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

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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.

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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 (SGDs) (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., 1013;

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., 1019), *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.

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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: https://ec.europa.eu/info/food-

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 at 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 km^2) 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   UNCDD, 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 providingng 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 estimates 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-variates 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-variates 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 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

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

codification

Codification refers to policy and regulation applied to soil resources in order to limit their

degradation and to ensure that they are suitably and sustainably managed. In this section, we

analyse the progress achieved on using broad-scale spatial soil information for soil *codification* (e.g.

market regulations, local, national and international policies) and what should be improved further

advance this 5th dimension of Soil Security.

Numerous results obtained on large areas, using repeated SM, DSM, DSMA, DSM combined with

space-for-time substitution processes, or SMS at country, continental, or global level (e.g., Bellamy et

al., 2005; Grønlund et al., 2008; van Wesemael et al., 2010; Meersmans et al., 2011; Liu et al., 2013;

Ausseil et al., 2015; Stockmann et al., 2015; Gray and Bishop, 2016; Ivushkin et al., 2019) clearly

showed that soil degradation is still ongoing and will continue if no action is taken. This kind of

scientific output is raising awareness of policy-makers. Many countries already have laws, regulation

and incitation mechanisms to protect their soils against degradation or to help farmers to manage

soil *condition* (e.g., Australia, Austria, Belgium, China, France, New Zealand, Switzerland, Thailand,

US). A comprehensive review is outside the scope of this paper but to mention just a few examples;

In the USA there is the Soil and Water Resources Conservation Act (RCA), (USDA RCA Interagency

Working Group Members, 2011). The RCA provides the United States Department of Agriculture

(USDA) broad strategic assessment and planning authority for the conservation, protection, and

enhancement of soil, water, and related natural resources. Very recently, the Australian

Government, state and territory governments, the National Soils Advocate and the soil community

developed the National Soil Strategy to secure and protect Australia's soil for the future (DAWE,

2021). Similar initiatives have been put in place in EU countries; the Netherlands have the Soil

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.

716   **Aknowledgements**

720   **References**

721   Allan, C., 2019. The Opportunities and Risks of the Soil Security Metaphor: A Review. Sustainability.

722   11, 16, DOI10.3390/su11164464

723   Amundson, R., Berhe, A.A., Hopmans, J.W., Olson, C., Sztein, A.E., Sparks, D.L., 2015. Soil and human

724   security in the 21st century. Science. 348, 6235. https://doi.org/10.1126/science.1261071

725   Arrouays, D., Daroussin, J., Kicin, J.L., Hassika, P., 1998. Improving topsoil carbon storage prediction

726   using a digital elevation model in temperate forest soils of France. Soil Science. 163, 103-108.

727   Arrouays, D., Grundy, M.G., Hartemink, A.E., Hempel, J.W., Heuvelink, G.B.M., Hong, S.Y., Lagacherie,

728   P., Lelyk, G., McBratney, A.B., McKenzie, N.J., Mendonça-Santos, M.d.L., Minasny, B., Montanarella,

729   L., Odeh, I.O.A., Sanchez, P.A., Thompson, J.A., Zhang, G.-L., 2014. GlobalSoilMap: towards a fine-

730   resolution   global   grid   of   soil   properties.   Advances   in   Agronomy.   125,   93-134.

731   https://doi.org/10.1016/B978-0-12-800137-0.00003-0

732   Arrouays, D., Lagacherie, P., Hartemink, A.E., 2017b. Digital soil mapping across the globe. Geoderma

733   Regional. 9, 1-4. https://doi.org/10.1016/j.geodrs.2017.03.002

734   Arrouays, D., Leenaars, J., Richer-de-Forges, A.C., Adhikari, K., Ballabio, C., Greve, M.H., Grundy, M.,

735   Guerrero, E., Hempel, J., Hengl, T., Heuvelink, G.B.M., Batjes, N.H., Carvalho, E., Hartemink, A.E.,

736   Hewitt, A., Hong, S.-Y., Krasilnikov, P., Lagacherie, P., Lelyk, G., Libohova, Z., Lilly, A., McBratney,

737   A.B., Mckenzie, N.J., Vasques, G., Mulder, V.L., Minasny, B., Montanarella, L., Odeh, I., Padarian, J.,

738   Poggio, L., Roudier, P., Saby, N., Savin, I., Searle, R., Stolbovoy, V., Thompson, J.A., Smith, S.,

739   Sulaeman, Y., Vintila, R., Viscarra Rossel, R., Wilson, P., Zhang, G.-L., Swerts, M., van Oorts, K.,

740   Karklins, A., Feng, L., Ibelles Navarro, A.R., Levin, A., Laktionova, T., Dell'Acqua, M., Suvannang, N.,

741   Ruam, W., Prasad, J., Patil, N., Husnjak, S., Pásztor, L., Okx, J., Hallet, S., Keay, C., Farewell, T., Lilja,

742   H., Juilleret, J., Marx, S., Takata, Y., Kayusuki, Y., Mansuy, N., Panagos, P., van Liedekerke, M.,

743   Skalsky, R., Sobocka, J., Kobza, J., Eftekhari, K., Kazem Alavipanah, S., Moussadek, R., Badraoui, M.,

744   da Silva, M., Paterson, G., da Conceição Gonçalves, M., Theocharopoulos, S., Yemefack, M., Tedou,

745   S., Vrscaj, B., Grob, U., Kozak, J., Boruvka, L., Dobos, E., Taboada, M., Moretti, L., Rodriguez, D.,

746   2017a. Soil legacy data rescue via GlobalSoilMap and other international and national initiatives.

747   GeoRes J. 14, 1-19. https://doi.org/10.1016/j.grj.2017.06.001

748   Arrouays, D., Marchant B.P., Saby N.P.A., Meersmans, J., Orton, T.G., Martin, M.P., Bellamy, P.H., Lark

749   R.M., Kibblewhite, M., 2012. Generic issues on broad scale soil monitoring schemes: A review.

750   Pedosphere. 22(4), 456-469.

751   Arrouays, D., Poggio, L., Salazar Guerrero, O., Mulder, V.L. 2020a. Digital Soil Mapping and

752   GlobalSoilMap. Main advances and ways forward. Geoderma Regional, 21. e000265.

753   https://doi.org/10.1016/j.geodrs.2020.e00265

754   Arrouays, D., Richer-de-Forges, A.C., Héliès, F., Mulder, V.L., Saby, N.P.A., Chen, S., Martin, M.P.,

755   Roman Dobarco, M., Follain, S., Jolivet, C., Laroche, B., Cousin, I., Lacoste, M., Ranjard, L., Toutain,

756   B., Le Bas, C., Eglin, T., Bardy, M., Antoni, V. Meersmans J, Ratié C., Bispo, A., 2020b. Impacts of

757   Digital Soil Mapping programs in France at national scale. Geoderma Regional. 23, e00337.

758   https://doi.org/10.1016/j.geodrs.2020.e00337

759   Arrouays, D., Vion, I., Kicin, J.L., 1995. Spatial analysis and modeling of topsoil carbon storage in forest

760   humic loamy soils of France. Soil Sci. 159, 191–198. https://doi.org/10.1097/00010694-199515930-

761   00006

762   Arrouays, D., Vogel, H., Eckelmann, W., Armstrong-Brown, S., Loveland, P., Coulter, B., 1998 Soil

763   monitoring networks in Europe. A review 16th World Congress of Soil Science, Montpellier, France,

764   August 1998.

765   Ausseil, A.-G.E., Jamali, H., Clarkson, B.R., Golubiewski, N.E. 2015. Soil carbon stocks in wetlands of

766   New Zealand and impact of land conversion since European settlement. Wetlands Ecology and

767   Management. 23, 947–961. https://doi.org/10.1007/s11273-015-9432-4

768   Balesdent, J., Arrouays, D., 1999. Usage des terres et stockage de carbone dans les sols du territoire

769   français. Une estimation des flux nets annuels pour la période 1900-1999. C.R. Acad. Agric. Fr. 85,

770   265–277.

