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Dominique Arrouays [a,*], Anne C. Richer-de-Forges [a], Florence Héliès [a], Vera Leatitia Mulder [b], Nicolas P.A. Saby [a], Songchao Chen [a,c], Manuel P. Martin [a], Mercedes Román Dobarco [a,j], Stéphane Follain [d], Claudy Jolivet [a], Bertrand Laroche [a], Thomas Loiseau [a], Isabelle Cousin [e], Marine Lacoste [e], Lionel Ranjard [d], Benoît Toutain [a], Christine Le Bas [a], Thomas Eglin [f], Marion Bardy [g], Véronique Antoni [h], Jeroen Meersmans [i], Céline Ratié [a], Antonio Bispo [a]

[a] *INRAE, US 1106, InfoSol, F-45000, Orléans, France*
[b] *Soil Geography and Landscape Group, Wageningen University, PO Box 47 6700 AA, Wageningen, the Netherlands*
[c] *UMR SAS, Inrae, Agrocampus Ouest, 35042 Rennes, France*
[d] *Agroécologie – AgroSup Dijon, INRAE, Univ. Bourgogne Franche-Comté, F-21000 Dijon, France*
[e] *Inrae, UR 0272 Sols, F-45075 Orléans, Cedex 02, France*
[f] *ADEME, 20 av. du Grésillé, F-49004, Angers, France*
[g] *Ministère de l'Agriculture et de l'Alimentation, Direction Générale de l'Enseignement et de la Recherche, 75 007 Paris, France*
[h] *Ministry for the Ecological and Inclusive Transition - Service de la donnée et des études statistiques, 5 route d'Olivet, CS 16105 - 45061 Orléans, cedex 2, France*
[i] *Université de Liège, Analyse des risques environnementaux, Passage des Déportés 2, 5030 Gembloux, Belgium*
[j] *Sydney Institute of Agriculture & School of Life and Environmental Sciences, The University of Sydney, New South Wales, Australia*

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ABSTRACT

During the last 10 years, several attempts to map soil attributes at the scale of mainland France have been realised. We exemplify them by seven major outputs: maps of organic C stocks, trace elements (TE), microbial density and diversity, soil thickness, available water capacity (AWC), extractable P, and changes in soil pH. We first briefly describe the data and the methods used to produce these maps and summarise their main results. We then focus on their impacts on various categories of the public, i.e. the general public and citizens; farmers; private companies; non-governmental organisations; agricultural development organisations, stakeholders, and national agencies; French governmental bodies; and international organisations. We also analyse the demands that came to the French National Soil Information Centre from 2008 to 2018 and the impact that our activities had in various media. Soil organic C had the largest impact in nearly all categories of end-users, which may be linked to the recent '4 per 1000' initiative launched by the French governmentduring the COP21 and to the fact that farmers are interested in increasing the organic matter content of their soil for increasing the fertility. TE obtained high scores, which may be related to citizens' care about health and to the fact that governmental bodies and national agencies have a major interest in site contamination assessments. The soil P content, pH, and AWC exhibited major impacts on the agricultural sector. Maps of the soil P content and pH were used as geomarketing tools by private companies selling fertilisers and soil amendments, whereas the AWC was already incorporated into decision-making aid tools for irrigation management developed by development organisations for farmers. Microbial diversity generated collaborations with a large network of farmers and had a large media impact. Nevertheless, the visibility of soil information to the general public should be increased. This can be done by using new multimedia and interactive tools. Overall, these selected examples of digital soil mapping of soil attributes at the national scale in France clearly indicate that the soil attributes have substantial impact on various categories of end-users, such as farmers, professional organisations, stakeholders, and policymakers at different levels of decision-making, among others. However, the impacts on the general public and citizens are more difficult to quantify, and increasing the soil awareness of the general public should be of high priority.

* Corresponding author.
E-mail address: Dominique.Arrouays@inra.fr (D. Arrouays).

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Contents

1. Introduction . . . 2
2. Materials and methods . . . 2
   2.1. French soil tests database . . . 2
   2.2. Soil point data used for national DSM . . . 3
      2.2.1. French soil profiles database 'DoneSol' . . . 3
      2.2.2. French soil quality monitoring network (RMQS) systematic grid . . . 3
      2.2.3. SOILHYDRO and GEVARNOVIA databases . . . 3
      2.2.4. Data and methods used for main national DSM products . . . 4
3. Synthesis of main results . . . 5
   3.1. Soil P maps . . . 5
   3.2. Changes in soil pH. . . . 5
   3.3. Trace elements . . . 5
   3.4. SOC maps and maps of potential of additional SOC storage . . . 5
   3.5. Soil thickness . . . 6
   3.6. Available water capacity . . . 6
   3.7. Soil microbial density and biodiversity . . . 6
4. Main impacts . . . 6
   4.1. Soil available P . . . 6
   4.2. Soil pH and changes in soil pH . . . 6
   4.3. Trace elements . . . 7
   4.4. Soil organic carbon . . . 7
   4.5. Soil thickness . . . 7
   4.6. Available water capacity . . . 7
   4.7. Soil microbial abundance and diversity . . . 7
5. Discussion. . . . 8
   5.1. Importance of data capturing and rescuing. . . . 8
   5.2. Impacts of DSM at French national scale and ways to increase them . . . 8
   5.3. Future of DSM in France . . . 10
6. Conclusion . . . 10

