM, DSM and SMS have
395 not yet fully achieved the provision of information concerning the delivery of soil functions
396 and soil-based ecosystem services. Some broad-scale estimates about soil based ecosystem
397 services have been produced using such broad-scale products, e.g. Soil Organic Carbon (SOC)
398 storage, dynamics (Bellamy et al., 2005; van Wesemael et al., 2010; Meersmans et al., 2011;
399 Stockmann et al., 2015) and sequestration potential (Martin et al., 2021), agricultural

400 production (Panagos et al., 2018). However a lot of other functions and ecosystem services
401 still need to be estimated, and often at more detailed scale than broad areas.

402 • The *condition* of the soil is concerned with the current state of the soil but also refers to the
403 shift in *capability* compared to the reference state. Some long-term SMS (Bellamy et al.,
404 2005) or repeated DSM of which some rely on remote sensing time series (Meersmans et al.,
405 2011; Kempen et al., 2012; Liu et al., 2013; Ivushkin et al., 2019) attempted to quantify these
406 shifts over large areas, but in most cases SMS don't have yet a long enough track record to
407 answer these questions. Another challenge is forecasting the changes in soil *condition* and
408 *capability*. It will often need coupling soil data with models, which raises the question the
409 uncertainty of these predictions.

410 • One major challenge is to enlarge the range of soil properties that we are currently
411 predicting and monitoring, by adding several soil physico-chemical and biotic such as
412 hydraulic properties, soil structure, soil biota, among others. For instance, monitoring soil
413 biota may be a significant and broad indicator of the soil's *condition*.

414 **4. The contribution of broad-scale SM, DSM and SMS to the 3rd dimension of Soil Security: soil** 415 **capital**

416 In this section, we analyze how broad-scale SM, DSM and SMS and the derived spatial soil
417 information progressed valuing soil services and evaluating the *capital dimension of soil security*, i.e.
418 the 3rd dimension of Soil Security. Placing monetary values on natural resources allows people to
419 better understand their significance (McBratney et al., 2019a, 2019b). Soil is part of a natural capital
420 defined as the "stock of materials of information contained within an ecosystem" (Costanza et al.,
421 1997). The stocks contained within the soil include, for instance, SOC stocks, available water for
422 plants, nutrients, material for building, areas available for different land uses. This capital, however,
423 does not necessarily have to be converted into financial or market values. The concept of *soil capital*
424 can be distinguished between the five principal forms being: financial, manufactured, human, social

425 and natural capital. When Sanderman et al. (2017) estimated the soil carbon debt of 12,000 years of
426 human land-use, they evidenced very large historical losses, but did not put any monetary value on
427 them. They just showed regions of the world where the largest losses occurred, and elaborated on
428 the feasibility and the time needed to recover part of this debt for climate change mitigation.
429 Nevertheless, some monetary values can be put on SOC stocks, they can be derived from the price of
430 carbon-exchange markets, or even, indirectly, from the potential loss or increase of agricultural yields
431 these stocks could generate (e.g. Lal, 2006, 2020; Soussana et al., 2019).

432 The same two sides of the same coin apply for soil erosion. Some studies remain factual on the
433 estimates of losses by combining broad-scale DSM with modeling. Panagos et al. (2015) estimated
434 mean and total soil loss rates in EU, which are a loss of *soil capital* per se. Another integrative
435 approach to estimate soil losses due to erosion may be to use long-term measurements of the
436 sediments that rivers export (Delmas et al., 2012). Other assessments include various estimates of
437 the costs of erosion in the same area (Panagos et al., 2018; Sartori et al., 2019). One drawback of
438 these estimates is, of course, the propagation of errors from the input data to the errors generated
439 by using and coupling different models. One merit is to give a rough estimate of costs of soil erosion
440 and to raise awareness of policy-makers about the urgent need to put in place regulations to fight
441 erosion (see section 6).