771   Barrios, E., 2007. Soil biota, ecosystem services and land productivity. Ecological Economics. 64, 269–

772   285. https://doi.org/10.1016/j.ecolecon.2007.03.004

773   Batjes, N.H., 1996. Total carbon and nitrogen in the soils of the world. Eur J Soil Science. 47, 151–163.

774   https://doi.org/10.1111/j.1365-2389.1996.tb01386.x

775   Batjes, N.H., 2016. Harmonized soil property values for broad-scale modelling (WISE30sec) with

776   estimates   of   global   soil   carbon   stocks.   Geoderma.   269,   61–68.

777   https://doi.org/10.1016/j.geoderma.2016.01.034

778   Bellamy, P.H., Loveland, P.J., Bradley, R.I., Lark, R.M., Kirk, G.J.D., 2005. Carbon losses from all soils

779   across England and Wales 1978-2003. Nature. 437, 245–248. https://doi.org/10.1038/nature04038

780   Bennett, J.M., McBratney, A.B., Field, D.J., Stockmann, U., Liddicoat, C., Grover, S., 2019. Soil Security

781   for Australia. Sustainability. 11(12), 3416. DOI10.3390/su11123416

782   Bennett, J.M., Roberton, S.D., Ghahramania, A., McKenzie, D.C., 2021. Operationalising soil security by

783   making soil data useful: Digital soil mapping, assessment and return-on-investment. Soil Security.

784   4, 100010. https://doi.org/10.1016/j.soisec.2021.100010

785   Boulaine, J.J., 1983. V. V. Dokouchaev et les débuts de la pédologie. Revue d'histoire des sciences. 36(3-

786   4), 285-306. [in French]. doi : https://doi.org/10.3406/rhs.1983.1942

787   Bouma, J., 2019. How to communicate soil expertise more effectively in the information age when

788   aiming   at   the   UN   Sustainable   Development   Goals.   Soil   Use   Manage.   35,   32-38.

789   https://doi.org/10.1111/sum.12415

790   Bouma, J., 2020. Soil security as a roadmap focusing soil contributions on sustainable development

791   agendas. Soil Security. 1, Article 100001. https://doi.org/10.1016/j.soisec.2020.100001

792   Bouma, J., Montanarella, L., 2016. Facing policy challenges with inter- and transdisciplinary soil

793   research focused on the UN sustainable development goals. Soil. 2, 135–145.

794   https://doi.org/10.5194/soil-2-135-2016

795   Bourennane, H., King, D., Chéry, P., Bruand, A., 1996. Improving the kriging of a soil variable using slope

796   gradient as external drift. Eur. J. Soil Sci. 47 (4), 473–483. https://doi.org/10.1111/j.1365-

797   2389.1996.tb01847.x

798   Brady, M.V., Hristov, J., Wilhelmsson, F., Hedlund, K., 2019. Roadmap for Valuing Soil Ecosystem

799   Services to Inform Multi-Level Decision-Making in Agriculture. Sustainability. 11(19), Article

800   Number5285, DOI10.3390/su11195285

801   Bren d'Amour, C., Reitsma, F., Baiocchi, G., Barthel, S., Guneralp, B., Erb, K.H., Haberl, H., Creutzig, F.,

802   Seto, K.C., 2017. Future urban land expansion and implications for global croplands. PNAS. 114(34),

803   8939-8944. DOI10.1073/pnas.1606036114

804   Brus, D.J., 2014. Statistical sampling approaches for soil monitoring: Sampling for soil monitoring.

805   European Journal of Soil Science. 65, 779–791. https://doi.org/10.1111/ejss.12176

806   Brus, D.J., 2021. Statistical approaches for spatial sample survey: Persistent misconceptions and new

807   developments. European Journal of Soil Science. 72(2), 686-703. DOI10.1111/ejss.12988

808   Carré, F., McBratney, A.B., Mayr, T., Montanarella, L., 2007. Digital soil assessments: Beyond DSM.

809   Geoderma. 142(1-2), 69-79. DOI10.1016/j.geoderma.2007.08.015

810   Caubet, M., Roman Dobarco, M., Arrouays, D., Minasny, B., Saby, N., 2019. Merging country,

811   continental and global predictions of soil texture: Lessons from ensemble modelling in France.

812   Geoderma. 337, 99-110. https://doi.org/10.1016/j.geoderma.2018.09.007

813   Cerdan, O., Le Bissonnais, Y., Souchère, V., King, C., Antoni, V., Surdyk, N., Dubus, I., Arrouays, D.,

814   Desprats, J.F., 2006. Guide méthodologique pour un zonage départemental de l'érosion des sols.

815   Rapport n°3 : synthèse et recommandations générales. BRGM/RP-55104-FR. 87 p. [in French].

816   Chen, S., Mulder, V.L., Heuvelink, G.B.M., Poggio, L., Caubet, M., Román Dobarco, M., Walter, C.,

817   Arrouays, D., 2020. Model averaging for mapping topsoil organic carbon in France. Geoderma. 366,

818   114237. https://doi.org/10.1016/j.geoderma.2020.114237

819   Costanza, R., d'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill,

820   R.V., Paruelo, J., Raskin, R.G., Sutton, P., van den Belt, M., 1997. The value of the world's ecosystems

821   services and natural capital. Nature. 387, 253-260. https://doi.org/10.1038/387253a0

822   CPCS., 1967. Commission de Pédologie et de Cartographie des Sols. Classification des sols. Laboratoire

823   de Géologie et de Pédologie, Ecole Nationale Supérieure d'Agronomie, Paris-Grignon, France, 87 p.

824   [in French].

825   Creamer, R.E., Hannula, S.E., Leeuwen, J.P.V., Stone, D., Rutgers, M., Schmelz, R.M., Ruiter, P.C. de,

826   Hendriksen, N.B., Bolger, T., Bouffaud, M.L., Buee, M., Carvalho, F., Costa, D., Dirilgen, T., Francisco,

827   R., Griffiths, B.S., Griffiths, R., Martin, F., Silva, P.M. da, Mendes, S., Morais, P.V., Pereira, C.,

828   Philippot, L., Plassart, P., Redecker, D., Römbke, J., Sousa, J.P., Wouterse, M., Lemanceau, P., 2016.

829   Ecological network analysis reveals the inter-connection between soil biodiversity and ecosystem

830   function as affected by land use across Europe. Applied Soil Ecology. 97, 112–124.

831   https://doi.org/10.1016/j.apsoil.2015.08.006

832   Daniel, F.J., Perraud, D., 2009. The multifunctionality of agriculture and contractual policies. A

833   comparative analysis of France and the Netherlands. Journal of environmental management. 90,

834   Supplement 2, S132-S138. DOI10.1016/j.jenvman.2008.11.015

835   DAWE, 2021. National Soil Strategy. Department of Agriculture, Water and the Environment, Canberra,

836   Australia. https://www.agriculture.gov.au/sites/default/files/documents/awe.gov.au/publications

837   (last access: 07/31/2021)

838   Debeljak, M., Trajanov, A., Kuzmanovski, V., Schröder, J., Sandén, T., Spiegel, H., Wall, D.P., Van de

839   Broek, M., Rutgers, M., Bampa, F., Creamer, R.E., Henriksen, C.B., 2019. A Field-Scale Decision

840   Support System for Assessment and Management of Soil Functions. Front. Environ. Sci. 7, 115.

841   https://doi.org/10.3389/fenvs.2019.00115

842   Delmas, M., Cerdan, O., Cheviron, B., Mouchel, J.M., Eyrolle, F., 2012. Sediment export from French

843   rivers to the sea. Earth Surface Processes and Landforms. 37(7), 754-762. DOI10.1002/esp.3219

844   Doran, J.W., 2002. Soil health and global sustainability: translating science into practice. Agriculture,

845   Ecosystems & Environment. 88, 119–127. https://doi.org/10.1016/S0167-8809(01)00246-8

846   Doran, J.W., Sarrantonio, M., Liebig, M.A., 1996. Soil Health and Sustainability, in: Advances in

847   Agronomy. Elsevier, pp. 1–54. https://doi.org/10.1016/S0065-2113(08)60178-9

848   Doran, J.W., Zeiss, M.R., 2000. Soil health and sustainability: managing the biotic component of soil

849   quality. Applied Soil Ecology. 15, 3–11. https://doi.org/10.1016/S0929-1393(00)00067-6

850   Droogers, P., Bouma, J., 1997. Soil survey input in exploratory modelling of sustainable soil

851   management practices. Soil Sci. Soc. Am. J. 61, 1704-1710.

