



**HAL**  
open science

## Impacts of national scale digital soil mapping programs in France

Dominique Arrouays, Anne C Richer-De-Forges, Florence Héliès, Vera Leatitia Mulder, Nicolas Saby, Songchao Chen, Manuel Martin, Mercedes Román Dobarco, Stéphane Follain, Claudy Jolivet, et al.

► **To cite this version:**

Dominique Arrouays, Anne C Richer-De-Forges, Florence Héliès, Vera Leatitia Mulder, Nicolas Saby, et al.. Impacts of national scale digital soil mapping programs in France. *Geoderma Régional*, 2020, 23, pp.e00337. 10.1016/j.geodrs.2020.e00337 . hal-02963971

**HAL Id: hal-02963971**

**<https://institut-agro-dijon.hal.science/hal-02963971>**

Submitted on 21 Sep 2022

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

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



Distributed under a Creative Commons Attribution - NonCommercial 4.0 International License

## 1 **Impacts of national scale digital soil mapping programs in France**

2 Dominique Arrouays<sup>1,\*</sup>, Anne C. Richer-de-Forges<sup>1</sup>, Florence Héliès<sup>1</sup>, Vera Leatitia Mulder<sup>2</sup>,  
3 Nicolas P.A. Saby<sup>1</sup>, Songchao Chen<sup>1,3</sup>, Manuel P. Martin<sup>1</sup>, Mercedes Román Dobarco<sup>1</sup>,  
4 Stéphane Follain<sup>4</sup>, Claudy Jolivet<sup>1</sup>, Bertrand Laroche<sup>1</sup>, Thomas Loiseau<sup>1</sup>, Isabelle Cousin<sup>5</sup>,  
5 Marine Lacoste<sup>5</sup>, Lionel Ranjard<sup>4</sup>, Benoît Toutain<sup>1</sup>, Christine Le Bas<sup>1</sup>, Thomas Eglin<sup>6</sup>, Marion  
6 Bardy<sup>7</sup>, Véronique Antoni<sup>8</sup>, Jeroen Meersmans<sup>9</sup>, Céline Ratié<sup>1</sup>, Antonio Bispo<sup>1</sup>.

7 1. INRAE, US 1106, InfoSol, F-45000, Orléans, France

8 2. Soil Geography and Landscape Group, Wageningen University, PO Box 47 6700 AA  
9 Wageningen, The Netherlands

10 3. UMR SAS, Inrae, Agrocampus Ouest, 35042 Rennes, France

11 4. Agroécologie – AgroSup Dijon, INRAE, Univ. Bourgogne Franche-Comté, F-21000, Dijon,  
12 France

13 5. Inrae, UR 0272 Sols, F-45075, Orléans cedex 02, France.

14 6. ADEME, 20 av. du Grésillé F-49004, Angers, France

15 7. Ministère de l'Agriculture et de l'Alimentation, Direction Générale de l'Enseignement et  
16 de la Recherche, 75 007 Paris, France

17 8. Ministry for the Ecological and Inclusive Transition - Service de la donnée et des études  
18 statistiques, 5 route d'Olivet - CS 16105 - 45061 ORLÉANS CEDEX 2, France

19 9. Université de Liège, Analyse des risques environnementaux, Passage des Déportés 2,  
20 5030, Gembloux, Belgium

21

22 \*Corresponding author: Dominique.Arrouays@inra.fr

23

24 **Abstract**

25 During the last 10 years, several attempts to map soil attributes at the scale of mainland  
26 France have been realised. We exemplify them by seven major outputs: maps of organic C  
27 stocks, trace elements (TE), microbial density and diversity, soil thickness, available water  
28 capacity (AWC), extractable P, and changes in soil pH. We first briefly describe the data and  
29 the methods used to produce these maps and summarise their main results. We then focus  
30 on their impacts on various categories of the public, i.e. the general public and citizens;  
31 farmers; private companies; non-governmental organisations; agricultural development  
32 organisations, stakeholders, and national agencies; French governmental bodies; and  
33 international organisations. We also analyse the demands that came to the French National  
34 Soil Information Centre from 2008 to 2018 and the impact that our activities had in various  
35 media. Soil organic C had the largest impact in nearly all categories of end-users, which may  
36 be linked to the recent '4 per 1000' initiative launched by the French government during the  
37 COP21 and to the fact that farmers are interested in increasing the organic matter content of  
38 their soil for increasing the fertility. TE obtained high scores, which may be related to  
39 citizens' care about health and to the fact that governmental bodies and national agencies  
40 have a major interest in site contamination assessments. The soil P content, pH, and AWC  
41 exhibited major impacts on the agricultural sector. Maps of the soil P content and pH were  
42 used as geomarketing tools by private companies selling fertilisers and soil amendments,  
43 whereas the AWC was already incorporated into decision-making aid tools for irrigation  
44 management developed by development organisations for farmers. Microbial diversity  
45 generated collaborations with a large network of farmers and had a large media impact.  
46 Nevertheless, the visibility of soil information to the general public should be increased. This

47 can be done by using new multimedia and interactive tools. Overall, these selected examples  
48 of digital soil mapping of soil attributes at the national scale in France clearly indicate that  
49 the soil attributes have substantial impact on various categories of end-users, such as  
50 farmers, professional organisations, stakeholders, and policymakers at different levels of  
51 decision-making, among others. However, the impacts on the general public and citizens are  
52 more difficult to quantify, and increasing the soil awareness of the general public should be  
53 of high priority.

#### 54 **Keywords**

55 Digital soil mapping, national scale, France, impacts

56

#### 57 **1. Introduction**

58 The 1:250.000 soil mapping program of France is nearly complete. During this program,  
59 mapping has mainly been conducted using conventional methods. However, there is a  
60 discernible need to obtain more precise soil data using other methods, among which digital  
61 soil mapping (DSM; McBratney et al., 2003) is attracting considerable attention (Richer-de-  
62 Forges et al., 2019; Voltz et al., 2018). In their seminal paper, McBratney et al. (2003)  
63 proposed a generic framework called the soil spatial prediction function with spatially auto-  
64 correlated errors (scorpan-SSPFe) for producing digital soil maps (Minasny and McBratney,  
65 2016). Since the early 1990s, a large number of French papers have dealt with DSM,  
66 although they most often focused on local applications. These applications included various  
67 methods, such as i) extrapolation of already mapped areas in various French regions (e.g.  
68 Lagacherie et al., 1995; Voltz et al., 1997; Lagacherie and Voltz, 2000; Grinand et al., 2008);  
69 ii) the use of disaggregation approaches (Nauman et al., 2012) such as DSMART (Odgers and  
70 Clifford, 2014) to disaggregate conventional soil maps for Brittany (Vincent et al., 2016); iii)  
71 DSM of specific soil attributes of interest (e.g. Bourennane et al., 1996, 2003; Bourennane

72 and King, 2003; Arrouays et al., 1995; Chaplot et al., 2000) or even of some diagnostic  
73 horizons (Richer-de-Forges et al., 2017). More recently, regional attempts to map soil  
74 attributes according to *GlobalSoiMap* specifications (Arrouays et al., 2014) have been made  
75 in Southern France (e.g. Vaysse and Lagacherie, 2015, 2017), and considerable effort has  
76 been directed towards investigating the potential of new sensors to map soil properties at  
77 the local or regional level (e.g. Gomez et al., 2015, 2019; Vaudour et al., 2014, 2016, 2019;  
78 Zaouche et al., 2017).

79 In addition to these regional attempts, national products have been delivered using all the  
80 soil information available in the centralised national database of soil profiles 'DoneSol' and  
81 in a centralised database of soil tests realised by various laboratories upon farmer requests,  
82 referred to as the French National Soil Test Database. These databases and some of their  
83 products are detailed in the Materials and methods section of this paper.

84 The objective of this study was to present an overview of the impacts of these products for  
85 various end-users, including citizens and the general public; farmers; private companies;  
86 stakeholders and national agencies; policymakers; and international bodies, such as the  
87 Global Soil Partnership (GSP) of the United Nations Food and Agriculture Organisation (UN-  
88 FAO). We present selected examples of predictions of soil organic C (SOC) stocks, the  
89 available P content, changes in the pH trace elements (TE) content, soil thickness (ST), soil  
90 available water capacity (AWC), and soil microbial density and diversity. We first briefly  
91 describe the data and methods used and the main results of these predictions, and we  
92 examine the impacts of these DSM products on various end-users.

## 93 **2. Materials and methods**

### 94 **2.1. French soil tests database**

95 The information stored in the French National Soil Test Database is a compilation of  
96 requested soil analyses by farmers and landowners helping to improve the management of  
97 their crops and non-permanent grasslands. Samples were taken from topsoil horizons of  
98 cultivated or grassland fields, but the specific reasons why individual farmers requested soil  
99 analysis were not known; therefore, the sampling strategy could not be controlled. In each  
100 sampled field, approximately 15 sub-samples of the ploughed layer (or the 0–30-cm topsoil  
101 layer in the case of pasture) were collected using a hand auger, and the extracted soil was  
102 bulked to provide a composite sample, which was analysed. Results obtained via  
103 standardised analytical procedures were sent by laboratories certified by the French Ministry  
104 of Agriculture and were stored in the national database.

105 In France, approximately 2600000 soil samples were analysed between 1990 and 2014,  
106 leading to a total of approximately 329000000 analytical results. Most of the analyses  
107 involve classical agronomic parameters, such as the pH, organic C and N, extractable P with  
108 various reagents, cation exchange capacity, and exchangeable cations. The uncontrolled  
109 sampling strategy led to a heterogeneous distribution of the samples in both space and time  
110 (Figure 1). For privacy, the location information in this dataset is limited to the  
111 administrative district from which the soil sample was collected. Changes in the sampling  
112 resolution may arise in space and time because the soil sample locations were selected  
113 according to the needs of farmers rather than a statistical design.

114

115 <Insert Figure 1 about here>

116

## 117 **2.2. Soil point data used for national DSM**

### 118 **2.2.1. French soil profiles database ‘DoneSol’**

119 This database contains all point-based soil information coming from conventional soil  
120 mapping and inventory programs at all scales (Inventaire Gestion et Conservation des Sols,  
121 IGCS). Consequently, these points (soil profiles and augering descriptions) are irregularly  
122 spread over the French mainland territory and are sometimes clustered in areas of specific  
123 economic interest, such as vineyards. As a whole, they represent approximately 160000  
124 point data.

### 125 **2.2.2. French Soil quality monitoring network (RMQS) systematic grid**

126 The French Soil quality monitoring network (Réseau de Mesures de la Qualité des Sols,  
127 RMQS) is a systematic grid (16 km × 16 km) covering the entire French mainland with 2240  
128 sites (Arrouays et al., 2002). This network covers a broad spectrum of climatic, soil, and land-  
129 use conditions (croplands, permanent grasslands, woodlands, orchards and vineyards,  
130 natural or weakly anthropogenic lands). Every 15 years at each site, soil samples are taken,  
131 measurements are performed and observations are made. The first campaign occurred from  
132 2000 to 2015, and the second is ongoing from 2016 to 2027. At these sites, the SOC content,  
133 particle-size distribution, main total TE (As, Cd, Co, Cr, Cu, Hg, Mo, Ni, Pb, Tl, Zn), and bulk  
134 densities were determined for 0–30- and 30–50-cm layers. Samples from the laboratory  
135 analyses were realised on a bulked sample of 25 core samples via unaligned sampling in a  
136 400-m<sup>2</sup> square area. A soil pit was dug 5 m away from the area to reduce disturbance of the  
137 test site. The pit allows to describe the soil horizons, to obtain samples from bulk density  
138 and coarse element fragments and to determine the ST when a lithic or paralithic material  
139 could be reached (Soil Survey Division Staff, 1993). The locations of the ICGS and RMQS sites  
140 are plotted in Figure 2.

141

142 <insert figure 2 about here>

143

### 144 **2.2.3. SOILHYDRO and GEVARNOVIA databases**

145 The SOLHYDRO database contains data on physical, chemical, and hydraulic characteristics  
146 of samples collected from 1985 (Bruand et al., 2004). The soil types are mainly Cambisols,  
147 Luvisols, Planosols, Albeluvisols, Podzols, and Fluvisols (IUSS Working Group WRB, 2015)  
148 sampled over the French metropolitan territory. The geographical distribution of the  
149 sampling locations is mostly concentrated in the northern half of France, with little  
150 representation of the more mountainous southern and eastern regions, but covers a wide  
151 range of parent materials and textures. The land use varies among the sampling locations,  
152 including forests, poplar plantations, vineyards, grasslands, fallow, and oleaginous crops, but  
153 mostly consists of cereal monocultures. In 2017, SOLHYDRO comprised 689 horizons, of  
154 which 157 were topsoil horizons (depth of 0–30 cm) and 532 were subsurface horizons  
155 (depth of >30 cm). Samples were collected when soil was close to the field capacity and  
156 stored in a cold chamber before measurements (Román Dobarco et al., 2019a). The  
157 gravimetric water content was determined via a pressure-plate apparatus at field capacity  
158 (FC) at –10 kPa and permanent wilting point (PWP) at –1580 kPa water potential, by using  
159 undisturbed aggregates (10–15 cm<sup>3</sup>) (Bruand and Tessier, 2000; Bruand et al., 2003). The  
160 particle-size distribution, SOC content, and bulk density were measured according to  
161 international standards. Then, the volumetric water content ( $\theta_{FC}$  and  $\theta_{PWP}$ ) for each horizon  
162 was calculated by multiplying the gravimetric soil moisture content measured for  
163 undisturbed aggregates by the horizon bulk density. In 2017, 689, and 457 horizons were  
164 subjected to measurements at –1580 kPa, and –10 kPa, respectively.

165 The GEVARNOVIA database was used as an independent validation dataset and consisted of  
166 309 observations from different French institutes, including academic institutes such as INRA  
167 and agricultural technical institutes dedicated to cereal crops, oleaginous fruits, or seed  
168 selection (Román Dobarco et al., 2019b). The soil samples were collected mostly in the  
169 northern half and southwest of metropolitan France, with few samples collected in the  
170 southeast quadrant. The predominant land use was agricultural land or pastures. The  
171 database comprises information regarding the particle-size distribution, SOC content, bulk  
172 density, and volumetric soil moisture content measured for soil aggregates after equilibrium  
173 at  $-10$  and  $-1580$  kPa.