Declaration of Competing Interest . . . 10

. . . 10

References . . . 10

1. Introduction

The 1:250.000 soil mapping program of France is nearly complete. During this program, mapping has mainly been conducted using conventional methods. However, there is a discernible need to obtain more precise soil data using other methods, among which digital soil mapping (DSM; McBratney et al., 2003) is attracting considerable attention (Richer-de-Forges et al., 2019; Voltz et al., 2018). In their seminal paper, McBratney et al. (2003) proposed a generic framework called the soil spatial prediction function with spatially auto-correlated errors (scorpan-SSPFe) for producing digital soil maps (Minasny and McBratney, 2016). Since the early 1990s, a large number of French papers have dealt with DSM, although they most often focused on local applications. These applications included various methods, such as i) extrapolation of already mapped areas in various French regions (e.g. Lagacherie et al., 1995; Voltz et al., 1997; Lagacherie and Voltz, 2000; Grinand et al., 2008); ii) the use of disaggregation approaches (Nauman and Thompson, 2012) such as DSMART (Odgers and Clifford, 2014) to disaggregate conventional soil maps for Brittany (Vincent et al., 2016); iii) DSM of specific soil attributes of interest (e.g. Bourennane et al., 1996, 2003; Bourennane and King, 2003; Arrouays et al., 1995; Chaplot et al., 2000) or even of some diagnostic horizons (Richer-de-Forges et al., 2017). More recently, regional attempts to map soil attributes according to *GlobalSoiMap* specifications (Arrouays et al., 2014) have been made in Southern France (e.g. Vaysse and Lagacherie, 2015, 2017), and considerable effort has been directed towards investigating the potential of new sensors to map soil properties at the local or regional level (e.g. Gomez et al., 2015; Gomez et al., 2019; Vaudour et al., 2014, 2016, 2019; Zaouche et al., 2017).

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

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

2. Materials and methods

2.1. French soil tests database

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

In France, approximately 2,600,000 soil samples were analysed between 1990 and 2014, leading to a total of approximately 329,000,000 analytical results. Most of the analyses involve classical agronomic parameters, such as the pH, organic C and N, extractable P with various reagents, cation exchange capacity, and exchangeable cations. The uncontrolled sampling strategy led to a heterogeneous distribution of the samples in both space and time (Fig. 1). For privacy, the location information in this dataset is limited to the administrative district from which the soil sample was collected. Changes in the sampling resolution may arise in space and time because the soil sample locations were selected according to the needs of farmers rather than a statistical design.

2.2. Soil point data used for national DSM

2.2.1. French soil profiles database 'DoneSol'

This database contains all point-based soil information coming from conventional soil mapping and inventory programs at all scales (Inventaire Gestion et Conservation des Sols, IGCS). Consequently, these points (soil profiles and augering descriptions) are irregularly spread over the French mainland territory and are sometimes clustered in areas of specific economic interest, such as vineyards. As a whole, they represent approximately 160,000 point data.

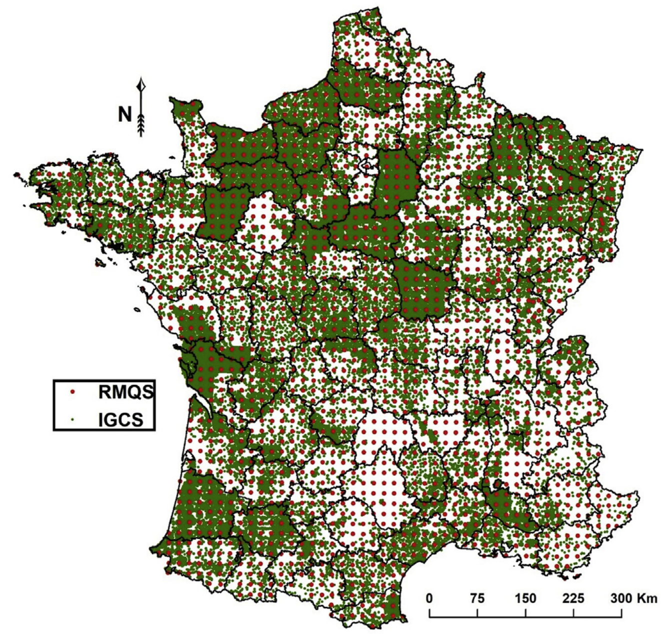

Fig. 2. Locations of point data available in the soil survey database (IGCS, in green) and the soil quality monitoring network (RMQS, in red) for mainland France.

2.2.2. French soil quality monitoring network (RMQS) systematic grid

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

2.2.3. SOILHYDRO and GEVARNOVIA databases

The SOLHYDRO database contains data on physical, chemical, and hydraulic characteristics of samples collected from 1985 (Bruand et al., 2004). The soil types are mainly Cambisols, Luvisols, Planosols, Albeluvisols, Podzols, and Fluvisols (IUSS Working Group WRB, 2015) sampled over the French metropolitan territory. The geographical distribution of the sampling locations is mostly concentrated in the northern half of France, with little representation of the more mountainous