852   https://doi.org/10.2136/sssaj1997.03615995006100060023x

853   ESDAC (European Soil Data Centre) 2021. European Soil Data Centre. Joint Research Centre, Ispra

854   [WWW document]. URL http://esdac.jrc.ec.europa.eu/ [accessed on 22 July 2021].

855   European Commission, 2019. COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN

856   PARLIAMENT, THE EUROPEAN COUNCIL, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL

857   COMMITTEE AND THE COMMITTEE OF THE REGIONS The European Green Deal - COM/2019/640

858   final. European Commission, Brussels. https://ec.europa.eu/info/strategy/priorities-2019-

859   2024/european-green-deal_en (last access: 07/31/2021)

860   European parliament, 2003. European Parliament legislative resolution on the proposal for a Council

861   regulation on establishing common rules for direct support schemes under the common agricultural

862   policy and support schemes for producers of certain crops (COM(2003) 23 – C5-0040/2003 –

863   2003/0006(CNS)) (No. P5_TA(2003)0256). European parliament - 5th parliamentary term.

864   FAO, 2015. Revised World Soil Charter. Food and Agriculture Organization of the United Nations.

865   Rome. Italy. 7p.

866   FAO, 2017. Voluntary Guidelines for Sustainable Soil Management. Food and Agriculture Organization

867   of the United Nations. Rome, Italy. 16p.

868   FAO/IIASA/ISRIC/ISS-CAS/JRC, 2008. Harmonized World Soil Database (version 1.0). FAO, Rome, Italy

869   and IIASA, Laxenburg, Austria. 37 p. http://www.fao.org/uploads/media/Harm-World-Soil-

870   DBv7cv_1.pdf (last access 06/28/2021)

871   FAO-ITPS, 2015. Status of the World's Soil Resources (SWSR). Main Report. Food and Agriculture

872   Organization of the United Nations and Intergovernmental Technical Panel on Soils. Rome, Italy.

873   Field, D.J., 2020. Sustaining agri-food systems framed using soil security and education. International

874   journal of agriculture and natural resources. 47, 3, 249-260. DOI10.7764/ijanr.v47i3.2289.

875   Field, D.J., Morgan, C.L.S., McBratney, A.B., (eds). 2017 Global Soil Security. Progress in Soil Science,

876   Springer, 463 p. 42 chapters. DOI10.1007/978-3-319-43394-3_1

877   Gardi, C., Florczyk, A.J., Scalenghe, R., 2021. Outlook from the soil perspective of urban expansion and

878   food security. Heliyon. 7(1), e05860. DOI10.1016/j.heliyon.2020.e05860

879 Gardi, P., Panagos, P., Van Liedekerke, M., Bosco, C., De Brogniez, D., 2015. Land take and food security:

880   assessment of land take on the agricultural production in Europe. Journal of Environmental

881   Planning and Management. 58, 5, 898-912. https://doi.org/10.1080/09640568.2014.899490

882 Glæsner, N., Helming, K., de Vries, W., 2014. Do Current European Policies Prevent Soil Threats and

883   Support Soil Functions? Sustainability. 6, 12, 9538-9563. DOI10.3390/su6129538

884 Gray, J.M., Bishop, T.F.A., 2016. Change in Soil Organic Carbon Stocks under 12 Climate Change

885   Projections over New South Wales, Australia. Soil Science Society of America Journal. 80(5), 1296-

886   1307. DOI10.2136/sssaj2016.02.0038

887 Grønlund, A., Hauge, A., Hovde, A., Rasse, D.P., 2008. Carbon loss estimates from cultivated peat soils

888   in Norway: a comparison of three methods. Nutrient Cycling in Agroecosystems. 81, 157–167.

889   https://doi.org/10.1007/s10705-008-9171-5

890 Grunwald, S., Thompson, J.A., Boettinger, J.L., 2011. Digital soil mapping and modeling at continental

891   scales: Finding solutions for global issues. Soil Science Society of America Journal. 75, 1201–1213.

892   https://doi.org/10.2136/sssaj2011.0025

893 Harms, B., Brough, D., Philip, S., Bartley, R., Clifford, D., Thomas, M., Willis, R., Gregory, L., 2015. Digital

894   soil assessment for regional agricultural land evaluation. Glob. Food Sec. 5, 25–36.

895   https://doi.org/10.1016/j.gfs.2015.04.001

896 Hartemink, A.E., McBratney, A.B., 2008. A soil science renaissance. Geoderma. 148,123–129.

897   https://doi.org/10.1016/j.geoderma.2008.10.006

898 Hengl, T., de Jesus, J.M., Heuvelink, G.B.M., Gonzalez, M.R., Kilibarda, M., Blagotic, A., Shangguan, W.,

899   Wright, M.N., Blagotic, A., Geng, X.Y., Bauer-Marschallinger, B., Guevara, M.A., Vargas, R.,

900   MacMillan, R.A., Batjes, N.H., Leenaars, J.G.B., Ribeiro, E., Wheeler, I., Mantel, S., Kempen, B.,

901   2017a. SoilGrids250m: global gridded soil information based on Machine Learning. PLoS ONE. 12(2),

902   e0169748. https://doi.org/10.1371/journal.pone.0169748

903   Hengl, T., de Jesus, J.M., MacMillan, R.A., Batjes, N.H., Heuvelink, G.B.M., Ribeiro, E., Samuel-Rosa, A.,

904   Kempen, B., Leenaars, J.G.B., Walsh, M.G., Gonzalez, M.R., 2014. SoilGrids1km-Global Soil

905   Information Based on Automated Mapping. PLoS ONE. 9(8), e105992.

906   DOI10.1371/journal.pone.0105992

907   Hengl, T., Heuvelink G.B.M., Kempen, B., Leenaars J.G.B., Walsh, M.G., Shepherd, K., Sila, A.,

908   MacMillan, R.A., de Jesus, J.M., Tamene, L., Tondoh, J.E., 2015. Mapping soil properties of Africa at

909   250 m resolution: random forests significantly improve current predictions. PLoS ONE. 10(6),

910   e0125814. https://doi.org/10.1371/journal.pone.0125814

911   Hengl, T., Leenaars, J.G.B., Shepherd, K.D., Walsh, M.G., Heuvelink, G.B.M., Mamo, T., Tilahun, H.,

912   Berkhout, E., Cooper, M., Fegraus, E., Wheeler, I., Kwabena, N.A., 2017b. Soil nutrient maps of Sub-

913   Saharan Africa: assessment of soil nutrient content at 250 m spatial resolution using machine

914   learning. Nutr Cycl Agroecosyst. 109, 77–102. https://doi.org/10.1007/s10705-017-9870-x

915   Heuvelink, G.B.M., 2014. Uncertainty quantification of *GlobalSoilMap* products. In: *GlobalSoilMap*:

916   Basis of the global spatial soil information system. Arrouays, D., McKenzie, N.J., Hempel, J., Richer-

917   de-Forges, A.C., McBratney, A.B., (eds). pp. 335-340. CRC Press-Taylor & Francis, Boca Raton, FL.