#### 174 **2.2.4. Data and methods used for main national DSM products**

##### 175 **2.1.4.1. Soil P**

176 In the database, a total of 850606 results from soil analyses contained available P content  
177 values (in  $\text{mg P}_2\text{O}_5 \text{ kg}^{-1}$ ). These values were determined by one of the three standardised  
178 methods (AFNOR, 1996) used by French soil analysis laboratories, i.e. the "Dyer" method  
179 (NFX 31-10), which involves the measurement of soluble P in a citric acid monohydrate  
180 solution; the "Joret-Hébert" method (NFX 31-161: determination of soluble P in an  
181 ammonium oxalate solution); and the "Olsen" method (ISO 11263: determination of P in a  
182 sodium hydrogen carbonate solution). The originality of the method used lies in quantitative  
183 results originating from the French Soil Test Database and their evaluation using the RegiFert  
184 software (Denoroy et al. 2004), which incorporates soil characteristics and crop sensitivity to  
185 nutrient availability. Briefly, RegiFert introduces two threshold values (L1 and L2, with  $L1 <$   
186  $L2$ ) to interpret the P content in soils according to crop needs. These threshold values  
187 depend on the sensitivity of plants to the P availability, on the analytical methods chosen for

188 P<sub>2</sub>O<sub>5</sub>, as well as on the soil characteristics: the CaCO<sub>3</sub> content, pH, clay fraction, and SOC  
189 content. This methodology constituted an attempt to gather all analytical results into a  
190 common diagnostic framework on the national scale (for France), while taking into account  
191 the local pedological context and crop production requirements. Data stored in BDAT over  
192 the period of 1990–2004 were originally geographically located on a municipal scale but  
193 were then aggregated on the "cantonal" scale for statistical and legal reasons. The French  
194 "cantons" are administrative jurisdictions defined as a grouping of several municipalities  
195 with a mean land area of 140 km<sup>2</sup>.

#### 196 **2.4.4.2. Changes in soil pH**

197 Recently, Saby et al. (2017) assessed the changes in the pH and cation saturation in French  
198 agricultural topsoils (1996–2010). Assessment of these changes considering values older  
199 than 1996 was not possible, because of a change in the standard analytical method after  
200 1995. Calcareous samples were excluded from this analysis. To obtain enough samples for  
201 spatiotemporal comparisons and to assess changes over a large time interval, two periods  
202 were analysed (1996–2000 and 2006–2010). Calcareous soil samples were excluded from  
203 this study. A total of 488117 samples were used for the statistical analysis. Data were  
204 aggregated into spatial entities corresponding to their small agricultural regions (SARs). In  
205 France, an SAR is an agricultural census unit that combines several districts. The average  
206 agricultural area of an SAR is 355.12 km<sup>2</sup>. Employing this spatial unit allows the use of  
207 sufficient data to run non-parametric statistics. For running these non-parametric statistics,  
208 Saby et al. (2017) proposed a statistical approach that takes into account the possible bias in  
209 the database using resampling techniques. Detailing this method is outside of the scope of  
210 this synthesis; however, a key point is that this methodology does not require any

211 assumption regarding the precise pH measurement location, this is important because we  
212 often do not know it due to privacy legislation..

### 213 **2.1.4.3. SOC stocks**

214 The most recent product predicting SOC stocks at the national scale (Mulder et al., 2016)  
215 used all available point data for France, from both the French Soil Mapping and Inventory  
216 Program and RMQS, i.e. the systematic monitoring grid. For estimating SOC stocks, only the  
217 soils that these profiles precisely georeferenced and that had measurements of the SOC  
218 content were retained, leading to a total of approximately 36000 profiles. Details regarding  
219 these two datasets were presented by Mulder et al. (2016). Briefly, Mulder et al. (2016) used  
220 these point data and 23 available covariates related to climate, relief, parent material and  
221 soils, biomass production, and land use to predict the SOC over a 90 × 90 m grid according to  
222 *GlobalSoilMap* specifications (Arrouays et al., 2014). The tool used for modelling was CUBIST  
223 (Kuhn et al., 2014; Quinlan, 1992), and the confidence intervals were determined using 10-  
224 fold cross-validations. Subsequently, the maps were masked by the modelled total soil depth  
225 (Lacoste et al., 2016), and the SOC stock was calculated in accordance with the work of  
226 Meersmans et al. (2012). This grid was further aggregated by Martin et al. (2017) to generate  
227 a 1-km<sup>2</sup> grid together with 90% confidence intervals and delivered to the UN-FAO GSP as a  
228 bottom-up product for the Global Soil Organic Carbon (GSOC) map  
229 ([http://www.fao.org/global-soil-partnership/pillars-action/4-information-and-data-  
230 new/global-soil-organic-carbon-gsoc-map/en/](http://www.fao.org/global-soil-partnership/pillars-action/4-information-and-data-new/global-soil-organic-carbon-gsoc-map/en/)).

### 231 **2.1.4.4. Trace elements**

232 TE data from the RMQS systematic grid were used to deliver various products. A first  
233 product was delivered by Villanneau et al. (2008) and is available online at

234 <https://doi.org/10.15454/UEZXBY>. These authors took into account both the natural  
235 pedogeochemical background and the diffuse contamination to quantify background levels  
236 of TE by using robust statistics (Tukey's whisker). Whiskers were calculated for each RMQS  
237 site using at least 10 neighbour sites within a 50-km circle. High background contents for  
238 four elements (Pb, Zn, Cu, and total and extractable Cd) indicated either high natural  
239 contents or anthropogenic diffuse contamination. Most importantly, their method allowed  
240 the calculation of an indicator for detecting a suspicious TE amount while taking into account  
241 the local context. Later, more sophisticated methods were developed by Marchant et al.  
242 (2010) and Saby et al. (2011). They developed robust geostatistical algorithms to map the  
243 underlying variation of six TEs (Cr, Cu, Pb, Ni, Tl, and Zn) across France, allowing background  
244 values attributable to a geogenic or large diffuse contamination origin to be mapped. A  
245 similar approach was employed by Marchant et al. (2017) for the As and Hg contents in  
246 French soils.

#### 247 **2.1.4.5. Soil microbial density and biodiversity**

248 Samples from the 0–30-cm layer of RMQS sites (first campaign) were used for DNA  
249 extraction. The total content of microbial DNA was determined. The methods for  
250 characterising the density and diversity of the microbial communities relied on molecular  
251 tools such as the quantitative polymerase chain reaction (PCR), DNA fingerprinting, and high-  
252 throughput sequencing of soil DNA extracts. Additional information was presented by  
253 Ranjard et al. (2010, 2013), Dequiedt et al. (2011), Terrat et al. (2017), and Karimi et al.  
254 (2018, 2019). The methods allowed the elaboration of simple indicators of microbial diversity  
255 and the mapping of their amounts and distribution across the French territory using DSM

256 techniques involving covariates such as the climate, soil parent material, clay content, and  
257 land use.

#### 258 **2.1.4.6. Soil thickness**

259 The first product predicting the ST at a national scale (Lacoste et al., 2016) was produced  
260 using 2116 sites from the RMQS database and 14113 sites from the IGCS database. The  
261 RMQS dataset had a better spatial coverage and was collected via a standardised procedure.  
262 The RMQS dataset was used for calibration; the IGCS dataset was used for validation. The ST  
263 (or depth) was defined according to the USDA Soil Survey Manual as the depth (in cm) to a  
264 lithic or paralithic contact (Soil Survey Division Staff, 1993).

265 Chen et al. (2019b) further demonstrated how right-censored data can be accounted for in  
266 the ST modelling of mainland France. They used the random survival forest (RSF) method for  
267 ST probability mapping within a DSM framework. Among 2109 sites of the French Soil quality  
268 monitoring network (RMQS), 1089 observed STs were defined as being right-censored. Using  
269 RSF, the probability of exceeding a given depth was modelled using freely available spatial  
270 data representing the main soil-forming factors.

#### 271 **2.1.4.7. Available water capacity**

272 The prediction of the AWC was performed in two steps. First, soil properties used as input  
273 for pedotransfer functions and coarse elements were predicted over mainland France using  
274 the *GlobalSoilMap* depth interval. Data of the particle-size distribution and coarse elements  
275 were extracted from the IGCS dataset, resulting in a total of 81671 soil profiles and soil  
276 cores. Particle-size fractions were predicted with regression-cokriging models [Cubist models  
277 (Kuhn et al., 2014; Quinlan, 1992) + linear model of coregionalisation (Goulard and Voltz,  
278 1992)], and coarse elements were predicted with a regression model (quantile regression

279 model, Meinshausen, 2006). All the regression models were fitted using 44 environmental  
280 covariates describing *scorpan* factors. For calibration, data of the particle-size distribution  
281 and coarse elements were extracted from the IGCS dataset, resulting in a total of 81671 soil  
282 profiles and soil cores. The RMQS dataset was used as an independent evaluation sample for  
283 particle-size distribution and coarse element predictions. Then, the volumetric soil moisture  
284 content ( $\text{cm}^3 \text{ cm}^{-3}$ ) at field capacity ( $-10\text{kPa} = \theta_{FC}$ ) and at a permanent wilting point ( $-1580$   
285  $\text{kPa} = \theta_{PWP}$ ) for the fine fraction were estimated with PTFs developed by Román Dobarco et  
286 al. (2019a) using the SOLHYDRO database. These PTFs used the content of clay (%) and sand  
287 (%) as predictor variables. The predictions of the volumetric soil moisture contents of the  
288 fine fraction were evaluated with the GEVARNOVIA georeferenced observations. Finally, the  
289 AWC (mm) was calculated as  $(\theta_{FC} - \theta_{PWP}) * (1 - R_v) * t$ , where  $R_v$  represents the  
290 volume of coarse elements (%), and  $t$  represents the thickness of the *GlobalSoilMap* depth  
291 interval (mm). The uncertainty of the AWC was quantified via first-order Taylor analysis. The  
292 uncertainty analysis accounted for two sources of uncertainty: the PTF coefficients and the  
293 soil input properties.

### 294 **3. Synthesis of main results**

#### 295 **3.1. Soil P maps**

296 Follain et al. (2009) assessed the P bioavailability in arable topsoils in France at a national  
297 scale. Using this procedure, they concluded that 77% of cantons were on average below the  
298 critical level regarding crop needs. In France, a canton is an administrative unit that  
299 combines several municipalities. From an environmental standpoint, this situation could be  
300 considered as generating the lowest water pollution risk. Nevertheless, 23% of the cantons  
301 exhibited a soil P accumulation that is not necessary with regard to agricultural uses. In this

302 case, no fertilisation is required, and the pollution risk is increased. For instance, focusing on  
303 Brittany—a region with intensive livestock production—Lemerrier et al. (2008) showed a  
304 strong P accumulation in soils with an increased risk of P losses into water bodies and thus of  
305 eutrophication.

### 306 **3.2. Changes in soil pH**

307 The authors showed that the soil pH increased in 36% of arable soils monitored from 1996 to  
308 2010, indicating that soils became less acidic across the country. Conversely, reductions in  
309 the pH were almost never detected. Their statistical framework smoothed the effects of  
310 some limitations of the database, i.e. the variable number of samples collected during both  
311 periods and sampling location uncertainties. For large parts of France, no trend was  
312 confirmed, indicating that the program should either gather more samples or wait for a  
313 longer time to detect such evolutions.

### 314 **3.3. Trace elements**

315 Detailed results are provided by Villanneau et al. (2008), Saby et al. (2011), and Marchant et  
316 al. (2017). Villanneau et al. (2008) and Saby et al. (2011) reported that high concentrations of  
317 Pb, Cr, Ni, and Zn occurred in soils on crystalline rocks, whereas the Cd concentrations were  
318 high in soils developed on Jurassic rocks. Volcanic parent material led to high concentrations  
319 of Cr, Cu, Ni, and Zn but low concentrations of Pb and Tl. The diffuse pollution of certain  
320 elements (mainly Pb and to a lesser extent Zn) was evident in industrial regions in the north  
321 and the northeast of France and close to Paris. The pattern of some outlying values was  
322 indicative of more local anthropogenic processes, such as diffuse industrial pollution in the  
323 north of France and close to Paris and application of Cu in vineyards, as well as of geological  
324 anomalies, such as high concentrations of some TEs in the south of the Massif Central

325 Mountains. Marchant et al. (2017) used geostatistical methods to map the expected  
326 concentrations of As and Hg in the topsoil and determine the probabilities that legislative  
327 thresholds are exceeded. They found that with the exception of some areas where the  
328 geogenic concentrations and soil adsorption capacities are very low, the As concentrations  
329 are often higher than the thresholds, indicating that further assessment of some areas is  
330 required. There were regions with elevated Hg concentrations, which could be related to  
331 volcanic material, natural mineralisation, and industrial contamination. These regions are  
332 more diffuse than the hotspots of As, reflecting the greater volatility of Hg and therefore the  
333 greater ease with which it can be transported and redeposited.

#### 334 **3.4. SOC maps and maps of potential of additional SOC storage**

335 A detailed description of SOC maps was presented by Mulder et al. (2016). Briefly, the maps  
336 showed large effects of climatic conditions (particularly in mountains), as well as major  
337 effects of the land use, soil parent material, and soil clay content. The predicted SOC content  
338 was unbiased and exhibited good agreement with the measured SOC, despite poor model  
339 diagnostics and a performance reduction with increasing depth. Moreover, the national map  
340 outperformed SoilGrids, which is a global map (Hengl et al., 2014). The total SOC for the  
341 upper 0–30-cm soils of France was estimated to be approximately 3.6 Pg. By aggregating  
342 these results to a coarser resolution (1 km), Martin et al. (2017) found similar geographic  
343 distributions and total SOC stocks.

344 The SOC storage potential was modelled by Chen et al. (2019a). They defined different C-  
345 landscape zones (CLZs) in France for modelling the soil C sequestration, thereby building  
346 upon the research of Mulder et al. (2015). They then computed estimates of the highest  
347 possible values using percentiles of 0.8, 0.85, 0.9, and 0.95 of the measured SOC stocks

348 within these CLZs for arable soils. The SOC storage potential was calculated as the difference  
349 between the maximum SOC stocks and the current SOC stocks.