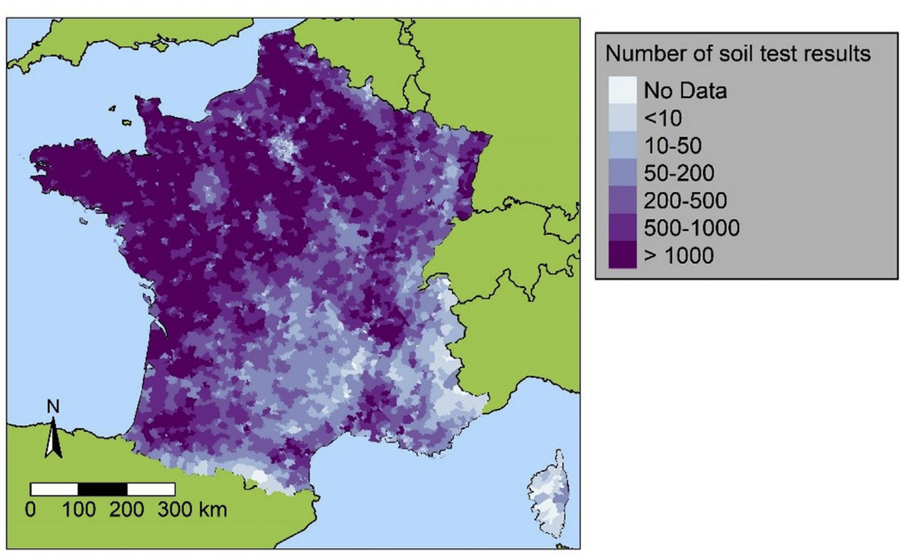

Fig. 1. Density of soil tests per canton. A canton is an administrative unit, the mean agricultural area of which is 148 km^2.

southern and eastern regions, but covers a wide range of parent materials and textures. The land use varies among the sampling locations, including forests, poplar plantations, vineyards, grasslands, fallow, and oleaginous crops, but mostly consists of cereal monocultures. In 2017, SOLHYDRO comprised 689 horizons, of which 157 were topsoil horizons (depth of 0–30 cm) and 532 were subsurface horizons (depth of >30 cm). Samples were collected when soil was close to the field capacity and stored in a cold chamber before measurements (Román Dobarco et al., 2019a). The gravimetric water content was determined via a pressure-plate apparatus at field capacity (FC) at −10 kPa and permanent welting point (PWP) at −1580 kPa water potential, by using undisturbed aggregates (10–15 cm^3) (Bruand and Tessier, 2000; Bruand et al., 2003). The particle-size distribution, SOC content, and bulk density ware measured according to international standards. Then, the volumetric water content (θ_{FC} and θ_{PWP}) for each horizon was calculated by multiplying the gravimetric soil moisture content measured for undisturbed aggregates by the horizon bulk density. In 2017, 689, and 457 horizons were subjected to measurements at −1580 kPa, and − 10 kPa, respectively.

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

2.2.4. Data and methods used for main national DSM products

2.2.4.1. Soil P. In the database, a total of 850,606 results from soil analyses contained available P content values (in mg P_2O_5 kg^{-1}). These values were determined by one of the three standardised methods (AFNOR, 1996) used by French soil analysis laboratories, i.e. the “Dyer” method (NFX 31–10), which involves the measurement of soluble P in a citric acid monohydrate solution; the “Joret-Hébert” method (NFX 31–161: determination of soluble P in an ammonium oxalate solution); and the “Olsen” method (ISO 11263: determination of P in a sodium hydrogen carbonate solution). The originality of the method used lies in quantitative results originating from the French Soil Test Database and their evaluation using the RegiFert software (Denoroy et al., 2004), which incorporates soil characteristics and crop sensitivity to nutrient availability. Briefly, RegiFert introduces two threshold values (L1 and L2, with L1 < L2) to interpret the P content in soils according to crop needs. These threshold values depend on the sensitivity of plants to the P availability, on the analytical methods chosen for P_2O_5, as well as on the soil characteristics: the $CaCO_3$ content, pH, clay fraction, and SOC content. This methodology constituted an attempt to gather all analytical results into a common diagnostic framework on the national scale (for France), while taking into account the local pedological context and crop production requirements. Data stored in BDAT over the period of 1990–2004 were originally geographically located on a municipal scale but were then aggregated on the “cantonal” scale for statistical and legal reasons. The French “cantons” are administrative jurisdictions defined as a grouping of several municipalities with a mean land area of 140 km^2.

2.2.4.2. Changes in soil pH. Recently, Saby et al. (2017) assessed the changes in the pH and cation saturation in French agricultural topsoils (1996–2010). Assessment of these changes considering values older than 1996 was not possible, because of a change in the standard analytical method after 1995. Calcareous samples were excluded from this analysis. To obtain enough samples for spatiotemporal comparisons and to assess changes over a large time interval, two periods were analysed (1996–2000 and 2006–2010). Calcareous soil samples were excluded from this study. A total of 488,117 samples were used for the statistical analysis. Data were aggregated into spatial entities corresponding to their small agricultural regions (SARs). In France, an SAR is an agricultural census unit that combines several districts. The average agricultural area of an SAR is 355.12 km^2. Employing this spatial unit allows the use of sufficient data to run non-parametric statistics. For running these non-parametric statistics, Saby et al. (2017) proposed a statistical approach that takes into account the possible bias in the database using resampling techniques. Detailing this method is outside of the scope of this synthesis; however, a key point is that this methodology does not require any assumption regarding the precise pH measurement location, this is important because we often do not know it due to privacy legislation.