918   USA.

919   Hewitt, A., Dominati, E., Webb, T., Cuthill, T., 2015. Soil natural capital quantification by the stock

920   adequacy method. Geoderma. 241, 107-114. DOI10.1016/j.geoderma.2014.11.014

921   Huang, J.Y., McBratney, A.B., Malone, B.P., D.J. Field, D.J., 2018. Mapping the transition from pre-

922   European settlement to contemporary soil conditions in the Lower Hunter Valley Australia.

923   Geoderma. 329, 27-42, 10.1016/j.geoderma.2018.05.016

924   Ivushkin, K., Bartholomeus, H.,Bregt, A.K., Pulatov, A., Kempen, B., de Sousa, L., 2019. Global mapping

925   of soil salinity change. Remote Sensing Env. 231, 111260. DOI10.1016/j.rse.2019.111260

926 Jamagne, M., 1967. Bases et techniques d'une cartographie des sols. Annales Agronomiques. 18,

927   numéro hors-série. 142 p. [in French].

928 Jamagne, M., 1973. Contribution à l'étude pédogénétique des formations loessiques du Nord de la

929   France. PhD Thesis, Fac. Sci. Agron. Gembloux. France. 475 p. [In French]

930 Jamagne, M., 1978. Les processus pédogénétiques dans une séquence évolutive progressive sur

931   formations limoneuses en zone tempérée froide et humide. C. R. Acad. Sci. 286(17), 25-27. [In

932   French]

933 Jamagne, M., Bornand, M., Hardy, R., 1989. La cartographie des sols en France à moyenne échelle.

934   Programmes en cours et évolution des démarches. Science du sol. 27, 301–318. [In French]

935 Jamagne, M., De Coninck, F., Robert, M., Maucorps, J., 1984. Mineralogy of the clay fractions of some

936   soils in northern France. Geoderma. 33, 319-342. https://doi.org/10.1016/0016-7061(84)90032-6

937 Jones, R.J.A., van Diepen, K., van Orshoven, J., Confalonieri, R., 2014. Scientific contribution on

938   combining biophysical criteria underpinning the delineation of agricultural areas affected by

939   specific constraints. Scientific and Technical Research Reports: Report EUR 26940 EN. EC-JRC

940   Publications Office, 85p.

941 Journal officiel de la République française., 1961. Loi n° 61-1489 du 26 décembre 1961 relative à

942   l'accueil et à la réinstallation des Français d'outre-mer. In: Journal officiel de la République

943   française. Lois et décrets, n° 0304, 11996-11997. [in French].

944   https://www.legifrance.gouv.fr/jorf/id/JORFTEXT000000508788 (last accessed, 07/30/2021).

945 Karimi, B., Terrat, S., Dequiedt, S., Saby, N.P.A., Horrigue, W., Lelièvre, M., Nowak, V., Jolivet, C.,

946   Arrouays, D., Wincker, P., Cruaud, C., Bispo, A., Maron, P.-A., Bouré, N.C.P., Ranjard, L., 2018.

947   Biogeography of soil bacteria and archaea across France. Sci. Adv. 4, eaat1808.

948   https://doi.org/10.1126/sciadv.aat1808

949   Karlen, D.L., Andrews, S.S., Doran, J.W., 2001. Soil quality: Current concepts and applications, in:

950   Advances in Agronomy. Elsevier, pp. 1–40. https://doi.org/10.1016/S0065-2113(01)74029-1

951   Karlen, D.L., Mausbach, M.J., Doran, J.W., Cline, R.G., Harris, R.F., Schuman, G.E., 1997. Soil Quality: A

952   Concept, Definition, and Framework for Evaluation (A Guest Editorial). Soil Science Society of

953   America Journal. 61, 4–10. https://doi.org/10.2136/sssaj1997.03615995006100010001x

954   Keesstra, S.D., Bouma, J., Wallinga, J., Tittonell, P., Smith, P., Cerdà, A., Montanarella, L., Quinton, J.N.,

955   Pachepsky, Y., Van Der Putten, W.H., Bardgett, R.D., Moolenaar, S., Mol, G., Jansen, B., Fresco, L.O.,

956   2016. The significance of soils and soil science towards realization of the United Nations sustainable

957   development goals. Soil. 2, 111–128.

958   Keesstra, S.D., Munkholm, L., Cornu, S., Visser, S.M., Faber, J., Kuikman, P., Thorsoe, M., de Haan, J.,

959   Vervuurt, W., Verhagen, J., Neumann, M., Fantappie, M., van Egmond, F., Bispo, A., Wall, D.,

960   Berggreen, L., Barron, J., Gascuel, C., Granjou, C., Gerasina, R., Chenu, C., 2021. Roadmap of the

961   European Joint Programme SOIL (EJP SOIL Report, deliverable 2.4.).

962   Kempen, B., Brus, D.J., Stoorvogel, J.J., Heuvelink, G.B.M., de Vries, F., 2012. Efficiency Comparison of

963   Conventional and Digital Soil Mapping for Updating Soil Maps. Soil Sci. Soc. Am. J. 76(6), 2097-2115.

964   DOI10.2136/sssaj2011.0424

965   Kidd, D., Field, D.J., McBratney, A.B., Webb, M., 2018. A preliminary spatial quantification of the soil

966   security dimensions for Tasmania. Geoderma. 322, 184-200. DOI10.1016/j.geoderma.2018.02.018

967   Kidd, D., Webb, M., Malone, B., Minasny, B., McBratney, A., 2015. Digital soil assessment of agricultural

968   suitability, versatility and capital in Tasmania, Australia. Geoderma Reg. 6, 7–21.

969   https://doi.org/10.1016/j.geodrs.2015.08.005

970   King, D., Daroussin, J., Tavernier, R., 1994. Development of a soil geographic database from the soil

971   map of the European Communities. CATENA. 21(1), 37-51.

972   Kirk, G.J.D., Bellamy, P.H., Lark, R.M., 2010. Changes in soil pH across England and Wales in response
973   to decreased acid deposition. Global change biology. 16(11), 3111-3119. DOI10.1111/j.1365-
974   2486.2009.02135.x

975   Koch, A., Chappell, A., Eyres, M., Scott, E., 2015. Monitor Soil Degradation or Triage for Soil Security?
976   An Australian Challenge. Sustainability. 7(5), 4870-4892. https://doi.org/10.3390/su7054870

977   Koch, A., McBratney, A.B., Adams, M., Field, D.; Hill, R., Crawford, J., Minasny, B., Lal, R., Abbott, L.,
978   O'Donnell, A., Angers, D.A., Baldock, J., Barbier, E., Binkley, D., Parton, W., Wall, D.H., Bird, M.,
979   Bouma, J., Chenu, C., Flora, C.B., Goulding, K., Grunwald, S., Hempel, J., Jastrow, J., Lehmann, J.,
980   Lorenz, K., Morgan, C.L.S., Rice, C.W., Whitehead, D., Young, I., Zimmermann, M., 2013. Soil
981   Security: Solving the Global Soil Crisis. Glob. Policy. 4, 434–441. DOI10.1111/1758-5899.12096

982   Koch, A., McBratney, A.B., Lal, R., 2012. Put soil security on the global agenda. Nature. 492, 7428, 186-
983   186. DOI10.1038/492186d

984   Kutter, T., Louwagie, G., Schuler, J., Zander, P., Helming, K., Hecker, J.-M., 2011. Policy measures for
985   agricultural soil conservation in the European Union and its member states: Policy review and
986   classification. Land Degrad. Dev. 22, 18–31. https://doi.org/10.1002/ldr.1015

987   Lagacherie, P., Depraetere, C., 1991. Analyse des relations sol-paysage au sein d'un secteur de
988   référence en vue d'un zonage pédologique semi-automatisé d'une petite région naturelle. In: Riou,
989   C. (Ed.), Le Zonage Agropédoclimatique, Séminaire Paris, 23 et 24 Mars 1989, pp. 116–138. [in
990   French]

991   Lagacherie, P., Legros, J.-P., Burrough, P.A., 1995. A soil survey procedure using the knowledge of soil
992   pattern established in a previously mapped reference area. Geoderma. 65 (3/4), 283–301.
993   https://doi.org/10.1016/0016-7061(94)00040-H

994   Lagacherie, P., McBratney, A.B., Voltz, M., 2006. Digital Soil Mapping: An Introductory Perspective,
995   Developments in Soil Science. 31, 600 p. Elsevier Science. Amsterdam, Boston.