### 350 **3.5. Soil thickness**

351 Lacoste et al. (2016) compared three spatially explicit modelling approaches for the ST for  
352 mainland France (540 km<sup>2</sup>): i) regression tree modelling (RTM), ii) gradient boosting  
353 modelling (GBM), and iii) multi-resolution kriging (MrK) for large datasets. The RMQS dataset  
354 was used for calibration; the IGCS dataset was used for validation. Exhaustive environmental  
355 data were used to characterise the climate, the organisms, the topography, and the other  
356 known soil forming factors, according to the Soil-Landscape paradigm (Jenny, 1941;  
357 McBratney et al., 2003). The maps' accuracy and difference were assessed by comparing the  
358 ST predictions to observed data (RMQS and IGCS datasets) and to an available soil map  
359 (1:1M). As expected, the three DSM approaches predicted the ST trend mainly from the  
360 covariates derived from the digital elevation model. The three predictive maps exhibited  
361 similar accuracy and were consistent with the 1:1M map. The four maps exhibited similar  
362 spatial patterns at the country scale. The three maps had poor performance for estimating  
363 the highest and lowest ST values. The mean soil depth for France was approximately 1 m.

364 Chen et al. (2019b) produced maps showing the probability of exceeding the thickness of  
365 each *GlobalSoilMap* standard depth: 5, 15, 30, 60, 100, and 200 cm. Additionally, a  
366 bootstrapping approach was used to assess the 90% confidence intervals. The results  
367 indicated that the RSF method was able to correct for right-censored data entries occurring  
368 within a given dataset. The RSF was more reliable for thin (0.3 m) and thick soils (1–2 m), as  
369 they performed better (overall accuracy ranging from 0.793 to 0.989) than soils with a

370 thickness between 0.3 and 1 m. This study provided a new approach for modelling right-  
371 censored soil information.

### 372 **3.6. Available water capacity**

373 Román Dobarco et al. (2019a) developed class-PTFs and continuous-PTFs with associated  
374 uncertainties and assessed their domain of applicability across metropolitan France. Román  
375 Dobarco et al. (2019b) predicted the AWC for mainland France according to the  
376 *GlobalSoilMap* specifications for depth intervals and uncertainty, to quantify the uncertainty  
377 of the AWC accounting for the uncertainty of the soil input variables and the PTF  
378 coefficients. Spatial predictions for  $\theta_{FC}$  and  $\theta_{PWP}$  overestimated the soil moisture contents for  
379 coarse textures and underestimated the soil moisture contents for fine and very fine texture  
380 classes. Across the majority of mainland France, the main sources of uncertainty of the  
381 elementary AWC were coarse elements and soil texture, but the contribution of the  
382 uncertainty of the PTF coefficients increased in areas dominated by very sandy and clayey  
383 textures. The modelling framework allows the continuous improvement of the AWC  
384 estimates through the replacement of each component of the AWC calculation when more  
385 accurate maps (e.g. next versions of *GlobalSoilMap* for clay, sand, and coarse elements) and  
386 new PTFs are developed (see sections 5.1 and 5.3).

### 387 **3.7. Soil microbial density and biodiversity**

388 Ranjard et al. (2010, 2013) provided the first extensive maps of the soil microbial biomass and  
389 bacterial biodiversity at the scale of mainland France. The maps revealed large  
390 biogeographical patterns of microbial density and bacterial biodiversity, indicating an  
391 heterogeneous and spatially structured distribution of these microbial parameters (Dequiedt  
392 et al., 2011; Terrat et al., 2017). The main factors driving the microbial distribution on a wide

393 scale are the physicochemical properties of soils (texture, pH, and organic C contents) and the  
394 land use. Soils from land used for intensive agriculture—particularly cropland and vineyards—  
395 exhibited the smallest biomass pools but the highest bacterial diversity. This observation  
396 supported a positive relationship between bacterial diversity and soil disturbance due to  
397 cropping intensity, which decreased in the following order: Vineyards-Orchards > Crops >  
398 Grasslands > Forests. Using the bacterial diversity data, Karimi et al. (2018) characterised the  
399 biogeography of each major and minor bacterial taxonomic group and deduced their  
400 ecological attributes as well as their distribution patterns.

401 They also investigated the bacterial interactions (co-occurrence) network of the bacterial  
402 community according to land use. In contrast to the bacterial richness, the network complexity  
403 was found to decrease from vineyards to forests, with a loss of >80% of the interactions  
404 (Karimi et al., 2019). Overall, they concluded that soil perturbation due to intensive cropping  
405 significantly reduces the complexity of the bacterial network, although the richness is  
406 increased, suggesting a potential negative impact on the soil bacterial functioning of the crop  
407 system. In this book, the soil microbial habitat was designed on a wide scale, as for macro-  
408 organisms. Sixteen distinct terrestrial microbial habitats were defined, emphasising the  
409 importance of upgrading policies for biodiversity conservation by integrating microbial  
410 habitats.

#### 411 **4. Main impacts**

412 In this section, we examine the main impacts of these examples of DSM and monitoring in  
413 France.

##### 414 **4.1. Soil available P**

415 Aggregated maps of classes of P availability for crops are freely available at  
416 <https://doi.org/10.1594/PANGEA.865249>. *Farmers* can access basic statistics for  
417 their canton and compare their results to those available in their region. Moreover, they can  
418 determine whether the amount of available P is reaching a critical threshold under which  
419 crop deficiency might occur. *Stakeholders*, such as river basin management agencies, can  
420 prioritise the areas where action is needed to protect the surface water quality. *Private*  
421 *companies*, such as producers of P fertilisers, use the maps to target areas exhibiting  
422 significant P deficiency, thus using the maps for geo-marketing. *Policymakers*, such as the  
423 ministries for agriculture or the environment, use these results to ensure broad  
424 communication to a large audience (e.g. CGDD/SOeS, 2009, 2014, 2015) regarding the status  
425 of P deficiency or P excess in French soils. They also use the results for reporting at a higher  
426 policy level or reviewing data, figures, maps, and fact sheets published by the European  
427 Environmental Agency (EEA and JRC, 2010).

#### 428 **4.2. Soil pH and changes in soil pH**

429 Regarding P, aggregated maps of classes of pH and pH changes are freely available at  
430 <https://doi.org/10.15454/SVDTOU>. *Farmers* can access basic statistics and compare their  
431 results with those available in their region. Although the pH is increasing slightly, many areas  
432 of France still have very low pH values; therefore, *private companies*, such as producers of  
433 liming products, may use the maps to target areas still exhibiting these values, thus using the  
434 maps for geo-marketing. Additionally, the French Union of Fertilizer Industries (UNIFA) can  
435 use these results to estimate the total amounts of liming products that are necessary to  
436 increase the pH values of all soils over commonly accepted standards (e.g. 6.2 or 6.5).  
437 *Policymakers*, such as the ministries for agriculture or the environment, use these results to

438 ensure broad communication regarding soil acidity (CGDD/SOeS, 2015) and liming  
439 recommendations to a large audience. We can validate changes only in areas with many  
440 samples, which suggests that additional collection may help detect new changes. Therefore,  
441 this study advocated for further pursuing and developing this program and obtaining funding  
442 from *governmental bodies*, such as the French Ministry for Agriculture. From a policy  
443 viewpoint, increasing the number of samples gathered by farmers would benefit the  
444 robustness of our estimates. As suggested by Saby et al. (2017): '*This policy could be*  
445 *accomplished via dedicated subsidies allocated to farmers for soil tests [...] or allocating*  
446 *existing subsidies to regularly perform soil analyses.*'

#### 447 **4.3. Trace elements**

448 The whiskers product (Villanneau et al., 2008) and more elaborated products (Saby et al.,  
449 2011; Marchant et al., 2017) are available online at <https://data.inra.fr/dataverse/gissol>.  
450 They are used by *private companies* in charge of assessing potentially contaminated sites as  
451 references to determine whether a given site is locally contaminated and requires further  
452 investigation/remediation. Using these tools, and as a major *stakeholder* being the  
453 organisation in charge of orphan sites (an orphan site is a site for which the person or  
454 corporation that created the pollution is unknown or out of business), the French  
455 Environment and Energy Management Agency (ADEME) recently published guidelines to  
456 estimate background values of TE in soils (ADEME, 2018a, 2018b). Background values of  
457 various TE (As, Ba, Cd, Cd, Cr, Cu, Hg, Mo, Ni, Pb, Sb, Se, and Zn) are also used to determine  
458 where non-contaminated excavated soil can be reused, as stated in the French reference  
459 guide on excavated soil management (MTES, 2017). The reused material should not degrade  
460 the soil quality of the receiver site.

#### 461 **4.4. Soil organic carbon**

462 From a *policy* viewpoint, soil C has become an important issue, as the French Government's  
463 Climate Plan aims to achieve carbon neutrality by 2050. Average SOC stock values by land  
464 use are now used to apply a Tier 2 approach for national greenhouse-gas emissions  
465 accounting (Citepa, 2017). SOC stocks maps were used for an expert report about the C  
466 storage potential at the demand of the French Ministry for Agriculture and ADEME (Pellerin  
467 et al., 2019). They helped to estimate the SOC storage potential under different scenarios of  
468 changes in land use and management and to indicate the areas/situations for which  
469 maintaining existing large stocks should be a priority. At a more local scale, changes in SOC  
470 are now mandatory for C accounting of medium to large intercommunal cooperation bodies  
471 (>20000 inhabitants) according to the French decree n°2016-849 of 28 June 2016,  
472 establishing the territorial climate–air–energy plan. ADEME, which is the state agency in  
473 charge of the climate policy implementation, has developed a diagnostic tool providing  
474 default estimates of the C stocks and stock changes at this French administrative level using  
475 data from the French soil quality monitoring network (ADEME, 2019) and encourages the  
476 development of spatially explicit analyses (Duparque et al., 2016). At the *international policy*  
477 *level*, the aggregated product at a 1-km resolution was delivered to the UN-FAO GSP as the  
478 French contribution to the GSOC map of the world ([http://www.fao.org/global-soil-](http://www.fao.org/global-soil-partnership/pillars-action/4-information-and-data-new/global-soil-organic-carbon-gsoc-map/en/)  
479 [partnership/pillars-action/4-information-and-data-new/global-soil-organic-carbon-gsoc-](http://www.fao.org/global-soil-partnership/pillars-action/4-information-and-data-new/global-soil-organic-carbon-gsoc-map/en/)  
480 [map/en/](http://www.fao.org/global-soil-partnership/pillars-action/4-information-and-data-new/global-soil-organic-carbon-gsoc-map/en/)). For the *general public*, results and statistics from the series of SOC maps  
481 produced in France via DSM were used by stakeholders and ministries to communicate the  
482 importance of SOC for preserving the soils and the environment from degradation and for  
483 mitigating climate change. For instance, the brochure 'Organic carbon in soils: Meeting  
484 climate change and food security challenge' was edited by ADEME to highlight the important

485 role of soil C in the French climate change mitigation strategy and to promote actions in the  
486 agricultural and forestry sectors (ADEME – GIS Sol, 2015).

487 Another example concerns the publication of a four-page leaflet focusing on the C amounts  
488 of French soils and their evolution over time (Ifen, 2007). For instance, it showed that the  
489 agricultural soils released C during the periods of 1990–1995 and 1999–2004.

490 Although the method developed by Chen et al. (2019a) suggests a high sensitivity of this  
491 approach to the selected percentile, it offers advantages from an operational viewpoint, as it  
492 allows targets for SOC storage to be set according to both *policymakers'* and *farmers'*  
493 considerations about their feasibility.

#### 494 **4.5. Soil thickness**

495 Surprisingly, the ST by itself had few noticeable impacts. However, it is one of the bases for  
496 calculating SOC stocks and AWC. We anticipate that the ST may have future impacts, for  
497 instance, on the engineering of large public works, such as the construction of new high-  
498 speed train lines and bypass roads around cities, as well as pipeline burial. In the recent past,  
499 we received such demands and replied using the conventional soil maps. We consider that  
500 the ST product is insufficiently publicised but that the use of DSM products will increase  
501 quickly. We also consider that the new product developed by Chen et al. (2019b), which  
502 involves mapping the probability to exceed a given ST, may be of interest for companies  
503 involved in geotechnical works. For geotechnical work, one would be also interested in soil  
504 geotechnical properties, e.g. shrinkage capability, clay content. A French map of shrinkage  
505 capability is already available at [https://www.georisques.gouv.fr/donnees/bases-de-](https://www.georisques.gouv.fr/donnees/bases-de-donnees/retrait-gonflement-des-argiles)  
506 [donnees/retrait-gonflement-des-argiles](https://www.georisques.gouv.fr/donnees/bases-de-donnees/retrait-gonflement-des-argiles) (last access 19 Aug. 2020), and the clay content  
507 product has been elaborated down to 2m by Mulder et al. (2016).

#### 508 **4.6. Available water capacity**

509 Román Dobarco et al. (2019a) provided various PTFs based on the available data. They also  
510 provided PTF *users* with tools for classifying new samples as within or outside the  
511 applicability domain of the PTFs. The majority of horizons outside the domain of applicability  
512 were located in forests and natural areas or managed pastures. This has a big impact on  
513 some *final end-users*, i.e. *agricultural development companies* and *farmers*. These PTFs are  
514 already incorporated into *decision-making aid tools for irrigation management* developed by  
515 development organisations for farmers. For example, the 'Arvalis-Institut du Végétal'  
516 institute, which is dedicated to cereal crops, included a new version of AWC estimation in its  
517 CHN model that is incorporated into a decision tool for irrigation. Provided that a detailed  
518 field-scale mapping is available (e.g. Duferra et al., 2007; Fortes et al., 2015; Li et al., 2019),  
519 these PTFs open the door to precision agriculture for optimising water efficiency for crops,  
520 particularly in drought situations (Lo et al., 2017). For larger areas, these PTFs associated  
521 with the uncertainties in the AWC were used in a regional project in southwest France in a  
522 decision tool dedicated to the evaluation of irrigation quotas (Lalu, 2017). At the national  
523 scale, such information is also needed by ministries and agencies to adapt agriculture and  
524 forest sectors to climate change. Apart from numerous scientific papers and  
525 communications, the necessity to develop PTFs with a high spatial resolution for the AWC  
526 was published in technical journals for farmers (Bouthier, 2015; Nicolas, 2015) and in  
527 newsletters (Labidi et al., 2017), as well as presented in numerous technical seminars, and  
528 was communicated to a broad audience of *citizens and farmers* during various agricultural  
529 events (e.g. International Agriculture Exhibition, Paris, 2016 (approximately 610000 visitors,  
530 mainly from a general public audience; French Agricultural Days 'Les culturales'

531 (approximately 13000 farmers from all French regions)). A practical guide on how to  
532 estimate the soil AWC will soon be freely released.