442 Soil sealing by urban and infrastructures sprawls are major issues in many parts of the planet (FAO-
443 ITPS, 2015). A rather straightforward way to monitor them could be using high-resolution remote
444 sensing data. This should allow to provide quantitative estimates, both in time and space of soils that
445 become impervious. This is, however, not trivial to implement in a consistent way. In a review paper,
446 Reba and Seto (2020) concluded that that an overwhelming majority of all studies identify only one
447 urban class. This is very worrying if we want to distinguish impervious areas from others, and to take
448 into account services provided by soil, such as water infiltration or hot-spot temperature regulation.
449 This also often results in a confusion between soil sealing by impervious materials, soil consumption,

450 or land-take. Nevertheless, most attempts to evaluate broad-scale *soil capital* losses due to these
451 processes are mainly restricted to the loss of land for agricultural production and related yields (e.g.
452 Gardi et al., 2015, 2021; Bren d'Amour et al., 2017; Wang et al., 2021; Nickayin et al., 2021). Similarly,
453 soil contamination is often accounted as a loss of suitable lands for agriculture and/or as a loss of
454 food and fodder due to their contamination (see for instance, Liu et al., 2013). Although restricted in
455 their estimates of *soil capital* changes, these approaches have the advantage to convert part of these
456 changes in monetary values.

457 Hewitt et al. (2015) proposed a stock adequacy index to estimate the degree to which the provision
458 of services is limited by natural *soil capital* stocks or advantaged by a stock surplus under a given land
459 use. Though this proposal is very interesting, it is unlikely that it will be readily applicable to large
460 areas SM, DSM or SMS in most of the countries of the world. Obviously, the soil data to calculate this
461 index are either missing or of poor quality in most of the regions of the world, which will result in a
462 very low confidence in using this index. This advocates for developing local DSM and SMS allowing to
463 increase the accuracy of the prediction of soil input data and developing digital soil mapping
464 assessment (DSMA) (Carré et al., 2007; Minasny et al., 2012; Harms et al., 2015). For example, Kidd
465 et al. (2015, 2018) used DSMA in Tasmania and conducted an economic gross margins analysis to
466 produce spatial estimates of potential values of soils. Recently, Bennett et al. (2021) argued that
467 farmers may have the opportunity to be rewarded for environmental services through payable
468 credits and/or offsets via commercial environmental markets. From a study in Sweden, Brady et al.
469 (2019) stated that a valuation method based on indicators of soil natural *capital* and ecosystem
470 services is necessary for influencing soil management decisions at multiple levels.

471 This brief review shows that there are several ways to estimate *soil capital*. This can be done by
472 estimating quantities of soil and related elements, by evaluating the ecosystem services they render,
473 or by transforming their capital or their services into monetary values. Concerning soil stocks capital,
474 Robinson et al. (2017) advocated that with LUCAS Soil and other EU monitoring programs, Europe is

475 well placed to develop pan-European accounts including resources such as soil. In a correspondence
476 to Nature, Obst (2015) writes that Integrating information on soil resources with other measures of
477 natural capital and economic activity remains one of the least developed areas of the United Nations
478 System of Environmental Economic Accounting (SEEA).

479 Therefore, although significant progresses in estimating the *capital* dimension of soil security have
480 been achieved thanks to broad-scale SM, DSM and SMS, there is still a lot of progress required to
481 monitor changes in *soil capital*. Remote sensing offers a promising tool for this, but we must keep in
482 mind that it cannot cover all the aspects of *soil capital* and that it is often limited to information
483 related to land-use, net primary production, or to topsoil properties.

484 **5.- The contribution of broad-scale SM, DSM and SMS to the 4th dimension of Soil Security: soil**
485 **connectivity.**

486 *Connectivity* brings in a social dimension concerning the global soil resource. It is partly concerning a
487 persons' awareness of having ownership for the soil and the responsibility that comes with that. This
488 does require the need of knowledge and resources to sustainably manage the soil according to its
489 *capability* and avoid negative shifts in its *condition*, both short and long term. This applies not only to
490 the immediate users but for the entire society, including citizens, decision- makers and policy-
491 makers.

492 *Connectivity* needs both communication and education. One of the best ways to communicate and
493 educate on issues related to soil degradation and to the need for good soil management practices is
494 to provide maps, or easy to understand figures or fact sheets, showing how soil *condition* is changing
495 rapidly, and alerting about the consequences and impacts that the most severe soil degradation
496 have. To be efficient, we should use a language adapted to the audience we are communicating with.