2.2.4.3. SOC stocks. The most recent product predicting SOC stocks at the national scale (Mulder et al., 2016) used all available point data for France, from both the French Soil Mapping and Inventory Program and RMQS, i.e. the systematic monitoring grid. For estimating SOC stocks, only the soils that these profiles precisely georeferenced and that had measurements of the SOC content were retained, leading to a total of approximately 36,000 profiles. Details regarding these two datasets were presented by Mulder et al. (2016). Briefly, Mulder et al. (2016) used these point data and 23 available covariates related to climate, relief, parent material and soils, biomass production, and land use to predict the SOC over a 90 × 90 m grid according to *GlobalSoilMap* specifications (Arrouays et al., 2014). The tool used for modelling was CUBIST (Kuhn et al., 2014; Quinlan, 1992), and the confidence intervals were determined using 10-fold cross-validations. Subsequently, the maps were masked by the modelled total soil depth (Lacoste et al., 2016), and the SOC stock was calculated in accordance with the work of Meersmans et al. (2012). This grid was further aggregated to generate a 1-km^2 grid together with 90% confidence intervals and delivered to the UN-FAO GSP as a bottom-up product for the Global Soil Organic Carbon (GSOC) map (http://www.fao.org/global-soil-partnership/pillars-action/4-information-and-data-new/global-soil-organic-carbon-gsoc-map/en/).

2.2.4.4. Trace elements. TE data from the RMQS systematic grid were used to deliver various products. A first product was delivered by Villanneau et al. (2008) and is available online at doi:10.15454/UEZXBY. These authors took into account both the natural pedogeochemical background and the diffuse contamination to quantify background levels of TE by using robust statistics (Tukey's whisker). Whiskers were calculated for each RMQS site using at least 10 neighbour sites within a 50-km circle. High background contents for four elements (Pb, Zn, Cu, and total and extractable Cd) indicated either high natural contents or anthropogenic diffuse contamination. Most importantly, their method allowed the calculation of an indicator for detecting a suspicious TE amount while taking into account the local context. Later, more sophisticated methods were developed by Marchant et al. (2010) and Saby et al. (2011). They developed robust geostatistical algorithms to map the underlying variation of six TEs (Cr, Cu, Pb, Ni, Tl, and Zn) across France, allowing background values attributable to a geogenic or large diffuse contamination origin to be mapped. A similar approach was employed by Marchant et al. (2017) for the As and Hg contents in French soils.

2.2.4.5. Soil microbial density and biodiversity. Samples from the 0–30-cm layer of RMQS sites (first campaign) were used for DNA extraction. The total content of microbial DNA was determined. The methods for characterising the density and diversity of the microbial communities relied on molecular tools such as the quantitative polymerase chain reaction (PCR), DNA fingerprinting, and high-throughout sequencing of soil DNA extracts. Additional information was presented by Ranjard et al. (2010), Ranjard et al., 2013), Dequiedt et al. (2011), Terrat et al. (2017), and Karimi et al. (2018, 2019).The methods allowed the elaboration of simple indicators of microbial diversity and the mapping of their amounts and distribution across the French territory using DSM techniques involving covariates such as the climate, soil parent material, clay content, and land use.

2.2.4.6. Soil thickness. The first product predicting the ST at a national scale (Lacoste et al., 2016) was produced using 2116 sites from the RMQS database and 14,113 sites from the IGCS database. The RMQS dataset had a better spatial coverage and was collected via a standardised procedure. The RMQS dataset was used for calibration; the IGCS dataset was used for validation. The ST (or depth) was defined according to the USDA Soil Survey Manual as the depth (in cm) to a lithic or paralithic contact (Soil Survey Division Staff, 1993).

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

2.2.4.7. Available water capacity. The prediction of the AWC was performed in two steps. First, soil properties used as input for pedotransfer functions and coarse elements were predicted over mainland France using the *GlobalSoilMap* depth interval. Data of the particle-size distribution and coarse elements were extracted from the IGCS dataset, resulting in a total of 81,671 soil profiles and soil cores. Particle-size fractions were predicted with regression-cokriging models [Cubist models (Kuhn et al., 2014; Quinlan, 1992) + linear model of coregionalisation (Goulard and Voltz, 1992)], and coarse elements were predicted with a regression model (quantile regression model, Meinshausen, 2006). All the regression models were fitted using 44 environmental covariates describing *scorpan* factors. For calibration, data of the particle-size distribution and coarse elements were extracted from the IGCS dataset, resulting in a total of 81,671 soil profiles and soil cores. The RMQS dataset was used as an independent evaluation sample for particle-size distribution and coarse element predictions. Then, the volumetric soil moisture content ($cm^3\ cm^{-3}$) at field capacity (-10 kPa $= \theta_{FC}$) and at a permanent wilting point (-1580 kPa $= \theta_{PWP}$) for the fine fraction were estimated with PTFs developed by Román Dobarco et al. (2019a) using the SOLHYDRO database. These PTFs used the content of clay (%) and sand (%) as predictor variables. The predictions of the volumetric soil moisture contents of the fine fraction were evaluated with the GEVARNOVIA georeferenced observations. Finally, the AWC (mm) was calculated as $(\theta_{FC} - \theta_{PWP}) * (1 - R_v) * t$, where R_v represents the volume of coarse elements (%), and t represents the thickness of the *GlobalSoilMap* depth interval (mm). The uncertainty of the AWC was quantified via first-order Taylor analysis. The uncertainty analysis accounted for two sources of uncertainty: the PTF coefficients and the soil input properties.