#### 533 **4.7. Soil microbial abundance and diversity**

534 The use of soil molecular techniques to characterise soil microbial abundance and diversity  
535 in >2200 soils allowed the standardisation of indicators and the design of corresponding  
536 wide-scale references for soil biological diagnosis (Horrigue et al., 2016; Bouchez et al.,  
537 2016). These indicators are now embedded in the *French biodiversity observatory* (ONB,  
538 <http://indicateurs-biodiversite.naturefrance.gf/en>), which aims to provide robust indicators  
539 for the French strategy for biodiversity (MEDTL, 2010). Other initiatives concerning soil  
540 biodiversity are communicated at a *regional level* (Gip Bretagne Environnement, 2016). From  
541 a *policy* viewpoint, they are also integrated into national reporting by the French Ministry of  
542 Environment (MEDTL, 2010) and embedded into the French Ministry of Agriculture  
543 Agricultural biodiversity observatory (OAB, <http://observatoire-agricole-biodoversite.fr/>).  
544 From an *agricultural development* viewpoint, these soil bioindicators have allowed the  
545 development of a *citizen science* project allowing researchers and farmers to work together  
546 with the same objective, to achieve a better understanding of the impact of agricultural  
547 practices on the soil biological quality and more largely on the durability of crop production  
548 (Cannavacciulo et al., 2017). To date, the network involves more than 400 farmers  
549 distributed across France in croplands and vineyards, and the data accumulated in this  
550 network are analysed to produce robust trends regarding the impacts of different practices  
551 (pesticide input, soil tillage, grassland, crop rotation, organic vs. conventional crops, etc.)  
552 on soil biological quality and services. Finally, for the general public, a didactic French atlas  
553 of soil bacteria (Karimi et al., 2018) based on the results obtained via the RMQS soil sampling

554 was published in 2018 and sold >1000 copies in less than a year. The publishing of this atlas  
555 was reported in numerous forms of media, e.g. radio, television (TV), and national press,  
556 highlighting the role of soil quality in the durability of agriculture for the public.

## 557 **5. Discussion**

### 558 **5.1. Importance of data capturing and rescuing**

559 Arrouays et al. (2017) gave some examples of success stories on data capturing and rescuing at the  
560 world, continental and country level from selected projects that achieved such kind of products,  
561 thereby demonstrating the importance of data rescue activities of existing soil data.

562 In France, an important data rescue effort led to a 69% increase of the number of soil profiles data  
563 from 2009 to 2015 giving an impressive coverage at adequate density of the French territory. In  
564 2015, the total number of points in mainland France soil database was about 160000 and is now (end  
565 of 2019) about 190000. This effort of capturing data benefited from the implementation of the  
566 1:250,000 soil mapping program for which it was mandatory to deliver the soil profiles information to  
567 the national database. For this purpose, INRA developed an easy-to-use data entry interface with a  
568 smallest error potential as possible. Meanwhile, many other legacy data from maps at other scales  
569 and from other programs were rescued by INRA, by entry and collation of legacy soil profiles and  
570 data (e.g. point location and year of recording, soil classification, soil morphologic observations and  
571 soil analytical measurements including values, units and methods used) from soil reports into the  
572 national soil profile database. The number of measurements, however, was highly variable,  
573 depending on the soil properties. In particular, AWC measurements are much less dense and  
574 irregularly spread over the territory. A sampling strategy has been designed to complete AWC  
575 measurements geographical coverage in the framework of the second campaign of the RMQS. Other  
576 hydraulic properties, such as for instance hydraulic conductivity, still remain very sparse in the  
577 national database. This type of measurements has mainly been realised in localised areas for

578 drainage of irrigation projects. Rescuing them to build PTFs would require specific efforts and funding  
579 that are still under discussion.

580 Trace elements measurements came from the RMQS, ensuring a perfect homogeneity in sampling,  
581 analytical procedures and geographical coverage. The data capturing for the BDAT came from  
582 contracting with private laboratories. From 1999 to 2014, the number of samples increased regularly  
583 at a rate of about 120000 per year, and reached about 2600000 in 2014. The analyses, however,  
584 mainly concern agricultural soils and routine agronomic measurements from topsoil (e.g. pH, SOC,  
585 CEC, clay content, available P and K). Even with such a number of measurements, they remain  
586 irregularly spread, and some temporal trends are not yet detectable over the entire French territory.  
587 This advocates for pursuing data capturing in order to confirm observed trends or to detect new  
588 ones.

## 589 **5.2. Impacts of DSM at French national scale and ways to increase them**

590 In this section, we first summarise and discuss the impacts of French national DSM products.  
591 Then, we elaborate on potential further developments. Striking impacts of DSM at the  
592 national scale in France are revealed. These impacts cover a wide range of end-users, some  
593 of which supply data to the French ministries for their own publications at the national  
594 (CGDD/SOeS, 2015; CGDD/SOeS, 2014) or at regional level (e.g. DREAL Centre Val de Loire,  
595 2015a, 2015b). At the European level, the indicators reported by France towards various  
596 instances (OCDE, Eurostat, DG Environment of the European Community, European  
597 Environmental Agency) are aggregated at the national or sub-national (French regions) level.  
598 In this study, we decided to focus on seven striking examples at the national scale, but many  
599 other ongoing projects are presently delivering new DSM products, often at a more local  
600 scale, such as an ongoing project that aims at using DSM to better quantify soil ecosystem  
601 services and to provide tools for land-use planning in peri-urban areas (see

602 <https://www6.inra.fr/soilserv/>). We decided to focus on these seven examples, but other  
603 DSM national products are available, for instance, on persistent organic pollutants (e.g.,  
604 Villanneau et al., 2013). These products, together with products related to TE, are largely  
605 used at a high policy level (French Ministry for the Environment) to evaluate the  
606 environmental exposure of populations to contaminants and to map environmental health  
607 inequalities (e.g. Caudeville, 2013, 2015; Caudeville et al., 2017; Saib et al., 2014, 2015).  
608 There is no doubt that relating human health to soil conditions will increase soil awareness  
609 among the general public and national and local authorities.

610 The examples provided here illustrate the impacts of DSM in France. However, many other  
611 traditional soil map products are also used at the national, regional, and local levels, in  
612 combination with other digital sources of information. Among the most important ones are  
613 the elaboration of guidelines for the delineation of erosion risk areas (Cerdan et al., 2006)  
614 and of wetlands to be protected (MEDDE and Gis Sol, 2013). At the European Union (E.U.)  
615 level, France was asked to contribute to the delineation of agricultural areas subject to  
616 natural constraints, i.e. 'Agricultural Areas with Natural Handicaps' (Jones et al., 2014), and  
617 used the 1:250000 soil map to assess the biophysical criteria for this delineation. However,  
618 prior to the use of the 1:250000 soil maps, boundaries between regions were harmonised  
619 using DSM methods. Other examples of the use of traditional soil maps include their use in  
620 conjunction with other environmental information for assessing soil ecosystem services and  
621 taking them into account for land-use planning (Keller et al., 2012), particularly in peri-urban  
622 areas. Another ongoing project called MUSE ([https://www.cerema.fr/fr/actualites/projet-](https://www.cerema.fr/fr/actualites/projet-muse-integrer-multifonctionnalite-sols-documents)  
623 [muse-integrer-multifonctionnalite-sols-documents](https://www.cerema.fr/fr/actualites/projet-muse-integrer-multifonctionnalite-sols-documents)) aims at developing tools for taking into  
624 account soil multifunctionality in urban land-use planning.

625 We attempted (Table 1) to classify the soil attributes mapped using DSM according to their  
 626 impacts on different categories of end-users.

627 Table 1: Classification of soil attributes predicted via DSM in France according to their  
 628 impacts on various end-users.

End users	Soil attribute						Microbial abundance and diversity
	Soil P	Soil pH	TE	SOC	ST	AWC	
<b>International organisations</b>	x	o	x	xxx	o	o	xx
<b>Governmental bodies</b>	xx	xx	xxx	xxx	o	xx	xxx
<b>Stakeholders/national agencies</b>	xx	xx	xxx	xxx	o	xx	xxx
<b>Agricultural development organisations</b>	xx	xxx	xx	xxx	xx	xxx	xx
<b>Non-governmental organisations (NGOs)</b>	x	o	xx	xxx	o	o	x
<b>Private companies</b>	xxx	xxx	xxx	xx	x	xx	xx
<b>Farmers</b>	xxx	xx	xx	xx	x	xxx	xxx
<b>Citizens/general public</b>	x	o	xx	xx	o	x	xx

629 Impact: xxx very high, xx high, x moderate, o unknown

630

631 As expected, the SOC topic had the largest impact in nearly all categories of end-users, which  
 632 may be linked to the recent '4 per 1000' initiative launched by France during the COP21  
 633 (Soussana et al., 2019) and to the fact that farmers are interested in increasing the organic-  
 634 matter content of their soil for increasing the fertility. TE obtained high scores, which may be  
 635 related to citizens' care about health and to the fact that governmental bodies and national  
 636 agencies have a major interest in site contamination assessment. Soil P and pH exhibited  
 637 large impacts on agricultural sectors, which is logical. Microbial abundance and diversity  
 638 attract increasing interest from citizens, farmers, governments, and international  
 639 organisations in biodiversity conservation and extinction prevention (IPBES, 2019).

640 It was challenging assessing whether the resulting maps led to changes in practices of the  
641 farmers. However, the maps have been consulted by technical advisers and consultants from  
642 agricultural development organisations (agricultural chambers, agricultural cooperatives).  
643 Therefore, we may think that farmers pay now more attention to order some soil tests to  
644 monitor several soil properties in the areas that were identified as problematic (e.g. areas  
645 with low pH, low P availability, low SOC content or high TE). The technical advisers also give  
646 recommendations to farmers to counter-balance undesirable evolutions (e.g. liming, organic  
647 or inorganic P fertilization, adopting conservation agriculture practices). Another example of  
648 impact is the farmers' network monitoring soil biological indicators under different practices  
649 (see section 4.7). Besides, the demand from farmers for microbial analyses is increasing and  
650 the biggest private soil analysis laboratory in France (55% of the market share) recently  
651 added microbial abundance and diversity to his laboratory test catalogue. AWC is already  
652 incorporated into decision-making aid tools for irrigation management developed by  
653 development organisations for farmers. This is briefly discussed in sections 4.6 and 5.3.

654 Another way to assess the impact on soil awareness is to analyse the demands that came  
655 since 2008 to the INRA InfoSol Unit, which can be considered as the national centre for soil  
656 information in France (Figure 3).

657

658 <insert Figure 3 about here>

659

660 Figure 3 shows that the largest demands to INRA InfoSol were related to research, either  
661 asking to provide data or asking for a research collaboration. Other major demands came  
662 from private companies, national stakeholders, policymakers, and agricultural development

663 companies. Interestingly, there were noticeable demands from citizens and the media,  
664 whereas demands from farmers and NGOs were almost absent. The low percentage of  
665 farmers' demands is not surprising as they usually ask questions to local advisers rather than  
666 at the national level. The sharp increase of demands beginning around 2009 corresponds to  
667 the period during which InfoSol began to publish online information, and the sharp decline  
668 from 2017 might be due to the fact that InfoSol developed numerous webservices allowing  
669 people to find information without having to ask for it. The low interest from citizens and the  
670 general public confirms that there is a real need to increase the soil awareness of the  
671 population (McBratney et al., 2014; Koch et al., 2014). One may wonder if this disinterest is  
672 due to a lack of communication from the national centre for soil information.

673 Since 2008, the INRA InfoSol has been involved in >210 media communications. Figure 4  
674 presents the proportions of the main categories of media in which InfoSol participated.

675

676 <insert Figure 4 about here>

677

678 Figure 4 indicates that the visibility of soil information to the general public should be  
679 increased (see the low proportions of TV and radio interviews). This can be done by using  
680 new multimedia tools, particularly targeting the young public, which gathers most of its  
681 information through internet tools. For instance, InfoSol recently created a Twitter account  
682 (@InfosolOrleans) to communicate regarding its activities and products and raise general  
683 awareness of soil issues. The most popular tweet thus far was the publication of the national  
684 map of C stocks. Moreover, interactive tools allowing people to visualise changes that may

685 occur under different scenarios (changes in land use, climate, agricultural practices, etc.)  
686 should be adopted.

687 It is expected that DSM will progressively move towards digital soil assessment (DSA, Carré  
688 et al., 2007; Minasny et al., 2012; Arrouays et al., 2020). DSA is the application and  
689 interpretation of DSM maps for specific uses (e.g. agricultural productivity, land suitability,  
690 land-use planning, C accounting), which often require using soil data as inputs to models  
691 (e.g. crop models, ecosystem services assessment tools, greenhouse-gas accounting models).  
692 For instance, national DSM maps are already used together with other information to model  
693 soil functions or services as soil habitats (Karimi et al., 2018; Rutgers et al., 2016) or to model  
694 the C storage potential depending on land use and practices (Pellerin et al., 2019). One main  
695 advantage of DSM is that it indicates the uncertainty on soil attributes, which can be used to  
696 test the sensitivity of these models or to use probability density functions of soil attributes  
697 instead of average of dominant values. Moreover, these interpretations may also include  
698 social and economic factors, allowing societal needs to be better addressed. Examples  
699 include the assessment of the services rendered by soils (e.g. Dominati et al., 2010; Turner et  
700 al., 2016), as in the programs Soilserv (<https://www6.inra.fr/soilserv/>) and SoilVer, i.e. a soil  
701 and land research funding platform for Europe (<https://www.soilver.eu/>), contributions to  
702 soil-related local decision making and economics issues (e.g. Cotching and Kidd, 2010; Kidd  
703 et al., 2014; 2015), and contributions of soils to the adaptation of agriculture and forest  
704 sectors to climate change and to the sustainable development goals and the achievement of  
705 Land Degradation Neutrality (e.g. Keesstra et al., 2016; Bouma, 2019). All these actions will  
706 increase the soil awareness of the general public and of policymakers.