497 Let us take the example of global issues like soil organic carbon (SOC) change, climate change and
498 food security. Most the citizens and the policy makers are now well aware about the deleterious
499 effects that climate change can have on humanity. However, how many of them made the

500 relationships with soil management before the magic *4 per mille* “slogan” emerged in the political
501 sphere? Historically, this slogan came from a rough calculation made by Balesdent and Arrouays
502 (1999). They used it because they were looking for a striking figure which raised awareness on the
503 importance of SOC for climate change mitigation. This figure came from simply dividing the world
504 anthropogenic C emissions in 1998 by a rough estimate of total SOC down to 1-m made by Batjes
505 (1996) which was mainly based on the combination of a world soil map, available soil profiles with
506 SOC data, and vegetation biomes. It took nearly 16 years of lobbying until this slogan was picked up
507 by the French Ministry of Agriculture who subsequently launched this initiative at the Paris COP21 in
508 2015 (Minasny et al., 2017; Soussana et al., 2019; Martin et al., 2021).

509 Now, let us talk to smallholder African farmers with typically limited resources, for example. Let us
510 suppose that they never heard about this *4 per mille* initiative and that they merely care about
511 climate change mitigation, as increasing drought events keep being a threat to the yield production
512 (Mulder et al., 2019). In this case, we must convince them of the personal perks of the initiative, and
513 explain to them how increasing SOC in soils will be beneficial for climate change adaptation and an
514 increased soil resilience will help fighting against the impact of drought, increasing yields and
515 subsequently the household incomes and food security.

516 Hence, demonstrating the need for SMS is useful for convincing stakeholders, funding agencies, and
517 policy makers at all levels (from sub-national to international). It might, however, be a source of fear
518 for those having intensive or industrial farming systems. They might be afraid that new binding
519 regulations will prevent them to manage their soils as they want, or will generate new controls, new
520 declarations to fill, or even fees. What we have to do with farmers, is to talk about the risk of
521 degrading their main patrimony and production resource, and how improving their soil’s “health” will
522 be beneficial for them, for the environment, and for their children and grandchildren. Moreover, we
523 need to ensure that when we talk about specific terminology with farmers that we have an equal
524 understanding of the meaning of the terminology used and understand the importance of

525 socioeconomics. Take for example 'Land suitability'. Traditionally, soil surveys would assess to which
526 extent the land qualities and land characteristics of a field would match the requirements of e.g.
527 specific land use types or crop requirements (Verheye et al., 1982). However, Møller et al. (2021)
528 assessed the added value of machine learning for agricultural land suitability assessment in Denmark,
529 allowing the integration of both environmental and socioeconomic processes for assessing the
530 suitability of agricultural land. They found that socioeconomic factors play a role at the farmers'
531 decisions which crops to grow rather than solely the land qualities and land characteristics.
532 Consequently, the land suitability assessment was more considered a socioeconomic suitability
533 rather than an ecological suitability assessment. This may very well have been often the case in many
534 of the assessments that we have done so far, yet we have hardly ever considered the socioeconomic
535 value in decision making. In order to improve Soil Security, we need to bridge the gap between the
536 socioeconomic side of decision making and ecological land suitability.

537 Let us talk next about the need to improve soil *condition* to citizens, most of which are living in
538 towns. They will be more convinced about the need for soil security if you explain that soil
539 contamination may have direct consequences on the food they eat, the water they drink, and the air
540 they breathe. Thus, illustrating our communication with maps of broad contamination gradients
541 around big cities might be more convincing than showing them a map of changes in soil pH in their
542 country.

543 There is a great potential of broad-scale SM, DSM and SMS to increase soil *connectivity*, simply
544 because maps and temporal changes are easily understandable and speak for themselves. Our main
545 challenge is to adapt our language and our communication tools to the target audience. There is
546 work to do beyond the soil science community. We should not talk vaguely about the importance of
547 soils. We should communicate according the target audience interests. We should avoid using too
548 much scientific jargon. We should also avoid communicating about the intense scientific debates we
549 have on some definitions. Soil science has been criticized for a long time because soil scientists could