996 Lal, R., 2006. Enhancing crop yields in the developing countries through restoration of the soil organic

997   carbon pool in agricultural lands. Land Degrad. Dev. 17, 197-209. https://doi.org/10.1002/ldr.696

998 Lal, R., 2020. Managing soils for negative feedback to climate change and positive impact on food and

999   nutritional security. Soil Sci. Plant Nutr. 66, 1–9. https://doi.org/10.1080/00380768.2020.1718548

1000 Leenaars, J.G.B., 2014. ISRIC Report 2012/03. Africa Soil Information Service (AfSIS) project.

1001   Wageningen, The Netherlands: ISRIC - World Soil Information. 148p.

1002 Leenaars, J.G.B., Claessens, L., Heuvelink, G.B.M., Hengl, T., Ruiperez González, M., van Bussel, L.G.J.,

1003   Guilpart, N., Yang, H., Cassman, K.G., 2018. Mapping rootable depth and root zone plant-available

1004   water holding capacity of the soil of sub-Saharan Africa. Geoderma. 324, 18–36.

1005   https://doi.org/10.1016/j.geoderma.2018.02.046

1006 Leenaars, J.G.B., Kempen, B., van Oostrum, A.J.M., Batjes, N.H., 2014a. Africa soil profiles database: a

1007   compilation of georeferenced and standardised legacy soil profile data for Sub-Saharan Africa. In:

1008   Arrouays, D., McKenzie, N.J., Hempel, J.W., Richer-de-Forges, A.C., McBratney, A.B., (eds).

1009   *GlobalSoilMap*: basis of the global soil information system. CRC Press-Taylor & Francis, Boca Raton,

1010   FL. USA. pp. 51–57.

1011 Leenaars, J.G.B., van Oostrum, A.J.M., Ruiperez Gonzalez, A.J.M., 2014b. ISRIC report 2014/01. Africa

1012   Soil Information Service (AfSIS) project. Wageningen, The Netherlands: ISRIC - World Soil

1013   Information.

1014 Legros, J.-P., 1996. Cartographies des sols: de l'analyse spatiale à la gestion des territoires, 1. éd. ed,

1015   Collection Gérer l'environnement. Presses Polytechniques et Univ. Romandes, Lausanne. [in

1016   French]

1017 Legros, J.P., Bonneric, P., 1979. Modélisation informatique de la répartition des sols dans le Parc

1018   Régional Naturel du Pilat. Ann. Univ. Savoie. 63–68. [in French]

1019   Lehmann, J., Bossio, D.A., Kogel-Knabner, I., Illig, M.C., 2020. The concept and future prospects of soil

1020   health. Nature Reviews Earth & Environment. 1, 10, 544-553. DOI10.1038/s43017-020-0080-8

1021   Leonhardt, H., Penker, M., Salhofer, K., 2019. Do farmers care about rented land? A multi-method

1022   study on land tenure and soil conservation. Land Use Policy. 82, 228–239.

1023   https://doi.org/10.1016/j.landusepol.2018.12.006

1024   Liu Y., Wen, C., Liu, X., 2013. China's Food Security Soiled by Contamination. Science. 339, 6126, 1382-

1025   1383. DOI: 10.1126/science.339.6126.1382-b

1026   Louis, B.P., Saby, N.P.A., Orton, T.G., Lacarce, E., Boulonne, L., Jolivet, C., Ratié, C., Arrouays, D., 2014.

1027   Statistical sampling design impact on predictive quality of harmonization functions between soil

1028   monitoring networks. Geoderma. 213, 133–143. https://doi.org/10.1016/j.geoderma.2013.07.018

1029   Martin M.P., Dimassi, B., Roman Dobarco, M., Guenet, B., Arrouays, D., Angers, D.A., Soussana, J.F.,

1030   Pellerin, S. 2021. Feasibility of the 4 per 1000 aspirational target for soil carbon. A case study for

1031   France. Global Change Biology. 27(11), 2458-2477. doi: 10.1111/GCB.15547.

1032   Martiny, J.B.H., Bohannan, B.J.M., Brown, J.H., Colwell, R.K., Fuhrman, J.A., Green, J.L., Horner-Devine,

1033   M.C., Kane, M., Krumins, J.A., Kuske, C.R., Morin, P.J., Naeem, S., Øvreås, L., Reysenbach, A.-L.,

1034   Smith, V.H., Staley, J.T., 2006. Microbial biogeography: putting microorganisms on the map. Nat.

1035   Rev. Microbiol. 4, 102–112. https://doi.org/10.1038/nrmicro1341

1036   McBratney, A.B., Field, D.J., 2015. Securing our soil. Soils Science and Plant Nutrition. 61, 4, 587-591.

1037   DOI10.1080/00380768.2015.1071060.

1038   McBratney, A.B., Field, D.J., Jarrett, L.E., 2017. General Concepts of Valuing and Caring for Soil, in: Field,

1039   D.J., Morgan, C.L.S., McBratney, A.B. (Eds.), Global Soil Security, Progress in Soil Science. Springer

1040   International Publishing, Cham, pp. 101–108. https://doi.org/10.1007/978-3-319-43394-3_9

1041   McBratney, A.B., Field, D.J., Koch, A., 2014. The dimensions of soil security. Geoderma. 213, 203-213.

1042   https://doi.org/10.1016/j.geoderma.2013.08.013

1043   McBratney, A.B., Field, D.J., Morgan, C.L.S., Huang, J., 2019a. On Soil Capability, Capacity, and

1044   Condition. Sustainability. 11(12), Article Number3350. DOI10.3390/su11123350

1045   McBratney, A.B., Mendonça Santos, M.L., Minasny, B., 2003. On digital soil mapping. Geoderma. 117,

1046   3–52. https://doi.org/10.1016/S0016-7061(03)00223-4

1047   McBratney, A.B., Moyce, M., Field, D.J., Bryce, E., 2019b. The concept of soil security. In: Richer-de-

1048   Forges, A.C., Carré, F., McBratney, A.B., Bouma, J., Arrouays, D., (eds). Global Soil Security. Towards

1049   more science-society interfaces. CRC Press, Taylor & Francis, London. pp. 11-17.

1050   MEA (Millenium Ecosystem Assessment), 2005. Ecosystems and human well-being: biodiversity

1051   synthesis. Washington D.C., World Resources Institute.

1052   MEDDE and Gis Sol, 2013. Guide pour l'identification et la délimitation des sols de zones humides.

1053   Ministère de l'Écologie, du Développement Durable et de l'Énergie. Groupement d'Intérêt

1054   Scientifique Sol. 63p. [in French].

1055   Meersmans, J., van Wesemael, B., Goidts, E., van Molle, M., De Baets, S., De Ridder, F., 2011. Spatial

1056   analysis of soil organic carbon evolution in Belgian croplands and grasslands, 1960-2006. Global

1057   Change Biology, 17(1), 466-479. DOI10.1111/j.1365-2486.2010.02183.x

1058   Minasny, B., Berglund, O., Connolly, J., Hedley, C., de Vries, F., Gimona, A., Kempen, B., Kidd, D., Lilja,

1059   H., Malone, B., McBratney, A.B., Roudier, P., O'Rourke, S., Rudiyanto, Padarian, J., Poggio, L., ten

1060   Caten, A., Thompson, D., Tuve, C., Widyatmanti, W., 2019. Digital mapping of peatlands - A critical

1061   review. Earth-Science Reviews. 196, DOI10.1016/j.earscirev.2019.05.014

1062   Minasny, B., Malone, B.P., McBratney, A.B., (eds), 2012. Digital Soil Assessments and Beyond. CRC

1063   Press, Taylor & Francis, Boca Raton, FL. USA. 446 p. + CD.

1064   Minasny, B., Malone, B.P., McBratney, A.B., Angers, D.A., Arrouays, D., Chambers, A., Chaplot, V., Chen,

1065   Z.-S., Cheng, K., Das, B.S., Field, D.J., Gimona, A., Hedley, C.B., Hong, S.Y., Mandal, B., Marchant,

1066   B.P., Martin, M., McConkey, B.G., Mulder, V.L., O'Rourke, S., Richer-de-Forges, A.C., Odeh, I.,

1067   Padarian, J., Paustian, K., Pan, G., Poggio, L., Savin, I., Stolbovoy, V., Stockmann, U., Sulaeman, Y.,

1068   Tsui, C.-C., Vågen, T.-G., van Wesemael, B., Winowiecki, L., 2017. Soil carbon 4 per mille. Geoderma

1069   292, 59–86. https://doi.org/10.1016/j.geoderma.2017.01.002

1070   Minasny, B., McBratney, A. B., 2016. Digital soil mapping: A brief history and some lessons. Geoderma.

1071   264, 301-311. https://doi.org/10.1016/j.geoderma.2015.07.017

1072   Ministry of Infrastructure and Water Management, 2013. Soil Protection Act. The Netherlands.

1073   https://rwsenvironment.eu/subjects/soil/legislation-and/ (last access: 07/31/2021)