707 Soil awareness is increasing at a policy level. Good examples are the GSP initiative from the  
708 UN-FAO (<http://www.fao.org/global-soil-partnership/en/>), the 4 per 1000 initiative  
709 (Soussana et al., 2019), which has already been signed by >40 countries, and large research  
710 initiatives launched in E.U., such as the European Joint Programme on Agricultural Soil  
711 Management 'Towards climate-smart sustainable management of agricultural soils' (EJP  
712 Soil), which will help to realise reporting under CAP, the sustainable development goals, and  
713 the achievement of set climate targets, among other objectives. Moreover, EJP Soil will  
714 support farmers in their role as stewards of land and soil resources. A central role in this  
715 project is data harmonisation and creation of soil information. Here, DSM will be used for  
716 generating bottom-up maps of soil and derived thematic information on soil functioning for  
717 Europe. In this framework, it is expected that France and the French experience in DSM will  
718 play a central role.

### 719 **5.3. Future of DSM in France**

720 At the *governmental* level, The French Ministry for Agriculture is now aware about the  
721 need to introduce an action plan that would incorporate DSM at regional levels to accelerate  
722 soil mapping programs and to boost DSM methods giving accuracy assessments and  
723 reproducible and updatable results. In order to reach this objective, the French Ministry for  
724 agriculture modified accordingly its annual call for soil mapping actions.

725 The RMQS is now in its second round of sampling. The sampling strategy has been revised to  
726 optimise the sampling in both space and time for detecting changes in soil conditions earlier  
727 (particularly regarding SOC stocks). New variables have been added to the analytical menu of  
728 the second campaign (AWC, particulate organic matter) or are subject to feasibility studies  
729 for future integration (pesticide contents, soil biodiversity parameters). Consequently, for

730 example, the validity of the evaluation statistics for soil hydraulic properties will improve  
731 when ongoing work of the RMQS second campaign increases the representativeness of  
732 pedoclimatic conditions and spatial distribution in soil hydraulic measurements at the  
733 national level. The BDAT collection of analytical results ordered by farmers is also ongoing.  
734 Both programmes will move from DSM to digital soil monitoring and will increase their  
735 impacts at all levels.

736 All RMQS soil samples are stored in a soil archive repository (European soil sample  
737 conservatory in Orléans) under light-, moisture-, and temperature-controlled conditions.  
738 This will allow use of these samples when new analysis technologies become operational. A  
739 large number of new projects are already employing this sample library (e.g. Silicon (Landré  
740 et al., 2018), <sup>35</sup>Cl by Rock Eval analysis, <sup>137</sup>Cs for modelling sedimentary transfers at the  
741 watershed scale, fungicide contents to assess the links with human infertility, SOC by Rock-  
742 Eval pyrolysis, etc.). This soil-sample archive also provides an excellent way to communicate  
743 about soil and has been visited by approximately 3000 people since 2014, including the  
744 general public, professional agencies, researchers, NGOs, sciences academies, stakeholders,  
745 and policymakers.

746 Similar to the soil-sample archive, a DNA archive and platform is now available at INRA Dijon:  
747 Genosol ([https://www2.dijon.inra.fr/plateforme\\_genosol/protocoles](https://www2.dijon.inra.fr/plateforme_genosol/protocoles)). It contains all DNA  
748 extracted from RMQS topsoil samples and allows genomics to be applied to a large spectra  
749 of topics, including topics related to plant and human health. Such topics will certainly have  
750 a large impact on the general public though their dissemination in national and international  
751 media.

752 Additionally, all samples from the RMQS were used to build a national spectral library  
753 including visible, near-infrared, and mid-infrared spectra (e.g. Caria et al., 2011; Goge et al.,  
754 2014). This library opens the door to low-cost mapping of new elements that were not  
755 initially included in the analytical menu of the RMQS (e.g. emerging contaminants such as  
756 antibiotics and microplastics and human exposure to some contaminants).

757 Finally, the efforts made by InfoSol to assemble national covariates will be beneficial to all  
758 people performing DSM at a more local scale. As an example, Loiseau et al. (2019) recently  
759 produced a multirate mosaic of bare soil data reflectance using the new Sentinel 2 satellite  
760 products, and this product is already employed for large-scale monitoring of the SOC in a  
761 cost-efficient way in small representative areas (Vaudour et al., 2019) using high-resolution  
762 Earth Observation (EO) data for generating DSM maps. Internationally, there is a large  
763 amount of interest in global soil monitoring using EO data (e.g. Chabrilat et al., 2019, and  
764 see <http://worldsoils2019.esa.int/>). Finally, the new partnership GLADSOILMAP  
765 (<https://www6.inra.fr/gladsoilmap-consortium/>) is a recently established consortium that  
766 was established to scientifically support many of these international initiatives and advance  
767 methods for realising urgently needed products.

## 768 **6. Conclusion**

769 The selected examples of DSM at the national scale in France clearly have substantial impact  
770 on various categories of end-users, such as farmers, professional organisations, private  
771 companies, stakeholders, and policymakers at different levels of decision making. If we  
772 consider the TE and SOC, the impacts on stakeholders and policymakers are very large. TE in  
773 soil are related to human exposure and health and are therefore popular research topics.  
774 The SOC is now considered a priority for climate adaptation and mitigation, as exemplified  
775 by the launch of the 4 per 1000 initiative by France at the COP21. The impact on private

776 companies is important, particularly for companies dealing with fertilisers or amendment  
777 production (see the results for P and pH) and those involved with potentially contaminated  
778 sites. The impacts on the general public and citizens are less quantifiable and should be a  
779 high priority if we wish to raise the soil awareness of the general public. It appears that  
780 increased efforts should be dedicated to deliver usable products rather than to deliver raw  
781 soil properties, even if the raw soil properties provide a basis without which DSA and digital  
782 soil monitoring cannot be developed. Formerly, the traditional soil survey was generally  
783 followed up by soil-survey interpretations (mainly empirical and qualitative). Soil mapping  
784 has been modernised through DSM, but the interpretation and the production of real digital  
785 assessment appears to still be in infancy in France. Additionally, relating human health to soil  
786 conditions will undoubtedly increase the soil awareness among the general public and  
787 national and local authorities.

## 788 **Acknowledgments**

789 The *GlobalSoilMap* activities of the INRA InfoSol Unit are partly funded by the Environment  
790 & Agronomy department of the National Institute for Agronomic Research (INRA). Most of  
791 the French point soil data has been collected or rescued thanks to funding from the national  
792 'Groupement d'Intérêt Scientifique Sol' involving the French Ministry of Ecology, the French  
793 Ministry of Agriculture, the French Environment and Energy Management Agency (ADEME),  
794 the French Office for Biodiversity (OFB), the French Institute for Research and Development  
795 (IRD), the Institute for National geographic and Forest Information (IGN) and the INRA. In  
796 most cases, these national funding were complemented by French Regions or more local  
797 agencies and organizations. We thank all the people involved in sampling the sites and  
798 populating the database. The European soil sample conservatory benefited from grants from

799 INRA, FEDER, the Region Centre Val de Loire, and the DRTT. The microbiological study was  
800 granted by ADEME (French Environment and Energy Management Agency) and by “France  
801 Génomique” through involvement of the technical facilities of Genoscope (project number  
802 ANR-10-INBS-09-08). Due to the involvement of technical facilities at the GenoSol platform  
803 of the infrastructure ANAEE France, it also received a grant from the French state through  
804 the National Agency for Research under the program “Investments for the Future”  
805 (reference ANR-11-INBS-0001). Songchao Chen received the support of China Scholarship  
806 Council for three years’ Ph.D. study in INRA and Agrocampus Ouest (under grant agreement  
807 no. 201606320211). Thomas Loiseau received the support of CNES for one year work  
808 (160102 agreement). This work has been supported by LE STUDIUM Loire Valley Institute for  
809 Advanced Studies through its LE STUDIUM Research Consortium Programme.

## 810 **References**

- 811 ADEME – GIS Sol, 2015. Organic carbon in soils: Meeting climate change and food security  
812 challenges. ADEME Editions. 32p.
- 813 ADEME, 2018a. Guide pour la détermination des valeurs de fonds dans les sols - échelle d'un  
814 territoire. ADEME Editions. Collection expertise. 141 p. (*in French*).
- 815 ADEME, 2018b. Guide pour la détermination des valeurs de fonds dans les sols - échelle d'un  
816 site. ADEME Editions. Collection expertise. 133 p. (*in French*).
- 817 ADEME, 2019. L’outil ALDO, pour une première estimation de la séquestration carbone dans  
818 les sols et la biomasse. Tool and manual available on [https://www.territoires-](https://www.territoires-climat.ademe.fr/actualite/loutil-aldo-pour-une-premiere-estimation-de-la-sequestration-carbone-dans-les-sols-et-la-biomasse)  
819 [climat.ademe.fr/actualite/loutil-aldo-pour-une-premiere-estimation-de-la-sequestration-](https://www.territoires-climat.ademe.fr/actualite/loutil-aldo-pour-une-premiere-estimation-de-la-sequestration-carbone-dans-les-sols-et-la-biomasse)  
820 [carbone-dans-les-sols-et-la-biomasse](https://www.territoires-climat.ademe.fr/actualite/loutil-aldo-pour-une-premiere-estimation-de-la-sequestration-carbone-dans-les-sols-et-la-biomasse) (accessed 25 June 2019). (*in French*).

821 AFNOR (1996) *Qualité des sols*, 3e éd., Recueil des normes françaises 1996, AFNOR, Paris,  
822 533 p.

823

824 Arrouays, D., Grundy, M.G., Hartemink, A.E., Hempel, J.W., Heuvelink, G.B.M., Hong, S.Y.,  
825 Lagacherie, P., Lelyk, G., McBratney, A.B., McKenzie, N.J. Mendonça-Santos, M.D., Minasny,  
826 B., Montanarella, L., Odeh, I.O.A., Sanchez, P.A., Thompson, J.A., Zhang, G.-L., 2014.  
827 *GlobalSoilMap: towards a fine-resolution global grid of soil properties*. *Advances in*  
828 *Agronomy*. 125, 93-134.

829 Arrouays, D., Jolivet, C., Boulonne, L., Bodineau, G., Saby, N., and Grolleau, E., 2002. A new  
830 initiative in France: a multi-institutional soil quality monitoring network. *Comptes Rendus de*  
831 *l'Académie d'Agriculture de France*. 88, 93–105.

832 Arrouays, D., Leenaars, J., Richer-de-Forges, A.C., Adhikari, K., Ballabio, C., Greve, M.,  
833 Grundy, M., Guerrero, E., Hempel, J., Hengl, T., Heuvelink, G., Batjes, N., Carvalho, E.,  
834 Hartemink, A., Hewitt, A., Hong, S.-Y., Krasilnikov, P., Lagacherie, P., Lelyk, G., Libohova, Z.,  
835 Lilly, A., McBratney, A., McKenzie, N., Vasques, G., Mulder, V.L., Minasny, B., Montanarella,  
836 L., Odeh, I., Padarian, J., Poggio, L., Roudier, P., Saby, N., Savin, I., Searle, R., Stolbovoy, V.,  
837 Thompson, J., Smith, S., Sulaeman, Y., Vintila, R., Viscarra Rossel, R., Wilson, P., Zhang, G.-L.,  
838 Swerts, M., van Oorts, K., Karklins, A., Feng, L., Ibelles, Navarro, A.R., Levin, A., Laktionova, T.,  
839 Dell'Acqua, M., Suvannang, N., Ruam, W., Prasad, J., Patil, N., Husnjak, S., Pásztor, L., Okx, J.,  
840 Hallet, S., Keay, C., Farewell, T., Lilja, H., Juilleret, J., Marx, S., Takata, Y., Kayusuki, Y.,  
841 Mansuy, N., Panagos, P., van Liedekerke, M., Skalsky, R., Sobocka, J., Kobza, J., Eftekhari, K.,  
842 Kazem Alavipanah, S., Moussadek, R., Badraoui, M., da Silva, M., Paterson, G., da Conceição  
843 Gonçalves, M., Theocharopoulos, S., Yemefack, M., Tedou, S., Vrscaj, B., Grob, U., Kozak, J.,

844 Boruvka, L., Dobos, E., Taboada, M., Moretti, L., Rodriguez, D. 2017. Soil legacy data rescue  
845 via GlobalSoilMap and other international and national initiatives. *GeoRes J*, 14, 1-19.

846 Arrouays, D., Richer-de-Forges, A.C., Roudier P., Poggio P., Mulder V.L., Libohova Z., Cristine  
847 M., Carré F., Bouma J., McBratney A.B., 2020. Impressions of digital soil maps: the good, the  
848 not so good, and making them ever better. *Geoderma Regional*, 21, e000265.

849 Arrouays, D., Vion, I., Kicin, J.L., 1995. Spatial analysis and modeling of topsoil carbon storage  
850 in forest humic loamy soils of France. *Soil Science*. 159, 191-198.

851 Bouchez, T., Blieux, A.L., Dequiedt, S., Domaizon, I., Dufresne, A., Ferreira, S., Godon, J.J.,  
852 Hellal, J., Joulain, C., Quaiser, A., Martin-Laurent, F., Mauffret, A., Monier, J.M., Peyret, P.,  
853 Schmitt-Koplin, P., Sibourg, O., D'oiron, E., Bispo, A., Deportes, I., Grand, C., Cuny, P., Maron,  
854 P.A., Ranjard, L., 2016. Molecular microbiology for environmental diagnosis. *Environmental*  
855 *Chemistry Letters*. 14, 423-441.

856 Bouma, J., 2019. How to communicate soil expertise more effectively in the information age  
857 when aiming at the UN Sustainable Development Goals. *Soil Use and Management*. 35, 32-  
858 38.

859 Bourennane, H., King, D., 2003. Using multiple external drifts to estimate a soil variable.  
860 *Geoderma*. 114(1/2), 1-18.

861 Bourennane, H., King, D., Chéry, P., Bruand, A., 1996. Improving the kriging of a soil variable  
862 using slope gradient as external drift. *European Journal of Soil Science*. 47(4), 473-483.

863 Bourennane, H., Salvador-Blanes, S., King, D., 2003. Scale of spatial dependence between  
864 chemical properties of topsoil and subsoil over a geologically contrasted area (Massif central,  
865 France). *Geoderma*. 112(3/4), 235-251.