550 not even agree on how to classify or give a common understandable name to the same pedon. There
551 are recurrent scientific debates or even disputes on new concepts as soon as they emerge. Related to
552 the topic of our paper, examples of opinion papers and letters to the editor about the concepts of
553 “Soil Quality”, “Soil Health”, and, unavoidably, now, “Soil Security” are numerous. These are scientific
554 discussions and we do not blame them. New concepts do need to withstand thorough scientific
555 debate prior to a general acceptance by the scientific community yet they should remain
556 constructive. Moreover, exacerbating these debates outside of our community is counter-productive.
557 A real question is “should we communicate only on what is scientifically defined and agreed”? We
558 may have to wait for years. Who will decide that a concept is “scientifically defined and agreed”? We
559 are afraid that it is not a good practice for communication. In this sense, we agree with White and
560 Andrew (2019) when they write “...soil scientists have failed to communicate effectively with the
561 public, the media and policymakers to gain recognition for their achievements and to encourage the
562 investment [...]. Soil science needs communication champions with credible stories to tell.” We are
563 also surprised about the debates on “soil health” which are still ongoing, though already largely used
564 for communication by the US, the FAO, and the EU. This word simply speaks to people. No matter if
565 its scientific definition or its measurement standardization exist. We agree with Lehmann et al.
566 (2020) when they write “Scientists should embrace soil health as an overarching principle that
567 contributes to sustainability goals, rather than only a property to measure.” Though there also some
568 debates about Soil Security concept (Allan, 2019), we also agree with the rather similar statement
569 written on the Global Soil Security website “Yet an overarching concept that brings together these
570 biophysical and socio-economic perspectives of soil is still lacking and this has led to the launch of the
571 Soil Security concept”.

572

573

574 **6. The contribution of broad-scale SM, DSM and SMS to the 5th dimension of Soil Security: soil**
575 **codification**

576 *Codification* refers to policy and regulation applied to soil resources in order to limit their
577 degradation and to ensure that they are suitably and sustainably managed. In this section, we
578 analyse the progress achieved on using broad-scale spatial soil information for soil *codification* (e.g.
579 market regulations, local, national and international policies) and what should be improved further
580 advance this 5th dimension of Soil Security.

581 Numerous results obtained on large areas, using repeated SM, DSM, DSMA, DSM combined with
582 space-for-time substitution processes, or SMS at country, continental, or global level (e.g., Bellamy et
583 al., 2005; Grønlund et al., 2008; van Wesemael et al., 2010; Meersmans et al., 2011; Liu et al., 2013;
584 Ausseil et al., 2015; Stockmann et al., 2015; Gray and Bishop, 2016; Ivushkin et al., 2019) clearly
585 showed that soil degradation is still ongoing and will continue if no action is taken. This kind of
586 scientific output is raising awareness of policy-makers. Many countries already have laws, regulation
587 and incitation mechanisms to protect their soils against degradation or to help farmers to manage
588 soil *condition* (e.g., Australia, Austria, Belgium, China, France, New Zealand, Switzerland, Thailand,
589 US). A comprehensive review is outside the scope of this paper but to mention just a few examples;
590 In the USA there is the Soil and Water Resources Conservation Act (RCA), (USDA RCA Interagency
591 Working Group Members, 2011). The RCA provides the United States Department of Agriculture
592 (USDA) broad strategic assessment and planning authority for the conservation, protection, and
593 enhancement of soil, water, and related natural resources. Very recently, the Australian
594 Government, state and territory governments, the National Soils Advocate and the soil community
595 developed the National Soil Strategy to secure and protect Australia's soil for the future (DAWE,
596 2021). Similar initiatives have been put in place in EU countries; the Netherlands have the Soil
597 Protection Act and the Environmental Protection Act (Ministry of Infrastructure and Water

598 Management, 2013), among many other European countries. Nevertheless, the EU countries are still
599 guided by EU laws and regulations.

600 A good example of how scientific initiatives led to global policy actions is provided by the Pillar 4
601 actions of the UN-FAO Global Soil Partnership (GSP), who already implemented top-down DSM
602 approaches, such as suggested by the *GlobalSoilMap* initiative (Sanchez et al., 2009; Arrouays et al.,
603 2014) to deliver global digital maps of some soil properties. The first example is the Global Soil
604 Organic Map (GSOCmap). The GSOCmap is the first global soil organic carbon map ever produced
605 through a consultative and participatory process involving a majority of member countries who used
606 DSM to provide national products to the GSP. The version 1.5 of the GSOCmap is freely available at
607 <http://54.229.242.119/GSOCmap/>. Further planned initiatives include a global map of salinization
608 and sodification and a map of global carbon sequestration potential.