3. Synthesis of main results

3.1. Soil P maps

Follain et al. (2009) assessed the P bioavailability in arable topsoils in France at a national scale. Using this procedure, they concluded that 77% of cantons were on average below the critical level regarding crop needs. In France, a canton is an administrative unit that combines several municipalities. From an environmental standpoint, this situation could be considered as generating the lowest water pollution risk. Nevertheless, 23% of the cantons exhibited a soil P accumulation that is not necessary with regard to agricultural uses. In this case, no fertilization is required, and the pollution risk is increased. For instance, focusing on Brittany—a region with intensive livestock production—Lemercier et al. (2008) showed a strong P accumulation in soils with an increased risk of P losses into water bodies and thus of eutrophication.

3.2. Changes in soil pH

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

3.3. Trace elements

Detailed results are provided by Villanneau et al. (2008), Saby et al. (2011), and Marchant et al. (2017). Villanneau et al. (2008) and Saby et al. (2011) reported that high concentrations of Pb, Cr, Ni, and Zn occurred in soils on crystalline rocks, whereas the Cd concentrations were high in soils developed on Jurassic rocks. Volcanic parent material led to high concentrations of Cr, Cu, Ni, and Zn but low concentrations of Pb and Tl. The diffuse pollution of certain elements (mainly Pb and to a lesser extent Zn) was evident in industrial regions in the north and the northeast of France and close to Paris. The pattern of some outlying values was indicative of more local anthropogenic processes, such as diffuse industrial pollution in the north of France and close to Paris and application of Cu in vineyards, as well as of geological anomalies, such as high concentrations of some TEs in the south of the Massif Central Mountains. Marchant et al. (2017) used geostatistical methods to map the expected concentrations of As and Hg in the topsoil and determine the probabilities that legislative thresholds are exceeded. They found that with the exception of some areas where the geogenic concentrations and soil adsorption capacities are very low, the As concentrations are often higher than the thresholds, indicating that further assessment of some areas is required. There were regions with elevated Hg concentrations, which could be related to volcanic material, natural mineralisation, and industrial contamination. These regions are more diffuse than the hotspots of As, reflecting the greater volatility of Hg and therefore the greater ease with which it can be transported and redeposited.

3.4. SOC maps and maps of potential of additional SOC storage

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

The SOC storage potential was modelled by Chen et al. (2019a). They defined different C-landscape zones (CLZs) in France for modelling the soil C sequestration, thereby building upon the research of Mulder et al. (2015). They then computed estimates of the highest possible values using percentiles of 0.8, 0.85, 0.9, and 0.95 of the measured SOC stocks within these CLZs for arable soils. The SOC storage potential was calculated as the difference between the maximum SOC stocks and the current SOC stocks.

3.5. Soil thickness

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

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

3.6. Available water capacity

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

3.7. Soil microbial density and biodiversity

Ranjard et al. (2010) Ranjard et al., 2013) provided the first extensive maps of the soil microbial biomass and bacterial biodiversity at the scale of mainland France. The maps revealed large biogeographical patterns of microbial density and bacterial biodiversity, indicating an heterogeneous and spatially structured distribution of these microbial parameters (Dequiedt et al., 2011; Terrat et al., 2017). The main factors driving the microbial distribution on a wide scale are the physicochemical properties of soils (texture, pH, and organic C contents) and the land use. Soils from land used for intensive agriculture—particularly cropland and vineyards—exhibited the smallest biomass pools but the highest bacterial diversity. This observation supported a positive relationship between bacterial diversity and soil disturbance due to cropping intensity, which decreased in the following order: Vineyards-Orchards > Crops > Grasslands > Forests. Using the bacterial diversity data, Karimi et al. (2018) characterised the biogeography of each major and minor bacterial taxonomic group and deduced their ecological attributes as well as their distribution patterns.

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

4. Main impacts

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

4.1. Soil available P

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

4.2. Soil pH and changes in soil pH

Regarding P, aggregated maps of classes of pH and pH changes are freely available at doi:10.15454/SVDTOU. *Farmers* can access basic statistics and compare their results with those available in their region. Although the pH is increasing slightly, many areas of France still have very low pH values; therefore, *private companies*, such as producers of liming products, may use the maps to target areas still exhibiting these values, thus using the maps for geo-marketing. Additionally, the French Union of Fertilizer Industries (UNIFA) can use these results to estimate the total amounts of liming products that are necessary to increase the pH values of all soils over commonly accepted standards (e.g. 6.2 or 6.5). *Policymakers*, such as the ministries for agriculture or the environment, use these results to ensure broad communication regarding soil acidity (CGDD/SOeS, 2015) and liming recommendations to a large audience. We can validate changes only in areas with many samples, which suggests that additional collection may help detect new changes. Therefore, this study advocated for further pursuing and developing this program and obtaining funding from *governmental bodies*, such as the French Ministry for Agriculture. From a policy viewpoint, increasing the number of samples gathered by farmers would benefit the robustness of our estimates. As suggested by Saby et al. (2017): '*This policy could be accomplished via dedicated subsidies allocated to farmers for soil tests […] or allocating existing subsidies to regularly perform soil analyses*.'