866 Bouthier, A., 2015. Réserve Utile des sols – une variable déterminante à mieux évaluer.  
867 Perspectives Agricoles. 425, 62-63. (*in French*).

868 Bruand, A., Duval, O., Cousin, I., 2004. Estimation des propriétés de rétention en eau des sols  
869 à partir de la base de données SOLHYDRO: Une première proposition combinant le type  
870 d'horizon, sa texture et sa densité apparente. Etude et Gestion des Sols. 11(3), 323-334. (*in*  
871 *French*).

872 Bruand, A., Pérez Fernández, P., Duval, O., 2003. Use of class pedotransfer functions based  
873 on texture and bulk density of clods to generate water retention curves. Soil Use Manage.  
874 19, 232–242.

875 Bruand, A., Tessier, D., 2000. Water retention properties of the clay in soils developed on  
876 clayey sediments: significance of parent material and soil history. Eur. J. Soil Sci. 51, 679–  
877 688.

878 Cannavacciuolo, M., Cassagne, N., Riou, V., Mulliez, P., Chemidlin, N., Dequiedt, S., Villenave,  
879 C., Cérémonie, H., Cluzeau, D., Cylly, D., Vian, J.-F., Peigné, J., Gontier, L., Fourrié, L., Maron,  
880 P.A., D'oiron Verame, E., Ranjard, L., 2017. Validation d'un tableau de bord d'indicateurs sur  
881 un réseau national de fermes en grande culture et en viticulture pour diagnostiquer la  
882 qualité biologique des sols agricoles. Innovations Agronomiques. 55, 41-54. (*in French*).

883 Caria, G., Arrouays, D., Dubromel, E., Jolivet, C., Ratié, C., Bernoux, M., Barthes, B.G., Brunet,  
884 D., Grinand, C., 2011. Black carbon estimation in French calcareous soils using chemo-  
885 thermal oxidation method. Soil Use and management. 27(3), 333-339.

886 Carré, F., McBratney, A.B., Mayr, T., Montanarella, L., 2007. Digital soil assessments: Beyond  
887 DSM. Geoderma. 142(1/2), 69-79.

888 Caudeville, J. 2015. Exemples de dispositifs d'évaluation des inégalités environnementales de  
889 santé : Méthodologie et premiers résultats de la plateforme française PLAINE. Annales des  
890 Mines - Responsabilité et environnement. N°79. *(in French)*.

891 Caudeville, J., 2013. Caractériser les inégalités environnementales » in Eloi Laurent (dir.),  
892 Vers l'égalité des territoires – Dynamiques, mesures, politiques, Rapport pour le Ministère  
893 de l'égalité des territoires et du logement. XX p. *(in French)*.

894 Caudeville, J., Ioannidou, D., Boulvert, E., Bonnard, R., 2017. Cumulative Risk Assessment in  
895 the Lorraine Region: A Framework to Characterize Environmental Health Inequalities. Int. J.  
896 Environ. Res. Public Health. 14(3), 291.

897 Cerdan, O., Le Bissonnais, Y., Souchère, V., King, C., Antoni, V., Surdyk, N., Dubus, I.,  
898 Arrouays, D., Desprats, J.F., 2006. Guide méthodologique pour un zonage départemental de  
899 l'érosion des sols. Rapport n°3 : synthèse et recommandations générales. BRGM/RP-55104-  
900 FR. 87 p. *(in French)*.

901 CGDD/SOeS, 2014. L'environnement en France - Édition 2014. Chapitre « Les sols ».  
902 Collection Références.104 p., pp. 77-88. *(in French)*.

903 CGDD/SOeS, 2015. Sols et environnement : chiffres-clés, édition 2015. Collection Repères.  
904 104 p. *(in French)*.

905 Chabrilat, S., Ben-Dor, E., Cierniewski, J., Gomez, C., Schmid, T., van Wesemael, B., 2019.  
906 Imaging Spectroscopy for Soil Mapping and Monitoring. Survey in Geophysics. 40(3), 361-  
907 399.

908 Chaplot, V., Walter, C., Curmi, P., 2000. Improving soil hydromorphy prediction according to  
909 DEM resolution and available pedological data. Geoderma 97 (3/4), 405-422.

910 Chen, S., Arrouays, D., Angers, D.A., Chenu, C., Barré, P., Martin, M.P., Saby, N.P.A., Walter,  
911 C., 2019a. National estimation of soil organic carbon storage potential for arable soils: A  
912 data-driven approach coupled with carbon-landscape zones. *Sci. Total Environ.* 666, 355–  
913 367.

914 Chen, S., Mulder, V.L., Martin, M.P., Walter, C., Lacoste, M., Richer-de-Forges, A.C., Saby,  
915 N.P.A., Loiseau, T., Hu, B., Arrouays, D., 2019b. Probability mapping of soil thickness by  
916 random survival forest at a national scale. *Geoderma.* 344, 184-194.

917 Citepa, 2017. Rapport Ominea - Organisation et méthodes des inventaires nationaux des  
918 émissions atmosphériques en France. ([https://www.citepa.org/images/III-](https://www.citepa.org/images/III-1_Rapports_Inventaires/OMINEA_2017.pdf)  
919 [1\\_Rapports\\_Inventaires/OMINEA\\_2017.pdf](https://www.citepa.org/images/III-1_Rapports_Inventaires/OMINEA_2017.pdf)). 838p. (*in French*)

920 Cotching, W.E., Kidd, D.B., 2010. Soil quality evaluation and the interaction with land use and  
921 soil order in Tasmania, Australia. *Agriculture Ecosystems & Environment.* 137(3/4), 358-366.

922 Denoroy, P., Dubrulle, P., Villette, C., Colomb, C., 2004. REGIFERT. Interpréter les résultats  
923 des analyses de terre. INRA éditions, Collection techniques et pratiques, Paris (France). 132  
924 p. (*in French*).

925 Dequiedt, S., Saby, N.P.A., Lelievre, M., Jolivet, C., Thioulouse, J., Toutain, B., Arrouays, D.,  
926 Bispo, A., Lemanceau, P., Ranjard, L., 2011. Biogeographical Patterns of Soil Molecular  
927 Microbial Biomass as Influenced by Soil Characteristics and Management. *Global Ecology and*  
928 *Biogeography.* 20, 641-652.

929 Dominati, E., Patterson, M., Mackay, A., 2010. A framework for classifying and quantifying  
930 the natural capital and ecosystem services of soils. *Ecological Economics.* 69(9), 1858-1868.

931 Dreal Centre-Val de Loire, 2015a. Le sol, des avancées dans la connaissance. Collection Les  
932 synthèses du profil environnemental régional. 13 p. (*in French*)

933 Dreal Centre-Val de Loire, 2015b. Sol et sous-sol : supports des activités humaines. Collection  
934 Les cahiers cartographiques du profil environnemental régional. 14 p. (*in French*)

935 Duffera, M., White, J.G., Weisz, R., 2007. Spatial variability of Southeastern US Coastal Plain  
936 soil physical properties: Implications for site-specific management. *Geoderma*. 137(3-4),  
937 327-339.

938 Duparque, A., Godard, A., Scheurer, O., van Dijk, P., Vandewalle, F., Martin, P., Sagot, S.,  
939 Fort, J.-L., Mata, L., Guichard, L., Mary, B., Piskiewicz, N., Rosenfelder, C., Saby, N., Vigot, M.,  
940 Eglin, T., 2016. Projet ABC'Terre : Atténuation du Bilan de gaz à effet de serre et stockage de  
941 carbone organique dans les sols agricoles à l'échelle d'un territoire. ADEME Editions. 69 p. (*in*  
942 *French*).

943 EEA and JRC, 2010. State of the environment: state and outlook, Soil. 2010. Soil. 48 p.  
944 doi:10.2800/58866.  
945 [https://esdac.jrc.ec.europa.eu/Library/JRC\\_SOIL/SOER2010/Docs/Soil.pdf](https://esdac.jrc.ec.europa.eu/Library/JRC_SOIL/SOER2010/Docs/Soil.pdf)

946 Follain, S., Schwartz, C., Denoroy, P., Villette, C., Arrouays, D., Walter, C., Lemerrier, B., Saby,  
947 N.P.A., 2009. From quantitative to agronomic assessment of soil available phosphorus  
948 content of French arable topsoils. *Agronomy for Sustainable Development*. 29, 371-380.

949 Fortes, R., Millan, S., Prieto, M.H., Campillo, C., 2015. A methodology based on apparent  
950 electrical conductivity and guided soil samples to improve irrigation zoning. *Precision*  
951 *Agriculture*. 16(4), 441-454.

952 Gip Bretagne Environnement, 2016. La biodiversité des sols bretons. Dossier n°12, novembre  
953 2016. 13 p. (*in French*).

954 Goge, F., Gomez, C., Jolivet, C., Joffre, R., 2014. Which strategy is best to predict soil  
955 properties of a local site from a national Vis-NIR database? *Geoderma*. 213, 1-9.

956 Gomez, C., Dharumarajan, S., Feret, J.B., Lagacherie, P., Ruiz, L., Sekhar, M., 2019. Use of  
957 Sentinel-2 Time-Series Images for Classification and Uncertainty Analysis of Inherent  
958 Biophysical Property: Case of Soil Texture Mapping. *Remote Sensing*. 11(5), no 565.

959 Gomez, C., Oltra-Carrio, R., Bacha, S., Lagacherie, P., Briottet, X., 2015. Evaluating the  
960 sensitivity of clay content prediction to atmospheric effects and degradation of image spatial  
961 resolution using Hyperspectral VNIR/SWIR imagery. *Remote Sensing of Environment*. 164, 1-  
962 15.

963 Goulard, M., Voltz, M., 1992. Linear coregionalization models – Tools for estimation and  
964 choice of cross-variogram matrix. *Mathematical Geology*, 24, 3, 269-286.

965 Grinand, C., Arrouays, D., Laroche, B., Martin, M.P., 2008. Extrapolating regional soil  
966 landscapes from an existing soil map: Sampling intensity, validation procedures, and  
967 integration of spatial context. *Geoderma*. 143, 180-190.

968 Hengl, T., de Jesus, J.M., MacMillan, R.A., Batjes, N.H., Heuvelink, G.B.M., Ribeiro, E., Samuel-  
969 Rosa, A., Kempen, B., Leenaars, J.G.B., Walsh, M.G., Gonzalez, M.R., Gonzalez, M., 2014.  
970 SoilGrids1km-Global Soil Information Based on Automated Mapping. *PLoSOne*, 9, 8. DOI:  
971 10.1371/journal.pone.0105992

972 Horrigue, W., Dequiedt, S., Chemidlin Prévost-Bouré, N., Jolivet, C., Saby, N.P.A., Arrouays,  
973 D., Bispo, A., Maron, P.A., Ranjard, L., 2016. Predictive Model of Soil Molecular Microbial  
974 Biomass. *Ecological Indicators*. 64, 203-211.

975 Ifen, 2007. Le stock de carbone dans les sols agricoles diminue. Le 4 pages Ifen. Numéro 121.  
976 Novembre 2007. (*in French*).

977 IPBES, 2019. Summary for policymakers of the global assessment report on biodiversity and  
978 ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and  
979 Ecosystem Services. Díaz, S., Settele, J., Brondizio, E.S., Ngo, H.T., Guèze, M., Agard, J.,  
980 Arneeth, A., Balvanera, P., Brauman, K.A., Butchart, S.H.M.K., Chan, M.A., Garibaldi, L.A., Ichii,  
981 K., Liu, J., Subramanian, S.M., Midgley, G.F., Miloslavich, P., Molnár, Z., Obura, D., Pfaff, A.,  
982 Polasky, S., Purvis, A., Razzaque, J., Reyers, B., Roy Chowdhury, R., Shin, Y.J., Visseren-  
983 Hamakers, I.J., Willis, K.J., Zayas, C.N. (eds.). IPBES secretariat, Bonn, Germany. 44 pages.

984 IUSS Working Group WRB, 2015. World Reference Base for Soil Resources 2014, Update  
985 2015. International Soil Classification System for Naming Soils and Creating Legends for Soil  
986 Maps. World Soil Resources Reports No. 106, Rome: FAO.

987 Jenny, H., 1941. *Factors of Soil Formation A System of Quantitative Pedology*. Dover  
988 Publications, New York, 281 p.

989 Jones, R.J.A., van Diepen, K., van Orshoven, J., Confalonieri, R., 2014. Scientific contribution  
990 on combining biophysical criteria underpinning the delineation of agricultural areas affected  
991 by specific constraints. Scientific and Technical Research Reports: Report EUR 26940 EN. EC-  
992 JRC Publications Office. 85 p.

993 Karimi, B., Terrat, S., Dequiedt, S., Chemidlin, N., Maron, P.A., Ranjard. L., 2018. Atlas  
994 Français des bactéries du sol, (édition Biotope, édition du Muséum). (*in French*).

995 Karimi, B., Terrat, S., Dequiedt, S., Jolivet, C., Arrouays, D., Wincker, P., Cruaud, C., Bispo, A.,  
996 Chemidlin-Prévost Bouré, N., Ranjard. L., 2019. Biogeography of Soil Bacterial Networks  
997 Along a Gradient of Cropping Intensity. Nature Scientific Report Nature. 9 : 3812.

998 Karimi, B., Terrat, S., Dequiedt, S., Saby, N.P.A., Horrigue, W., Lelievre, M., Nowak, V., Jolivet,  
999 C., Arrouays, D., Wincker, P., Cruaud, C., Bispo, A., Maron, P.A., Chemidlin-Prevost Boure, N.,  
1000 Ranjard, L., 2018. Biogeography of Soil Bacteria and Archaea across France. Science  
1001 Advances. 4(7), eaat1808, DOI: 10.1126/sciadv.aat1808

1002 Keesstra, S.D., Bouma, J., Wallinga, J., Tiftonell, P., Smith, P., Cerda, A., Montanarella, L.,  
1003 Quinton, J.N., Pachepsky, Y., van der Putten, W.H., Bardgett, R.D., Moolenaar, S., Mol, G.,  
1004 Jansen, B., Fresco, L.O., 2016. The significance of soils and soil science towards realization of  
1005 the United Nations Sustainable Development Goals. SOIL. 2(2), 111-128.