609 Another positive message is the adoption of the revised world soil charter (WSC) by the UN-FAO
610 nations. In June 2015, Member States of the Food and Agriculture Organization of the UN (FAO)
611 unanimously endorsed an updated version of the WSC. This is a clear political message that soils are
612 now on the top of the political agenda. In particular, the WSC ask all members countries:

613 1) “to incorporate the principles and practices of sustainable soil management into policy guidance
614 and legislation at all levels of government, ideally leading to the development of a national soil
615 policy”,

616 2) “to establish and implement regulations to limit the accumulation of contaminants beyond
617 established levels to safeguard human health and wellbeing and facilitate remediation of
618 contaminated soils that exceed these levels where they pose a threat to humans, plants, and
619 animals”, and,

620 3) “to develop a national institutional framework for monitoring implementation of sustainable soil
621 management and overall state of soil resources”.

622 The Voluntary Guidelines for Sustainable Soil Management (VGSSM, FAO, 2017) were also endorsed
623 by the 155th session of the FAO Council (Rome, 5 December 2016). They complement the WSC by
624 further elaborating principles and practices for incorporation into policies and decision-making.

625 Another strongly encouraging initiative at the EU level is the “European Green Deal” (European
626 Commission, 2019). The new European Green Deal strives to make the European Union the first
627 climate-neutral continent by 2050. The European Commission presented a package of measures,
628 including actions to protect our soils (Montanarella and Panagos, 2021b). Among many ambitions,
629 the strategy addresses soil pollution and aims for severe reductions in the usages of chemical
630 pesticides, fertilizer use plus a decrease of nutrient losses. Moreover, there are ambitions to limit
631 urban sprawl, reduce the pesticides risk and bring back agricultural area under high-diversity
632 landscapes and strongly promote organic farming systems. Furthermore, they aim to progress in the
633 remediation of contaminated sites, reduce land degradation and plant billions of trees. In addition,
634 wetland protection and carbon sequestration are embedded within the European Climate Law. This
635 brief summary of the soil-related aspects of the EU Green Deal shows that soils are on the agenda.
636 However, for the Green Deal to be successful, many organizations in the agricultural sector and other
637 polluting industries but also urban planners and nature organizations will need to be able to
638 understand Soil Security and need local soil information to meet the ambitions set by the Green Deal.
639 Obviously, SM, DSM and SMS can make a substantial contribution to help achieving the ambition of
640 the EU and strive to be the first climate-neutral continent.

641 One main concern of some scientists is to which degree these international endorsements and EU
642 policies will enable a sustainable management of soils and be translated into national policies? There
643 are, for instance, at this moment, no real global concerted actions at EU level for improving soil
644 *codification* (Panagos and Montanarella, 2018; Montanarella and Panagos, 2021a). Glæsner et al.
645 (2014) reviewed the European policies that prevent soil threats and support soil Functions. They
646 concluded that there is currently no legislation at the European level that focuses exclusively on soil

647 conservation. They argued that addressing soil functions individually in various directives fails to
648 account for the multifunctionality of soil. Kutter et al. (2011) stated that only a few EU Member
649 States have enacted comprehensive national soil legislation and although some EU legislation and
650 guidelines are integrated into national laws and programmes, the content and implementation of
651 these policies can differ greatly among the countries. This disparity was also shown by comparing the
652 content and implementation of agricultural contractual policies between France and the Netherlands
653 (Daniel and Perraud, 2009). In a recent comparative analysis of the different approaches adopted by
654 EU Member States, Ronchi et al. (2019) revealed the absence of a common EU strategy to address
655 soil protection and insisted on the inefficacy of the subsidiary principle in the sustainable
656 management of soil resources. This is why in a recent paper, Montanarella and Panagos (2021a)
657 concluded that “binding legal framework is a necessary condition for assuring soil security for the EU
658 and protecting this natural resource from further degradation processes”.