4.3. Trace elements

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

4.4. Soil organic carbon

From a *policy* viewpoint, soil C has become an important issue, as the French Government's Climate Plan aims to achieve carbon neutrality by 2050. Average SOC stock values by land use are now used to apply a Tier 2 approach for national greenhouse-gas emissions accounting (Citepa, 2017). SOC stocks maps were used for an expert report about the C storage potential at the demand of the French Ministry for Agriculture and ADEME (Pellerin et al., 2019). They helped to estimate the SOC storage potential under different scenarios of changes in land use and management and to indicate the areas/situations for which maintaining existing large stocks should be a priority. At a more local scale, changes in SOC are now mandatory for C accounting of medium to large intercommunal cooperation bodies (>20,000 inhabitants) according to the French decree n°2016–849 of 28 June 2016, establishing the territorial climate–air–energy plan. ADEME, which is the state agency in charge of the climate policy implementation, has developed a diagnostic tool providing default estimates of the C stocks and stock changes at this French administrative level using data from the French soil quality monitoring network (ADEME, 2019) and encourages the development of spatially explicit analyses (Duparque et al., 2016). At the *international policy level*, the aggregated product at a 1-km resolution was delivered to the UN-FAO GSP as the French contribution to the GSOC map of the world (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 produced in France via DSM were used by stakeholders and ministries to communicate the importance of SOC for preserving the soils and the environment from degradation and for mitigating climate change. For instance, the brochure ‘Organic carbon in soils: Meeting climate change and food security challenge’ was edited by ADEME to highlight the important role of soil C in the French climate change mitigation strategy and to promote actions in the agricultural and forestry sectors (ADEME – GIS Sol, 2015).

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

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

4.5. Soil thickness

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

4.6. Available water capacity

Román Dobarco et al. (2019a) provided various PTFs based on the available data. They also provided PTF *users* with tools for classifying new samples as within or outside the applicability domain of the PTFs. The majority of horizons outside the domain of applicability were located in forests and natural areas or managed pastures. This has a big impact on some *final end-users*, i.e. *agricultural development companies* and *farmers*. These PTFs are already incorporated into *decision-making aid tools for irrigation management* developed by development organisations for farmers. For example, the ‘Arvalis-Institut du Végétal’ institute, which is dedicated to cereal crops, included a new version of AWC estimation in its CHN model that is incorporated into a decision tool for irrigation. Provided that a detailed field-scale mapping is available (e.g. Duffera et al., 2007; Fortes et al., 2015; Li et al., 2019), these PTFs open the door to precision agriculture for optimising water efficiency for crops, particularly in drought situations (Lo et al., 2017). For larger areas, these PTFs associated with the uncertainties in the AWC were used in a regional project in southwest France in a decision tool dedicated to the evaluation of irrigation quotas (Lalu, 2017). At the national scale, such information is also needed by ministries and agencies to adapt agriculture and forest sectors to climate change. Apart from numerous scientific papers and communications, the necessity to develop PTFs with a high spatial resolution for the AWC was published in technical journals for farmers (Bouthier, 2015; Nicolas, 2015) and in newsletters (Labidi et al., 2017), as well as presented in numerous technical seminars, and was communicated to a broad audience of *citizens and farmers* during various agricultural events (e.g. International Agriculture Exhibition, Paris, 2016 (approximately 610,000 visitors, mainly from a general public audience; French Agricultural Days ‘Les culturales’ (approximately 13,000 farmers from all French regions)). A practical guide on how to estimate the soil AWC will soon be freely released.

4.7. Soil microbial abundance and diversity

The use of soil molecular techniques to characterise soil microbial abundance and diversity in >2200 soils allowed the standardisation of indicators and the design of corresponding wide-scale references for soil biological diagnosis (Horrigue et al., 2016; Bouchez et al., 2016). These indicators are now embedded in the *French biodiversity observatory* (ONB, http://indicateurs-biodiversite.naturefrance.gf/en), which aims to provide robust indicators for the French strategy for biodiversity (MEDTL, 2010). Other initiatives concerning soil biodiversity are communicated at a *regional level* (Gip Bretagne Environnement, 2016). From a *policy* viewpoint, they are also integrated into national reporting by the French Ministry of Environment (MEDTL, 2010) and embedded into the French Ministry of Agriculture Agricultural biodiversity observatory (OAB, http://observatoire-agricole-biodoversite.fr/). From an *agricultural development* viewpoint, these soil bioindicators have allowed the development of a *citizen science* project allowing researchers and farmers to work together with the same objective, to achieve a better understanding of the impact of agricultural practices on the soil biological quality and more largely on the durability of crop production (Cannavacciulo et al., 2017). To date, the network involves more than 400 farmers distributed across France in croplands and vineyards, and the data accumulated in this network are analysed to produce robust trends regarding the impacts of different practices (pesticide input, soil tillage, grasslanding, crop rotation, organic vs. conventional crops, etc.) on soil biological quality and services. Finally, for the general public, a didactic French atlas of soil bacteria (Karimi et al., 2018) based on the results obtained via the RMQS soil sampling was published in 2018 and sold >1000 copies in less than a year. The publishing of this atlas was reported in numerous forms of media, e.g. radio, television (TV), and national press, highlighting the role of soil quality in the durability of agriculture for the public.

5. Discussion

5.1. Importance of data capturing and rescuing

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

In France, an important data rescue effort led to a 69% increase of the number of soil profiles data from 2009 to 2015 giving an impressive coverage at adequate density of the French territory. In 2015, the total number of points in mainland France soil database was about 160,000 and is now (end of 2019) about 190,000. This effort of capturing data benefited from the implementation of the 1:250,000 soil mapping program for which it was mandatory to deliver the soil profiles information to the national database. For this purpose, INRA developed an easy-to-use data entry interface with a smallest error potential as possible. Meanwhile, many other legacy data from maps at other scales and from other programs were rescued by INRA, by entry and collation of legacy soil profiles and data (e.g. point location and year of recording, soil classification, soil morphologic observations and soil analytical measurements including values, units and methods used) from soil reports into the national soil profile database. The number of measurements, however, was highly variable, depending on the soil properties. In particular, AWC measurements are much less dense and irregularly spread over the territory. A sampling strategy has been designed to complete AWC measurements geographical coverage in the framework of the second campaign of the RMQS. Other hydraulic properties, such as for instance hydraulic conductivity, still remain very sparse in the national database. This type of measurements has mainly been realised in localised areas for drainage of irrigation projects. Rescuing them to build PTFs would require specific efforts and funding that are still under discussion.