1006 Keller, C., Ambrosi, J.P., Rabot, E., Robert, S., Lambert, M.L., Criquet, S., Ajmone Marsan, F.,  
1007 Biasioli, M., 2012. Soil Quality Assessment for Spatial Planning in Urban and Peri-Urban Areas  
1008 - Municipalities of Gardanne and Rousset (southern France). Bulletin of the European Land  
1009 and Soil Alliance Local land and soil news. 40/41, 12-14.

1010 Kidd, D.B., Malone, B.P., McBratney, A.B., Minasny, B., Webb, M.A., 2014. Digital mapping of  
1011 a soil drainage index for irrigated enterprise suitability in Tasmania, Australia. Soil Research.  
1012 52(2), 107-109.

1013 Kidd, D.B., Webb, M., Malone, B., Minasny, B., McBratney, A.B., 2015. Digital soil assessment  
1014 of agricultural suitability, versatility and capital in Tasmania, Australia. *Geoderma Regional*.  
1015 6, 7-21.

1016 Koch, A., McBratney, A., Adams, M., Field, D., Hill, R., Crawford, J., Minasny, B., Lal, R.,  
1017 Abbott, L., O'Donnell, A., Angers, D., Baldock, J., Barbier, E., Binkley, D., Parton, W., Wall,  
1018 D.H., Bird, M., Bouma, J., Chenu, C., Butler Flora, C., Goulding, K., Grunwald, S., Hempel, J.,  
1019 Jastrow, J., Lehmann, J., Lorenz, K., Morgan, C.L., Rice, C.W., Whitehead, D., Young, I.,  
1020 Zimmermann, M., 2014. Soil Security: Solving the Global Soil Crisis. *Global Policy*. 4(4), 434–  
1021 441.

1022 Kuhn, M., Weston, S., Keefer, C., Coulter, N., 2014. Cubist: Rule- and Instance-Based  
1023 Regression Modeling. R package version.

1024 Labidi, A., Bouthier, A., Cousin, I., 2017. Comment évaluer simplement la Réserve Utile d'un  
1025 sol ? Confrontation de modèles d'estimation des teneurs en eau des 2 bornes de la RU  
1026 utilisant des caractéristiques du sol couramment mesurées. *Newsletter, GIS GCHP2E*.  
1027 ([https://www.gchp2e.fr/Bourse-de-stages/Bilan-des-stages-soutenus-par-le-GIS-GC-HP2E-](https://www.gchp2e.fr/Bourse-de-stages/Bilan-des-stages-soutenus-par-le-GIS-GC-HP2E-en-2015-2016)  
1028 *en-2015-2016*) (*In French*).

1029 Lacoste, M., Mulder, V.L., Richer-de-Forges, A.C, Martin, M.P., Arrouays, D., 2016. Evaluating  
1030 large-extent spatial modelling approaches: a case study for total soil depth for France.  
1031 *Geoderma Regional*. 7, 137-152.

1032 Lagacherie, P., Legros, J.-P., Burrough, P.A., 1995. A soil survey procedure using the  
1033 knowledge of soil pattern established in a previously mapped reference area. *Geoderma*.  
1034 65(3/4), 283-301.

1035 Lagacherie, P., Voltz, M., 2000. Predicting soil properties over a region using sample  
1036 information from a mapped reference area and digital elevation data: a conditional  
1037 probability approach. *Geoderma*. 97(3/4), 187-208.

1038 Lalu, R., 2017. Impact des incertitudes relatives à l'estimation des réserves en eau des sols  
1039 d'un territoire sur les sorties de simulation d'un modèle de gestion quantitative territoriale  
1040 de l'eau. Mémoire de fin d'étude. Université ?. *(in French)*.

1041 Landre, A., Saby, N.P.A., Barthès, B.G., Ratié, C., Guérin, A., Etayo, A., Minasny, B., Bardy, M.,  
1042 Meunier, J.-D., Cornu, S., 2018. Prediction of total silicon concentrations in French soils using  
1043 pedotransfer functions from mid-infrared spectrum and pedological attributes. *Geoderma*.  
1044 331, 70-80.

1045 Lemerrier, B., Gaudin, L., Walter, C., Aurousseau, P., Arrouays, D., Schvartz, C., Saby, N.P.A.,  
1046 Follain, S., Abrassart, J., 2008. Soil phosphorus monitoring at the regional level by means of a  
1047 soil test database. *Soil Use and Management*. 24, 131-138.

1048 Li, N., Zhao, X.Y., Wang, J., Sefton, M., Triantafilis, J., 2019. Digital soil mapping based site-  
1049 specific nutrient management in a sugarcane field in Burdekin. *Geoderma*. 340, 38-48.

1050 Lo, T., Heeren, D.M., Mateos, L., Luck, J.D., Martin, D.L., Miller, K.A., Barker, J.B., Shaver,  
1051 T.M., 2017. Field characterization of field capacity and root zone Available Water Capacity  
1052 for variable rate irrigation. *Applied Engineering in Agriculture*. 33(4), 559-572.

1053 Loiseau, T., Chen, S., Mulder, V.L., Román Dobarco, M., Richer-de-Forges, A.C., Lehmann, S.,  
1054 Bourenanne, H, Saby, N.P.A., Martin, M.P., Vaudour, E., Gomez, C., Lagacherie, P., Arrouays,  
1055 D., 2019. Satellite data integration for soil clay content modelling, at a national scale.

1056 International Journal of Applied Earth Observation and Geoinformation. 82,  
1057 <https://doi.org/10.1016/j.jag.2019.101905>.

1058 Marchant, B.P, Saby, N.P.A., Arrouays, D., 2017. A survey of topsoil arsenic and mercury  
1059 concentrations accross France. Chemosphere. 181, 635-644.

1060 Marchant, B.P., Saby, N.P.A., Lark, R.M., Bellamy, P.H., Jolivet, C., Arrouays, D., 2010. Robust  
1061 prediction of soil properties at the national scale: Cadmium content of French soils.  
1062 European Journal of Soil Science. 61(1), 144-152.

1063 McBratney, A.B., Field, D.J., Koch, A., 2014. The dimensions of soil security. Geoderma, 213,  
1064 203-213.

1065 McBratney, A.B., Mendonça Santos, M.L., Minasny, B., 2003. On digital soil mapping.  
1066 Geoderma. 117(1/2), 2-52.

1067 MEDDE and Gis Sol, 2013. Guide pour l'identification et la délimitation des sols de zones  
1068 humides. Ministère de l'Écologie, du Développement Durable et de l'Énergie, Groupement  
1069 d'Intérêt Scientifique Sol, 63 pages. (*in French*).

1070 MEDTL, 2010. Stratégie nationale pour la biodiversité 2011-2020. Texte intégral. 60 p. (see  
1071 <http://www.naturefrance.fr/> (accessed 28 August 2019)). (*in French*).

1072 Meersmans, J., Martin, M.P., Lacarce, E., De Baets, S., Jolivet, C., Boulonne, L., Lehmann, S.,  
1073 Saby, N.P.A., Bispo, A., Arrouays, D., 2012. A high resolution map of French soil organic  
1074 carbon. Agron. Sustain. Dev. 32 (4), 841–851.

1075 Meinshausen, N., 2006. Quantile regression forests. J. Mach. Learn. Res. 7, 983-999.

1076 Minasny, B., Malone, B.P., McBratney, A.B., 2012. Digital Soil Assessments and Beyond.  
1077 Proceedings of the 5th Global Workshop on Digital Soil Mapping, Sydney Australia, CRC  
1078 Press, London, 472 p.

1079 Minasny, B., McBratney, A.B., 2016. Digital soil mapping: a brief history and some lessons.  
1080 Geoderma. 264, 301–311.

1081 MTES, 2017. Guide de valorisation hors site des terres excavées issues de sites et sols  
1082 potentiellement pollués dans des projets d'aménagement. MTES - Ministère de la transition  
1083 écologique et solidaire. (*in French*).

1084 Mulder, V.L., Lacoste, M., Martin, M.P., Richer-de-Forges, A.C., Arrouays, D., 2015.  
1085 Understanding large-extent controls of soil organic carbon storage in relation to soil depth  
1086 and soil-landscape systems. Global Biogeochemical Cycles. 29(8), 1210-1229.

1087 Mulder, V.L., Lacoste, M., Richer-de-Forges, A.C., Martin, M.P., Arrouays, D., 2016. National  
1088 versus global modelling the 3D distribution of soil organic carbon in mainland France.  
1089 Geoderma 263, 16–34. <https://doi.org/10.1016/j.geoderma.2015.08.035>

1090 Nauman, T.W., [Thompson, J.A.](#), 2012. Fuzzy disaggregation of conventional soil maps using  
1091 database knowledge extraction to produce soil property maps. In: Digital Soil Assessments  
1092 and Beyond. Minasny, B., Malone, B.P., McBratney, A.B. (Eds). pp 203-207. CRC Press,  
1093 London.

1094 Nicolas, D. 2015. La Réserve Utile des sols gouverne les besoins en eau. Réussir Grandes  
1095 Cultures. 297, 53-54. (*in French*).

1096 Odgers, N.P., Clifford, D., 2014. DSMART: An algorithm to spatially disaggregate soil map  
1097 units. In: GlobalSoilMap: Basis of the Global Spatial Soil Information System. Arrouays D.,

1098 McKenzie N., Hempel J., Richer-de-Forges A.C., McBratney A.B. (Eds). pp 261-266. Taylor and  
1099 Francis, CRC Press, London.

1100 Pellerin, S., Bamière, L., (Coords.), Launay, C., Martin, R., Schiavo, M., Angers, D.A., Augusto,  
1101 L., Balesdent, J., Basile-Doelsch, I., Bellassen, V., Cardinael, R., Cécillon, L., Ceschia, E., Chenu,  
1102 C., Constantin, J., Daroussin, J., Delacote, P., Delame, N., Gastal, F., Gilbert, D., Graux, A.-I.,  
1103 Guenet, B., Houot, S., Klumpp, K., Letort, E., Litrico, I., Martin, M.P., Menasseri, S., Mézière,  
1104 D., Morvan, T., Mosnier, C., Roger-Estrade, J., Saint-André, L., Sierra, J., Thérond, T., Viaud,  
1105 V., Grateau, R., Le Perchec, S., Savini, I., Réchauchère, O., 2019. Stocker du carbone dans les  
1106 sols français, Quel potentiel au regard de l'objectif 4 pour 1000 et à quel coût ? Synthèse du  
1107 rapport d'étude, INRA (France), 114p. (*in French*).

1108 Quinlan, J.R., 1992. Learning with continuous classes. In 5th Australian Joint Conference on  
1109 Artificial Intelligence. 92, 343–348.

1110 Ranjard, L., Dequiedt, S., Chemidlin Prévost-Bouré, N., Thioulouse, J., Saby, N.P.A., Lelievre,  
1111 M., Maron, P.A., Morin, F.E.R., Bispo, A., Jolivet, C., Arrouays, D., Lemanceau P., 2013.  
1112 Turnover of soil bacterial diversity driven by wide-scale environmental heterogeneity.  
1113 Nature Communications. 4:134. DOI : 10.1038/ncomms2431.

1114 Ranjard, L., Dequiedt, S., Jolivet, C., Saby, N.P.A., Thioulouse, J., Harmand, J., Loisel, P.,  
1115 Rapaport, A., Saliou, F., Simonet, P., Joffre, R., Chemidlin-Prévost Bouré, N., Maron, P.A.,  
1116 Mougél, C., Martin, M.P., Toutain, B., Arrouays, D., Lemanceau, P., 2010. Biogeography of  
1117 soil microbial communi-ties: a review and a description of the ongoing French national  
1118 initiative. Agron. Sustain. Dev. 30, 359–365. DOI: 10.1051/agro/2009033

1119 Richer-de-Forges, A.C., Arrouays, D., Bispo, A., Lagacherie, P., Laroche, B., Lemerrier, B.,  
1120 Sauter, J., Voltz, M., 2019. Mapping of soils and land-related environmental attributes in

1121 France: analysis of end-users' needs. *Sustainability*. 11(10),  
1122 <https://doi.org/10.3390/su11102940>.

1123 Richer-de-Forges, A.C., Saby, N.P.A., Mulder, V.L., Laroche, B., Arrouays, D., 2017. Probability  
1124 mapping of iron pan presence in sandy podzols in South-West France, using Digital Soil  
1125 Mapping. *Geoderma Regional*. 9, 39-46.

1126 Román Dobarco, M., Bourennane, H., Arrouays, D., Saby, N.P.A., Cousin, I., Martin, M.P.,  
1127 2019b. Uncertainty assessment of *GlobalSoilMap* soil available water capacity products: a  
1128 French case study. *Geoderma*. 344, 14-30.

1129 Román Dobarco, M., Cousin, I., Le Bas, C., Martin, M.P., 2019a. Pedotransfer functions for  
1130 predicting available water capacity in French soils, their applicability domain and associated  
1131 uncertainty. *Geoderma*. 336, 81-95.

1132 Rutgers, M., Orgiazzi, A., Gardi, C., Römbke, J., Jänsch, S., Keith, A. M., Neilson, R., Boag, B.,  
1133 Schmidt, O., Murchie, A.K., Blackshaw, R.P., Pérès, G., Cluzeau, D., Guernion, M., Briones,  
1134 M.J.I., Rodeiro, J., Piñeiro, R., Díaz Cosín, D.J., Sousa, J.P., Suhadolc, M., Kos, I., Krogh, P.-H.,  
1135 Faber, J.H., Mulder, C., Bogte, J.J., van Wijnen, H.J., Schouten, A.J., de Zwart, D., 2016.  
1136 Mapping earthworm communities in Europe. *Applied Soil Ecology*. 97, 98-111.

1137 Saby, N., Swiderski, C., Lemerrier, B., Walter, C., Benjamin, P., Louis, B.P., Eveillard, P.,  
1138 Arrouays, D., 2017. Is pH increasing in the non-calcareous topsoils of France under  
1139 agricultural management? A statistical framework to overcome the limitations of a soil test  
1140 database *Soil Use Manag*. 33, 460-470.

1141 Saby, N.P.A., Marchant, B.P., Lark, R.M., Jolivet, C.C., Arrouays, D., 2011. Robust  
1142 geostatistical prediction of trace elements across France. *Geoderma*. 162, 303-311.