659 As stated by the same authors, however, “soils are considered a crucial national asset and turns out
660 to be a highly sensitive topic for inclusion in binding EU legislative frameworks”. Thus, though we
661 think that soil security has to be included in international treaties, conventions, and even in binding
662 laws, we are afraid that for many countries soils will remain considered a national asset. If we want
663 to change this situation, we believe that the priority should be to increase soil *connectivity*, especially
664 towards citizens, polluting industries, NGO’s and policy-makers. This may ensure soils to become
665 considered a common resource for human beings, at the same level of importance as water and air.
666 One way could be to focus on anthropogenic global issues such as, for instance, food security or
667 human health.

668 **7. Reflection and Conclusion**

669 How do broad-scale SM, DSM and SMS contribute to the 1st and 2nd dimension of Soil Security, the
670 soil *capability and condition*? Our review shows that SM, DSM and SMS can provide the basis for
671 assessing soil *capability and condition* over large areas, especially if we assume that *capability* mainly

672 depends on rather stable soil attributes. Repeated DSM or SMS are appropriated tool to monitor
673 changes in soil *condition* with time at these scales. In case of some drastic changes, they may even
674 allow to map changes in soil *capability*. However, broad-scale SM, DSM and SMS had not yet fully
675 achieved the provision of information concerning the delivery of some soil functions and soil-based
676 ecosystem services. Thus, we must enlarge the range of soil properties that we are monitoring.
677 Physico-chemical and biotic soil data are lacking about changes in nutrient status, biota, compaction,
678 soil structure, soil hydrological parameters, among others. We must also keep in mind that improving
679 soil *capability* and *soil condition* needs local actions. Therefore, we also need to provide SM, DSM
680 and SMS methods and products which are relevant at the local scale.

681 How has spatial soil information progressed valuing soil services and evaluating the *capital* dimension
682 Soil Security? We clearly show examples demonstrating that *soil capital* state and changes can be
683 assessed by estimating quantities of soil and related elements, by evaluating the ecosystem services
684 they render, or by transforming their capital or their services into monetary values. Although
685 significant progress in estimating the *capital* dimension of soil security has been achieved thanks to
686 broad-scale SM, DSM and SMS, yet there is the need to progress monitoring changes in *soil capital*.
687 Remote sensing offers a promising tool for this, but we must keep in mind that it cannot cover all the
688 aspects of *soil capital* and that it is often limited to information related to land-use change, net
689 primary productivity, or to topsoil properties. We must also keep in mind that *soil capital* may be
690 perceived in different ways by different actors, and that our estimates of changes in *soil capital*
691 should cover these different perceptions.

692 How does the development of SM, DSM and SMS contribute to the *soil connectivity*? Does it enable
693 an increase in soil *connectivity* and awareness, and to which target audiences? We show that there is
694 a great potential of broad-scale SM, DSM and SMS to increase soil *connectivity*. One of the best ways
695 to communicate and educate on issues related to soil degradation and to the need for good soil
696 management practices is to provide maps, or easy to understand figures or fact sheets, showing how

697 soil *condition* is changing rapidly, and alerting about the consequences and impacts that the most
698 severe soil degradation have. Our main challenge is to adapt our language and our communication
699 tools to the target audience. Exacerbating some scientific debates outside of the soil science
700 community may be counter-productive.

701 How much have we progressed on using spatial soil information for soil *codification* and what should
702 be improved to further advance soil *codification*? There are obviously encouraging initiatives to
703 enhance soil *codification*. The awareness of policy-makers is raising. Many countries already have
704 laws, regulation and incitation mechanisms to protect their soils against degradation or to help
705 farmers to manage soil *condition*. For example in Europe, numerous EU and international initiatives
706 are very promising and encouraging. However, we are still afraid that for many countries, soils will
707 remain considered a national asset, and that for some local actors even a private asset, such as some
708 EU farmers, EU regulations on soil management may be perceived just as a new constraining tool.
709 We showed that the evolution in SM, DSM and SMS suggests that the main changes were not driven
710 by the soils' Security dimensions, but by issues related to policy priorities. As soil *codification* issues
711 are largely driven by the political agenda, we suggest that there is still an urgent need increase soil
712 *connectivity*, especially towards citizens, NGOs and policy-makers.

713 Finally, we must keep in mind that improving Soil Security requires local actions. Supporting these
714 local actions will require more detailed-scale assessment of the five C's and on how they will be
715 perceived and adopted by local actors.

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