Trace elements measurements came from the RMQS, ensuring a perfect homogeneity in sampling, analytical procedures and geographical coverage. The data capturing for the BDAT came from contracting with private laboratories. From 1999 to 2014, the number of samples increased regularly at a rate of about 120,000 per year, and reached about 2,600,000 in 2014. The analyses, however, mainly concern agricultural soils and routine agronomic measurements from topsoil (e.g. pH, SOC, CEC, clay content, available P and K). Even with such a number of measurements, they remain irregularly spread, and some temporal trends are not yet detectable over the entire French territory. This advocates for pursuing data capturing in order to confirm observed trends or to detect new ones.

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

In this section, we first summarise and discuss the impacts of French national DSM products. Then, we elaborate on potential further developments. Striking impacts of DSM at the national scale in France are revealed. These impacts cover a wide range of end-users, some of which supply data to the French ministries for their own publications at the national (CGDD/SOeS, 2015; CGDD/SOeS, 2014) or at regional level (e.g. de Loire, 2015a, 2015b). At the European level, the indicators reported by France towards various instances (OCDE, Eurostat, DG Environment of the European Community, European Environmental Agency) are aggregated at the national or sub-national (French regions) level.

In this study, we decided to focus on seven striking examples at the national scale, but many other ongoing projects are presently delivering new DSM products, often at a more local scale, such as an ongoing project that aims at using DSM to better quantify soil ecosystem services and to provide tools for land-use planning in peri-urban areas (see https://www6.inra.fr/soilserv/). We decided to focus on these seven examples, but other DSM national products are available, for instance, on persistent organic pollutants (e.g, Villanneau et al., 2013). These products, together with products related to TE, are largely used at a high policy level (French Ministry for the Environment) to evaluate the environmental exposure of populations to contaminants and to map environmental health inequalities (e.g. Caudeville, 2013; Caudeville, 2015; Caudeville et al., 2017; Saib et al., 2014, 2015). There is no doubt that relating human health to soil conditions will increase soil awareness among the general public and national and local authorities.

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

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

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

It was challenging assessing whether the resulting maps led to changes in practices of the farmers. However, the maps have been consulted by technical advisers and consultants from agricultural development organisations (agricultural chambers, agricultural

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

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

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

cooperatives). Therefore, we may think that farmers pay now more attention to order some soil tests to monitor several soil properties in the areas that were identified as problematic (e.g. areas with low pH, low P availability, low SOC content or high TE). The technical advisers also give recommendations to farmers to counter-balance undesirable evolutions (e.g. liming, organic or inorganic P fertilization, adopting conservation agriculture practices). Another example of impact is the farmers' network mnitoring soil biological indicators under different practices (see Section 4.7). Besides, the demand from farmers for microbial analyses is increasing and the biggest private soil analysis laboratory in France (55% of the market share) recently added microbial abundance and diversity to his laboratory test catalogue. AWC is already incorporated into decision-making aid tools for irrigation management developed by development organisations for farmers. This is briefly discussed in Sections 4.6 and 5.3.

Another way to assess the impact on soil awareness is to analyse the demands that came since 2008 to the INRA InfoSol Unit, which can be considered as the national centre for soil information in France (Fig. 3). Fig. 3 shows that the largest demands to INRA InfoSol were related to research, either asking to provide data or asking for a research collaboration. Other major demands came from private companies, national stakeholders, policymakers, and agricultural development companies. Interestingly, there were noticeable demands from citizens and the media, whereas demands from farmers and NGOs were almost absent. The low percentage of farmers' demands is not surprising as they usually ask questions to local advisers rather than at the national level. The sharp increase of demands beginning around 2009 corresponds to the period during which InfoSol began to publish online information, and the sharp decline from 2017 might be due to the fact that InfoSol developed numerous webservices allowing people to find information without having to ask for it. The low interest from citizens and the general public confirms that there is a real need to increase the soil awareness of the population (McBratney et al., 2014; Koch et al., 2014). One may wonder if this disinterest is due to a lack of communication from the national centre for soil information.

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

Fig. 4 indicates that the visibility of soil information to the general public should be increased (see the low proportions of TV and radio interviews). This can be done by using new multimedia tools, particularly targeting the young public, which gathers most of its information through internet tools. For instance, InfoSol recently created a Twitter account (@InfosolOrleans) to communicate regarding its activities and products and raise general awareness of soil issues. The most popular tweet thus far was the publication of the national map of C stocks. Moreover, interactive tools allowing people to visualise changes that may occur under different scenarios (changes in land use, climate, agricultural practices, etc.) should be adopted.