1143 Saib, M.S., Caudeville, J., Beauchamp, M., Carre, F., Ganry, O., Trugeon, A., Cicolella, A. 2015.  
1144 Building spatial composite indicators to analyze environmental health inequalities on a  
1145 regional scale. *Environmental Health*. 14, article n°68. DOI: 10.1186/s12940-015-0054-3

1146 Saib, M.S., Caudeville, J., Carre, F., Ganry, O., Cicolella, A., 2014. Spatial relationship  
1147 quantification between environmental, socioeconomic and health data at different  
1148 geographic levels. *International Journal of Environmental Research and Public Health*. 11(4),  
1149 3765-3786.

1150 Soil Survey Division Staff, 1993. Soil survey manual. In: Soil Conservation Service U.S.  
1151 Department of Agriculture Handbook, pp. 18.

1152 Soussana, J.-F., Lutfalla, S., Ehrhardt, F., Rosenstock, T., Lamanna, C., Havlík, P., Richards, M.,  
1153 Wollenberg, E., Chotte, J.-L., Torquebiau, E., Ciais, P., Smith, P., Lal, R., 2019. Matching policy  
1154 and science: Rationale for the '4 per 1000 - soils for food security and climate' initiative. *Soil  
1155 and Tillage Research*. 188, 2-14.

1156 Terrat, S., Dequiedt, S., Saby, N., Horrigue, W., Lelievre, M., Nowak, V., Tripied, J., Regnier, T.,  
1157 Jolivet, C., Arrouays, D., Wincker, P., Cruaud, C., Karimi, B., Bispo, A., Maron, P.A., Chemidlin  
1158 Prévost-Bouré, N., Ranjard, L., 2017. Mapping and Predictive Variations of Soil Bacterial  
1159 Richness across French National Territory. *PlosOne*. 12(10): e0186766.

1160 Turner, K.G., Anderson, S., Gonzales-Chang, M., Costanza, R., Courville, S., Dalgaard, T.,  
1161 Dominati, E., Kubiszewski, I., Ogilvy, S., Porfirio, L., Ratna, N., Sandhu, H., Sutton, P.C.,  
1162 Svenning, J.C., Turner, G.M., Varennes, Y.D., Voinov, A., Wratten, S., 2016. A review of  
1163 methods, data, and models to assess changes in the value of ecosystem services from land  
1164 degradation and restoration. *Ecological Modelling*. 319, 190-207.

1165 Vaudour, E., Baghdadi, N., Gilliot, J.M., 2014. Mapping tillage operations over a peri-urban  
1166 region using combined SPOT4 and ASAR/ENVISAT images. *International Journal of Applied*  
1167 *Earth Observation and Geoinformation*. 28, 43–59.

1168 Vaudour, E., Gilliot, J.M., Bel, L., Lefevre, J., Chehdi, K., 2016. Regional prediction of soil  
1169 organic carbon content over temperate croplands using visible near-infrared airborne  
1170 hyperspectral imagery and synchronous field spectra. *International Journal of Applied Earth*  
1171 *Observation and Geoinformation*. 49, 24–38. <https://doi.org/10.1016/j.jag.2016.01.005>

1172 Vaudour, E., Gomez, C., Fouad, Y., Lagacherie, P., 2019. Sentinel-2 image capacities to  
1173 predict common topsoil properties of temperate and Mediterranean agroecosystems.  
1174 *Remote Sensing of Environment*. 223, 21–33. <https://doi.org/10.1016/j.rse.2019.01.006>

1175 Vaysse, K., Lagacherie, P., 2015. Evaluating digital soil mapping approaches for mapping  
1176 *GlobalSoilMap* soil properties from legacy data in Languedoc-Roussillon (France). *Geoderma*  
1177 *Regional*. 4, 20–30.

1178 Vaysse, K., Lagacherie, P., 2017. Using quantile regression forest to estimate uncertainty of  
1179 digital soil mapping products. *Geoderma*. 291, 55-64.

1180 Villanneau, E., Perry-Giraud, C., Saby, N., Jolivet, C., Marot, F., Maton, D., Floch-Barneaud, A.,  
1181 Antoni, V., Arrouays, D., 2008. Détection de valeurs anomaliques dans les teneurs en ETM  
1182 des sols, basée sur le Réseau de Mesure de la Qualité des Sols. *Etude et Gestion des Sols*.  
1183 15(3), 183-200. (*in French*).

1184 Villanneau, E.J., Saby, N.P.A., Orton, T.G., Jolivet, C.C., Boulonne, L., Caria, G., Barriuso, E.,  
1185 Bispo, A., Briand, O., Arrouays, D., 2013. First evidence of large-scale PAH trends in French  
1186 soils. *Environmental Chemistry Letters*. 11(1), 99-104.

1187 Vincent, S., Lemerrier, B., Berthier, L., Walter, C., 2016. Spatial disaggregation of complex  
1188 Soil Map Units at the regional scale based on soil-landscape relationships. *Geoderma*. 311,  
1189 130-142.

1190 Voltz, M., Arrouays, D., Bispo, A., Lagacherie, P., Laroche, B., Lemerrier, B., Richer-de-Forges,  
1191 A.C., Sauter, J., Schnebelen, N., 2018. La cartographie des sols en France: Etat des lieux et  
1192 perspectives; INRA: Paris, France, 112 p. (*in French*).

1193 Voltz, M., Lagacherie, P., Louchart, X., 1997. Predicting soil properties over a region using  
1194 sample information from a mapped reference area. *European Journal of Soil Science*. 48(1),  
1195 19-30.

1196 Zaouche, M., Bel, L., Vaudour, E., 2017. Geostatistical mapping of topsoil organic carbon and  
1197 uncertainty assessment in Western Paris croplands (France). *Geoderma Regional*. 10, 126–  
1198 137.

1199

## 1200 **Captions to figures**

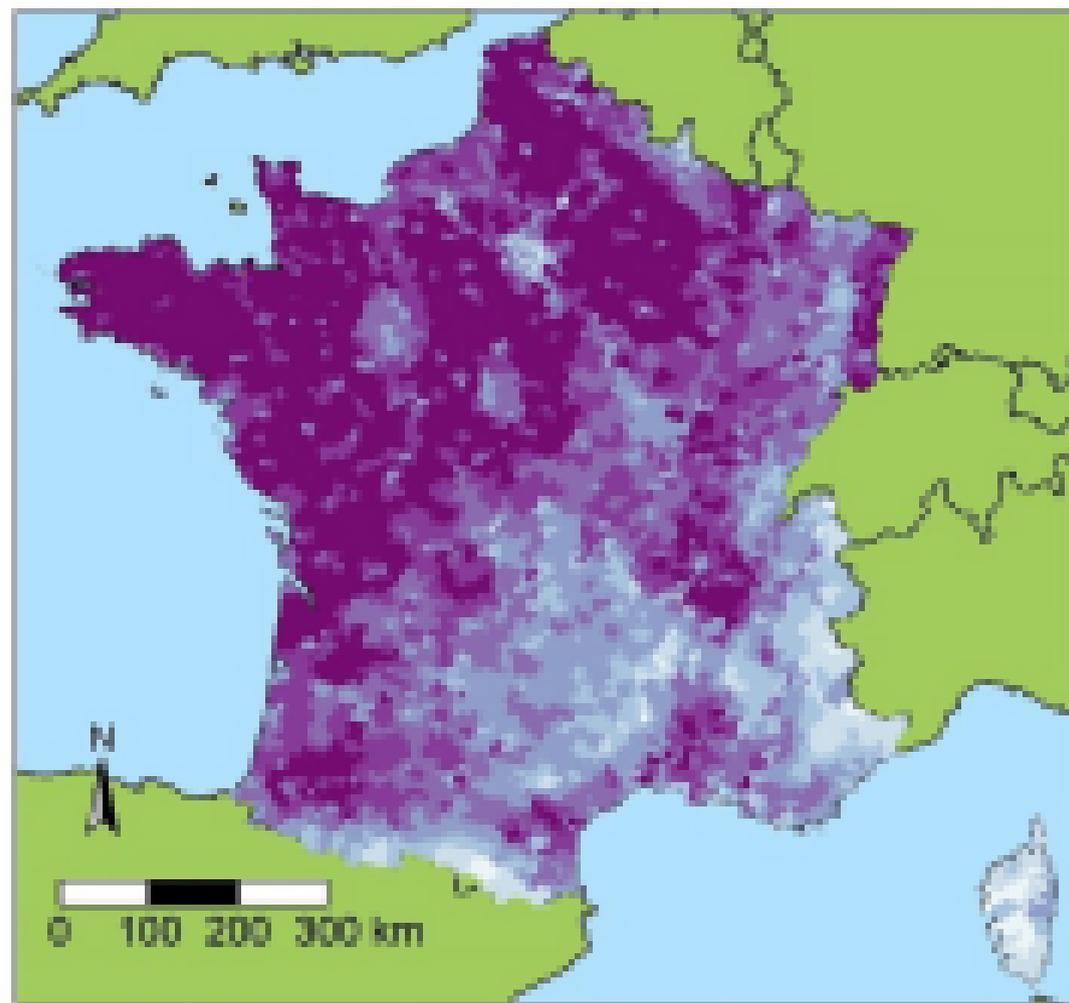
1201

1202 Figure 1. Density of soil tests per canton. A canton is an administrative unit, the mean  
1203 agricultural area of which is 148 km<sup>2</sup>.

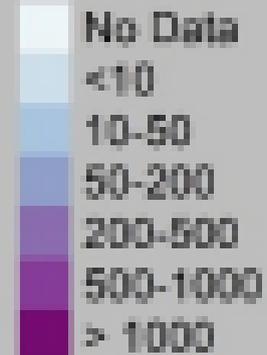
1204 Figure 2. Locations of point data available in the soil survey database (IGCS, in green) and the  
1205 soil quality monitoring network (RMQS, in red) for mainland France.

1206 Figure 3. Number of demands arriving to the national centre for soil information INRA  
1207 InfoSol from 2008 to 2018.

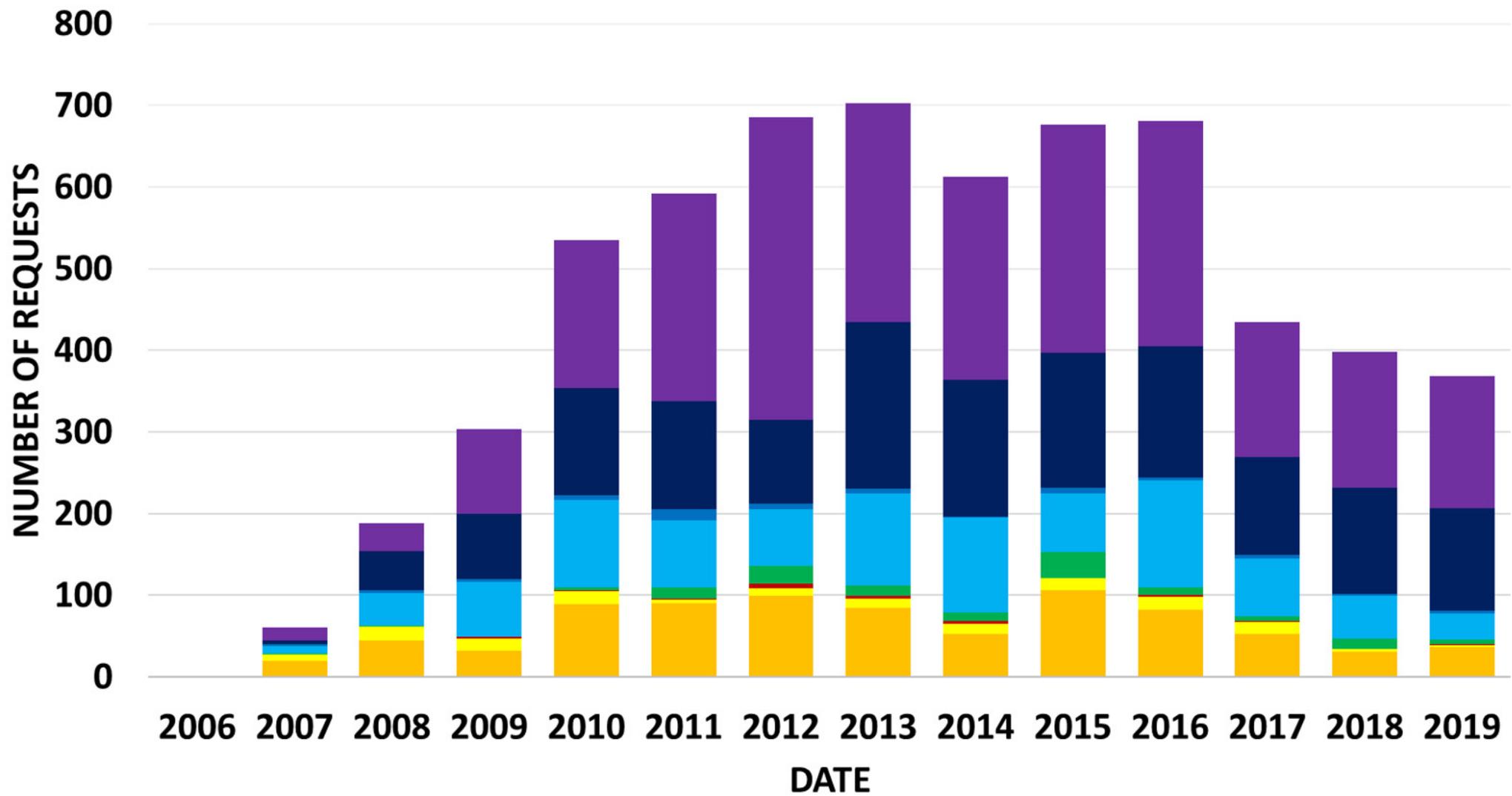
1208 Figure 4. Proportions of the media categories in which the INRA InfoSol Unit has participated  
1209 since 2008. 1: Daily national press; 2: National general public magazines; 3: Magazines  
1210 specialising in agriculture or the environment; 4: Magazines of scientific vulgarisation; 5:  
1211 Radio interviews or debates; 6: TV studio interviews or TV report broadcasts; 7: information  
1212 on websites. Calculations on about 200 communications from 2008 to 2018.



### Number of soil test results







- Agricultural development companies
- Citizens-general public
- Farmers
- Medias
- National stakeholders and policy makers
- Non governmental organisations
- Private companies
- Research