1074   Møller, A.B., Mulder, V.L., Heuvelink, G.B.M., Jacobsen, N.M., Greve, M.H., 2021. Can We Use Machine

1075   Learning   for   Agricultural   Land   Suitability   Assessment?   Agronomy.   11,   703.

1076   https://doi.org/10.3390/agronomy11040703

1077   Montanarella, L., 2015. Govern our soils. Nature. 528, 32-33. https://doi.org/10.1038/528032a

1078   Montanarella, L., Panagos, P., 2021a. Soil Security for the European Union. Soil Security. 4, 100009.

1079   https://doi.org/10.1016/j.soisec.2021.100009

1080   Montanarella, L., Panagos, P., 2021b. The relevance of sustainable soil management within the

1081   European   Green   Deal.   Land   Use   Policy.   100,   104950.

1082   https://doi.org/10.1016/j.landusepol.2020.104950

1083   Montanarella, L., Pennock, D.J., McKenzie, N.J., Badraoui, M., Chude, V., Baptista, I., Mamo, T.

1084   Yemefack, M., Singh Aulakh, M., Yagi, K., Young Hong, S., Vijarnsorn, P., Zhang, G.-L., Arrouays, D.,

1085   Black, H., Krasilnikov, P., Sobocká, J., Alegre, J., Henriquez, C.R., Mendonça-Santos, M.d.L., Taboada,

1086   M., Espinosa-Victoria, D., AlShankiti, A., AlaviPanah, S.K., Elsheikh, E.A.E., Hempel, J., Camps-

1087   Arbestain, M., Nachtergaele, F., Vargas, R., 2016. World's soils are under threat. Soil. 2, 79-82.

1088   https://doi.org/10.5194/soil-2-79-2016

1089   Morgan, C.L.S., McBratney, A.B., 2020. Editorial: Widening the disciplinary study of soil. Soil Security.

1090   1, 100003. https://doi.org/10.1016/j.soisec.2020.100003

1091   Morvan, X.P.P., Saby, N.P.A., Arrouays, D., Le Bas, C., Jones R.J.A., Verheijen, F.G.A, Bellamy P.H.,

1092   Stephens, M., Kibblewhite, M.G., 2008. Soil monitoring in Europe: a review of existing systems and

1093   requirements   for   harmonisation.   Sci.   Tot.   Env.   391,   1-12.

1094   https://doi.org/10.1016/j.scitotenv.2007.10.046

1095   Mulder, V.L., van Eck, C.M., Friedlingstein, P., Arrouays, D., Regnier, P., 2019. Controlling factors for

1096   land productivity under extreme climatic events in continental Europe and the Mediterranean

1097   Basin. CATENA. 182, 104124. https://doi.org/10.1016/j.catena.2019.104124

1098   Murphy, B., Fogarty, P., 2019. Application of the Soil Security Concept to Two Contrasting Soil

1099   Landscape Systems-Implications for Soil Capability and Sustainable Land Management.

1100   Sustainability. 11(20), Article Number5706. DOI10.3390/su11205706

1101   Nickayin, S.S., Perrone, F., Ermini, B., Quaranta, G., Salvia, R., Gambella, F., Egidi, G., 2021. Soil Quality

1102   and Peri-Urban Expansion of Cities: A Mediterranean Experience (Athens, Greece). Sustainability.

1103   13(4), 2042. DOI10.3390/su13042042

1104   Obst, C.G., 2015. Economics: Account for soil as natural capital. Nature. 527, 165–165.

1105   https://doi.org/10.1038/527165b

1106   Orgiazzi, A., Ballabio, C., Panagos, P., Jones, A., Fernández-Ugalde, O., 2018. LUCAS Soil, the largest

1107   expandable soil dataset for Europe: a review. European Journal of Soil Science. 69, 140–153,

1108   https://doi.org/10.1111/ejss.12499

1109   Padarian, J., McBratney, A.B., 2020. A new model for intra- and inter-institutional soil data sharing.

1110   SOIL. 6(1), 89-94. DOI10.5194/soil-6-89-2020

1111   Padarian, J., Minasny, B., McBratney A.B., 2019. Online machine learning for collaborative biophysical

1112   modelling.   Environmental   Modelling   &   Software.   122,   104548.

1113   https://doi.org/10.1016/j.envsoft.2019.104548

1114   Panagos, P., Borrelli, P., Poesen, J., Ballabio, C., Lugato, E., Meusburger, K., Montanarella, L., Alewell,

1115   C., 2015. The new assessment of soil loss by water erosion in Europe. Environmental Science &

1116   Policy. 54, 438-447. DOI10.1016/j.envsci.2015.08.012

1117   Panagos, P., Montanarella, L., 2018. Soil Thematic Strategy: an important contribution to policy

1118   support, research, data development and raising the awareness. Curr. Opin. Environ. Sci. Health. 5,

1119   38-41. https://doi.org/10.1016/j.coesh.2018.04.008

1120   Panagos, P., Standardi, G., Borrelli, P., Lugato, E., Montanarella, L., Bosello, F., 2018. Cost of agricultural

1121   productivity loss due to soil erosion in the European Union: from direct cost evaluation approaches

1122   to the use of macroeconomic models. Land Degrad. Dev. 29, 471-484.