It is expected that DSM will progressively move towards digital soil assessment (DSA, Carré et al., 2007; Minasny et al., 2012; Arrouays et al., 2020). DSA is the application and interpretation of DSM maps for specific uses (e.g. agricultural productivity, land suitability, land-use planning, C accounting), which often require using soil data as inputs to models (e.g. crop models, ecosystem services assessment tools, greenhouse-gas accounting models). For instance, national DSM maps are already used together with other information to model soil functions or services as soil habitats (Karimi et al., 2018; Rutgers et al., 2016) or to model the C storage potential depending on land use and

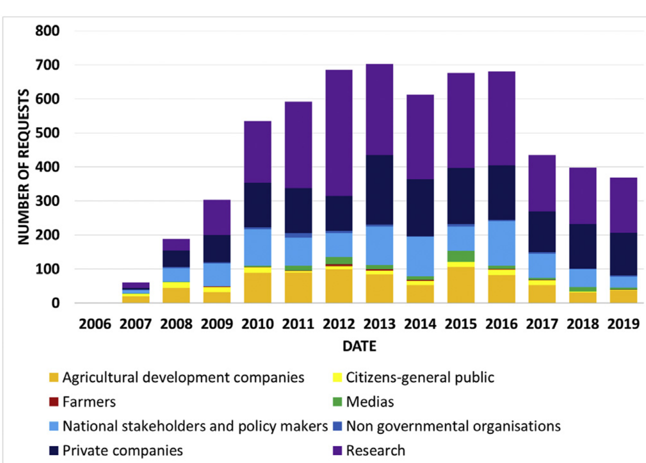

Fig. 3. Number of demands arriving to the national centre for soil information INRA InfoSol from 2008 to 2018.

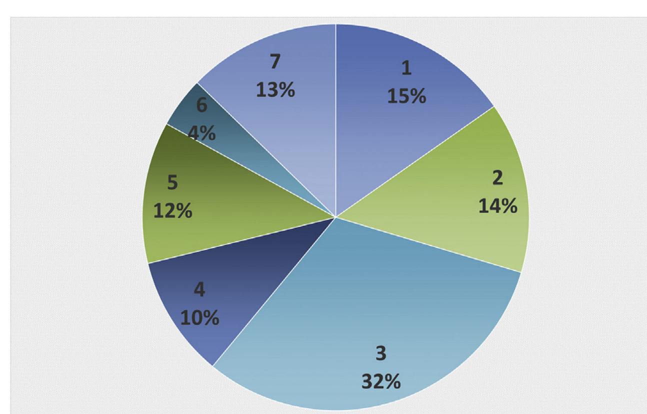

Fig. 4. Proportions of the media categories in which the INRA InfoSol Unit has participated since 2008. 1: Daily national press; 2: National general public magazines; 3: Magazines specialising in agriculture or the environment; 4: Magazines of scientific vulgarisation; 5: Radio interviews or debates;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

practices (Pellerin et al., 2019). One main advantage of DSM is that it indicates the uncertainty on soil attributes, which can be used to test the sensitivity of these models or to use probability density functions of soil attributes instead of average of dominant values. Moreover, these interpretations may also include social and economic factors, allowing societal needs to be better addressed. Examples include the assessment of the services rendered by soils (e.g. Dominati et al., 2010; Turner et al., 2016), as in the programs Soilserv (https://www6.inra.fr/soilserv/) and SoilVer, i.e. a soil and land research funding platform for Europe (https://www.soilver.eu/), contributions to soil-related local decision making and economics issues (e.g. Cotching and Kidd, 2010; Kidd et al., 2014, 2015), and contributions of soils to the adaptation of agriculture and forest sectors to climate change and to the sustainable development goals and the achievement of Land Degradation Neutrality (e.g. Keesstra et al., 2016; Bouma, 2019). All these actions will increase the soil awareness of the general public and of policymakers.

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

5.3. Future of DSM in France

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

The RMQS is now in its second round of sampling. The sampling strategy has been revised to optimise the sampling in both space and time for detecting changes in soil conditions earlier (particularly regarding SOC stocks). New variables have been added to the analytical menu of the second campaign (AWC, particulate organic matter) or are subject to feasibility studies for future integration (pesticide contents, soil biodiversity parameters). Consequently, for example, the validity of the evaluation statistics for soil hydraulic properties will improve when ongoing work of the RMQS second campaign increases the representativeness of pedoclimatic conditions and spatial distribution in soil hydraulic measurements at the national level. The BDAT collection of analytical results ordered by farmers is also ongoing. Both programmes will move from DSM to digital soil monitoring and will increase their impacts at all levels.

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

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

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

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

6. Conclusion

The selected examples of DSM at the national scale in France clearly have substantial impact on various categories of end-users, such as farmers, professional organisations, private companies, stakeholders, and policymakers at different levels of decision making. If we consider the TE and SOC, the impacts on stakeholders and policymakers are very large. TE in soil are related to human exposure and health and are therefore popular research topics. The SOC is now considered a priority for climate adaptation and mitigation, as exemplified by the launch of the 4 per 1000 initiative by France at the COP21. The impact on private companies is important, particularly for companies dealing with fertilisers or amendment production (see the results for P and pH) and those involved with potentially contaminated sites. The impacts on the general public and citizens are less quantifiable and should be a high priority if we wish to raise the soil awareness of the general public. It appears that increased efforts should be dedicated to deliver usable products rather than to deliver raw soil properties, even if the raw soil properties provide a basis without which DSA and digital soil monitoring cannot be developed. Formerly, the traditional soil survey was generally followed up by soil-survey interpretations (mainly empirical and qualitative). Soil mapping has been modernised through DSM, but the interpretation and the production of real digital assessment appears to still be in infancy in France. Additionally, relating human health to soil conditions will undoubtedly increase the soil awareness among the general public and national and local authorities.

Declaration of Competing Interest

None.

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