1123   https://doi.org/10.1002/ldr.2879

1124   Panagos, P., Van Liedekerke, M., Jones, A., Montanarella, L., 2012. European Soil Data Centre:

1125   Response to European policy support and public data requirements. Land Use Policy. 29 (2), 329-

1126   338. doi:10.1016/j.landusepol.2011.07.003

1127   Phillips, H.R.P., Guerra, C.A., Bartz, M.L.C., Briones, M.J.I., Brown, G., Crowther, T.W., Ferlian, O.,

1128   Gongalsky, K.B., van den Hoogen, J., Krebs, J., Orgiazzi, A., Routh, D., Schwarz, B., Bach, E.M.,

1129   Bennett, J.M., Brose, U., Decaëns, T., König-Ries, B., Loreau, M., Mathieu, J., Mulder, C., van der

1130   Putten, W.H., Ramirez, K.S., Rillig, M.C., Russell, D., Rutgers, M., Thakur, M.P., de Vries, F.T., Wall,

1131   D.H., Wardle, D.A., Arai, M., Ayuke, F.O., Baker, G.H., Beauséjour, R., Bedano, J.C., Birkhofer, K.,

1132   Blanchart, E., Blossey, B., Bolger, T., Bradley, R.L., Callaham, M.A., Capowiez, Y., Caulfield, M.E.,

1133   Choi, A., Crotty, F.V., Crumsey, J.M., Dávalos, A., Diaz Cosin, D.J., Dominguez, A., Duhour, A.E., van

1134   Eekeren, N., Emmerling, C., Falco, L.B., Fernández, R., Fonte, S.J., Fragoso, C., Franco, A.L.C., Fugère,

1135   M., Fusilero, A.T., Gholami, S., Gundale, M.J., López, M.G., Hackenberger, D.K., Hernández, L.M.,

1136   Hishi, T., Holdsworth, A.R., Holmstrup, M., Hopfensperger, K.N., Lwanga, E.H., Huhta, V., Hurisso,

1137   T.T., Iannone, B.V., Iordache, M., Joschko, M., Kaneko, N., Kanianska, R., Keith, A.M., Kelly, C.A.,

1138   Kernecker, M.L., Klaminder, J., Koné, A.W., Kooch, Y., Kukkonen, S.T., Lalthanzara, H., Lammel, D.R.,

1139 Lebedev, I.M., Li, Y., Jesus Lidon, J.B., Lincoln, N.K., Loss, S.R., Marichal, R., Matula, R., Moos, J.H.,

1140 Moreno, G., Morón-Ríos, A., Muys, B., Neirynck, J., Norgrove, L., Novo, M., Nuutinen, V., Nuzzo, V.,

1141 Mujeeb Rahman P95, Pansu, J., Paudel, S., Pérès, G., Pérez-Camacho, L., Piñeiro, R., Ponge, J.-F.,

1142 Rashid, M.I., Rebollo, S., Rodeiro-Iglesias, J., Rodríguez, M.Á., Roth, A.M., Rousseau, G.X., Rozen, A.,

1143 Sayad, E., van Schaik, L., Scharenbroch, B.C., Schirrmann, M., Schmidt, O., Schröder, B., Seeber, J.,

1144 Shashkov, M.P., Singh, J., Smith, S.M., Steinwandter, M., Talavera, J.A., Trigo, D., Tsukamoto, J., de

1145 Valença, A.W., Vanek, S.J., Virto, I., Wackett, A.A., Warren, M.W., Wehr, N.H., Whalen, J.K.,

1146 Wironen, M.B., Wolters, V., Zenkova, I.V., Zhang, W., Cameron, E.K., Eisenhauer, N., 2019. Global

1147 distribution of earthworm diversity. Science. 366, 480–485.

1148 https://doi.org/10.1126/science.aax4851

1149 Poggio, L., de Sousa, L.M., Batjes, N.H., Heuvelink, G.B.M., Kempen, B., Riberio, E., Rossiter, D., 2021.

1150 SoilGrids 2.0: producing quality-assessed soil information for the globe. SOIL. 7(1), 217-240.

1151 DOI10.5194/soil-7-217-2021

1152 Pulleman, M., Creamer, R., Hamer, U., Helder, J., Pelosi, C., Pérès, G., Rutgers, M., 2012. Soil

1153 biodiversity, biological indicators and soil ecosystem services—an overview of European

1154 approaches. Current Opinion in Environmental Sustainability. 4, 529–538.

1155 https://doi.org/10.1016/j.cosust.2012.10.009

1156 Reba, M., Seto, K.C., 2020. A systematic review and assessment of algorithms to detect, characterize,

1157 and monitor urban land change. Remote Sensing of Environment. 242, 111739.

1158 DOI10.1016/j.rse.2020.111739

1159 Richer-de-Forges., A.C., Arrouays, D., Bardy, M., Bispo, A., Lagacherie, P., Laroche, B., Lemercier, B.,

1160 Sauter, J., Voltz, M., 2019b. Mapping of Soils and Land-Related Environmental attributes in France:

1161 analysis of end-users' needs. Sustainability. 11, 2940. doi:10.3390/su11102940.

1162 Richer-de-Forges, A.C., Baffet, M., Berger, C., Coste, S., Courbe, C., Jalabert, S., Lacassin, J.-C., Maillant,

1163 S., Michel, F., Moulin, J., Party, J.-P., Renouard, C., Sauter, J., Scheurer, O., Verbèque, B.,

1164   Desbourdes, S., Héliès, F., Lehmann, S., Saby, N.P.A., Tientcheu, E., Jamagne, M., Laroche, B., Bardy,

1165   M., Voltz, M., 2014b. La cartographie des sols à moyennes échelles en France métropolitaine. Etude

1166   et Gestion des sols. 21, 25–36. [in French].

1167   Richer-de-Forges, A.C., Carré, F., McBratney, A.B., Bouma, J., Arrouays, D., (eds)., 2019a. Global Soil

1168   Security. Towards more science-society interfaces. CRC Press, Taylor & Francis, London. 137 p. 19

1169   chapters.

1170   Robinson, D.A., Panagos, P., Borrelli, P., Jones, A., Montanarella, L., Tye, A., Obst, C.G., 2017. Soil

1171   natural capital in Europe; a framework for state and change assessment. Sci. Rep. 7 (1), 1-14.

1172   https://doi.org/10.1038/s41598-017-06819-3

1173   Ronchi, S., Salata, S., Arcidiacono, A., Piroli, E., Montanarella, L., 2019. Policy instruments for soil

1174   protection among the EU member states: a comparative analysis. Land Use Policy. 82, 763-780.

1175   https://doi.org/10.1016/j.landusepol.2019.01.017

1176   Rossiter, D.G., Bouma, J., 2018. A new look at soil phenoforms - Definition, identification, mapping.

1177   Geoderma. 314, 113-121. DOI10.1016/j.geoderma.2017.11.002

1178   Rutgers, M., van Leeuwen, J.P., Vrebos, D., van Wijnen, H.J., Schouten, T., de Goede, R.G.M., 2019.

1179   Mapping Soil Biodiversity in Europe and the Netherlands. Soil Syst. 3, 39.

1180   https://doi.org/10.3390/soilsystems3020039

1181   Sanchez, P.A., Ahamed, S., Carré, F., Hartemink, A.E., Hempel, J.W., Huising, J., Lagacherie, P.,

1182   McBratney, A.B., McKenzie, N.J., Mendonça-Santos, M.d.L., Minasny, B., Montanarella, L., Okoth,

1183   P., Palm, C.A., Sachs, J.D., Shepherd, K.D., Vagen, T.G., Vanlauwe, B., Walsh, M.G., Winowiecki, L.A.,

1184   Zhang, G.-L., 2009. Digital soil map of the world. Science. 325(5941), 680–681.

1185   https://doi.org/10.1126/science.1175084

1186   Sanderman, J., Hengl, T., Fiske, G.J., 2017. Soil carbon debt of 12,000 years of human land use. PNAS.

1187   114(36), 9575-9580. DOI10.1073/pnas.1706103114

1188   Sartori, M., Philippidis, G., Ferrari, E., Borrelli, P., Lugato, E., Montanarella, L., Panagos, P., 2019. A

1189   linkage between the biophysical and the economic: assessing the global market impacts of soil

1190   erosion. Land Use Policy. 86, 299-312. https://doi.org/10.1016/j.landusepol.2019.05.014

1191   Smith, G.R., Crowther, T.W., Eisenhauer, N., van den Hoogen, J., 2019. Building a global database of

1192   soil microbial biomass and function: a call for collaboration. Soil Organisms. 91(3), 139–142.

1193   https://doi.org/10.25674/SO91ISS3PP140

1194   Soussana, J.-F., Lutfalla, S., Ehrhardt, F., Rosenstock, T., Lamanna, C., Havlík, P., Richards, M.,

1195   Wollenberg, E., Chotte, J.-L., Torquebiau,E., Ciais, P., Smith, P., Lal, R., 2019. Matching policy and

1196   science: Rationale for the '4 per 1000 - soils for food security and climate' initiative. Soil and Tillage

1197   Research. 188, 3-15. https://doi.org/10.1016/j.still.2017.12.002

1198   Stockmann, U., Padarian, J., McBratney, A.B., Minasny, B., de Brogniez, D., Montanarella, L., Hong, S.

1199   Y., Rawlins, B. G., Field, D. J., 2015. Global soil organic carbon assessment, Global Food Security. 6,

1200   9–16. https://doi.org/10.1016/j.gfs.2015.07.001

1201   Stoorvogel, J.J., Bakkenes, M., Temme, A.J.A.M., Batjes, N.H., ten Brink, B.J.E., 2017. S-World: A Global

1202   Soil Map for Environmental Modelling. Land Degradation & Development. 28(1), 22-33.

1203   DOI10.1002/ldr.2656

1204   Stoorvogel, J.J., Mulder, V.L., 2021. A Comparison, Validation, and Evaluation of the S-world Global Soil

1205   Property Database. Land. 10, 544. https://doi.org/10.3390/land10050544

1206   The European common policy, n.d. The European common policy at a glance [WWW Document]. URL

1207   https://ec.europa.eu/info/food-farming-fisheries/key-policies/common-agricultural-policy/cap-

1208   glance_en (accessed 7.28.21).

1209   Tifafi, M., Guenet, B., Hatte, C., 2018. Large Differences in Global and Regional Total Soil Carbon Stock

1210   Estimates Based on SoilGrids, HWSD, and NCSCD: Intercomparison and Evaluation Based on Field

1211   Data From USA, England, Wales, and France. Global Biogeochemical Cycles. 32, 42–56.

1212   https://doi.org/10.1002/2017GB005678

1213   Tonitto, C., David, M.B., Drinkwater, L.E., 2006. Replacing bare fallows with cover crops in fertilizer-

1214   intensive cropping systems: A meta-analysis of crop yield and N dynamics. Agriculture, Ecosystems

1215   & Environment. 112, 58–72. https://doi.org/10.1016/j.agee.2005.07.003

1216   UNCCD (United Nations Convention to Combat Desertification), 1994. Elaboration of an international

1217   convention to combat desertification in countries experiencing serious drought and/or

1218   desertification, particularly in Africa. Final text of the Convention.

1219   http://www.unccd.int/Lists/SiteDocumentLibrary/conventionText/conv-eng.pdf (last access,

1220   07/30/2021)

1221   UNFCCC, 1997. Kyoto Protocol to the United Nations Framework Convention on Climate Change

1222   adopted at COP3 in Kyoto, Japan, on 11 December 1997.

1223   %20http://unfccc.int/resource/docs/cop3/07a01.pdf Website: https://www.eea.europa.eu/data-

1224   and-maps/indicators/primary-energy-consumption-by-fuel/unfccc-1997-kyoto-protocol-to (last

1225   access 07/30/2021)

1226   United Nations, 1992. Convention on Biological Diversity. https://www.cbd.int/doc/legal/cbd-en.pdf

1227   (last access 07/31/2021)

1228   USDA RCA Interagency Working Group Members, 2011. RCA Appraisal - Soil and Water Resources

1229   Conservation Act. USDA RCA Interagency Working Group Members.

1230   https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/nra/rca/ (last access:

1231   07/31/2021)

1232   van den Hoogen, J., Geisen, S., Wall, D.H., Wardle, D.A., Traunspurger, W., de Goede, R.G.M., Adams,

1233   B.J., Ahmad, W., Ferris, H., Bardgett, R.D., Bonkowski, M., Campos-Herrera, R., Cares, J.E., Caruso,

1234   T., de Brito Caixeta, L., Chen, X., Costa, S.R., Creamer, R., da Cunha e Castro, J.M., Dam, M., Djigal,

D., Escuer, M., Griffiths, B.S., Gutiérrez, C., Hohberg, K., Kalinkina, D., Kardol, P., Kergunteuil, A., Korthals, G., Krashevska, V., Kudrin, A.A., Li, Q., Liang, W., Magilton, M., Marais, M., Martín, J.A.R., Matveeva, E., Mayad, E.H., Mzough, E., Mulder, C., Mullin, P., Neilson, R., Nguyen, T.A.D., Nielsen, U.N., Okada, H., Rius, J.E.P., Pan, K., Peneva, V., Pellissier, L., da Silva, J.C.P., Pitteloud, C., Powers, T.O., Powers, K., Quist, C.W., Rasmann, S., Moreno, S.S., Scheu, S., Setälä, H., Sushchuk, A., Tiunov, A.V., Trap, J., Vestergård, M., Villenave, C., Waeyenberge, L., Wilschut, R.A., Wright, D.G., Keith, A.M., Yang, J., Schmidt, O., Bouharroud, R., Ferji, Z., van der Putten, W.H., Routh, D., Crowther, T.W., 2020. A global database of soil nematode abundance and functional group composition. Sci. Data. 7, 103. https://doi.org/10.1038/s41597-020-0437-3

van Leeuwen, C.C.E., Mulder, V.L., Batjes, N.H., Heuvelink, G.B.M., 2021. Statistical modelling of measurement error in wet chemistry soil data. Eur J Soil Sci. ejss.13137. https://doi.org/10.1111/ejss.13137

van Leeuwen, J.P., Saby, N.P.A., Jones, A., Louwagie, G., Micheli E., Rutgers, M., Schulte, R.P.O., Spiegel, H., Toth, G., Creamer, R.E., 2017. Gap assessment in current soil monitoring networks across Europe for measuring soil functions. Environ. Res. Lett. 12(12), Article 124007. https://doi.org/10.1088/1748-9326/aa9c5c

van Wesemael, B., Paustian, K., Meersmans, J., Goidts, E., Barancikova, G., Easter, M., 2010. Agricultural management explains historic changes in regional soil carbon stocks. PNAS. 107, 33, 14926-14930. DOI10.1073/pnas.1002592107

Vazquez, C., Goede, R.G.M., Rutgers, M., Koeijer, T.J., Creamer, R.E., 2021. Assessing multifunctionality of agricultural soils: Reducing the biodiversity trade-off. Eur J Soil Sci. 72, 1624–1639. https://doi.org/10.1111/ejss.13019

Verheye, W., Koohafkan, P., Nachtergaele, F., 1982. The FAO Guidelines for Land Evaluation, in: Land Use, Land Cover and Soil Sciences. p. 9.

1259   Voltz, M., Arrouays, D., Bispo, A., Lagacherie, P., Laroche, B., Lemercier, B., Richer-de-Forges, A.C.,

1260   Sauter, J., Schnebelen, N., 2020. Possible futures of soil mapping in France. Geoderma Regional. 23,

1261   e00334. https://doi.org/10.1016/j.geodrs.2020.e00334

1262   Voltz, M., Lagacherie, P., Louchart, X., 1997. Predicting soil properties over a region using sample

1263   information from a mapped reference area. Eur. J. Soil Sci. 48 (1), 19–30.

1264   https://doi.org/10.1111/j.1365-2389.1997.tb00181.x

1265   Wadoux, A.M.J-C., Román-Dobarco, M., McBratney, A.B., 2021. Perspectives on data-driven soil

1266   research. European Journal of Soil Science. 72(4), 1675-1689. DOI10.1111/ejss.13071

1267   Wadoux, A.M.J-C., McBratney, A.B., 2021. Hypotheses, machine learning and soil mapping. Geoderma.

1268   383, 114725. DOI10.1016/j.geoderma.2020.114725

1269   Wang, M., Xu, Q.C., Fan, Z.M., Sun, X.F., 2021. The Imprint of Built-Up Land Expansion on Cropland

1270   Distribution and Productivity in Shandong Province. Land. 10(6), 639. DOI10.3390/land10060639

1271   White, R.E., Andrew, M., 2019. Orthodox Soil Science versus Alternative Philosophies: A Clash of

1272   Cultures in a Modern Context. Sustainability. 11(10), 2919. https://doi.org/10.3390/su11102919

1273   Yaalon, D.H., 1996. Soil science in transition: soil awareness and soil care research strategies. Soil

1274   Science. 161, 3–8. https://doi.org/10.1097/00010694-199601000-00002

1275   Zak, D.R., Holmes, W.E., White, D.C., Peacock, A.D., Tilman, D., 2003. Plant diversity, soil microbial

1276   communities, and ecosystem function: are there any links? Ecology. 84, 2042–2050.

1277   https://doi.org/10.1890/02-0433

1278   Zwetsloot, M.J., Leeuwen, J., Hemerik, L., Martens, H., Simó Josa, I., Broek, M., Debeljak, M., Rutgers,

1279   M., Sandén, T., Wall, D.P., Jones, A., Creamer, R.E., 2021. Soil multifunctionality: Synergies and

1280   trade-offs across European climatic zones and land uses. Eur J Soil Sci. 72, 1640–1654.

1281   https://doi.org/10.1111/ejss.13051