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Marc Voltz [a,b,*], Dominique Arrouays [c], Antonio Bispo [b,c,g], Philippe Lagacherie [a,b,g], Bertrand Laroche [b,c,g], Blandine Lemercier [d,g], Anne Richer-de-Forges [c], Joëlle Sauter [b,e,g], Nathalie Schnebelen [f]

[a] LISAH, Univ Montpellier, INRAE, IRD, Institut Agro, Montpellier, France
[b] Scientific Council of the French Soil Inventory Programme (IGCS), France
[c] INRAE US 1106 InfoSol, Orléans, France
[d] UMR SAS, AGROCAMPUS OUEST, INRAE, Rennes, France
[e] Regional Chamber of Agriculture of Grand Est, Strasbourg, France
[f] Agroecosystems Division, INRAE, Orléans, France
[g] Combined technology network on soils and territories (RMT Sols et Territoires), France

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ABSTRACT

The need for soil data has largely increased worldwide given the growing general concern about the maintenance and recovery of ecosystem resources and services. The development of digital soil mapping (DSM) is often seen as a means for answering this demand. In France, the national soil mapping strategy has been defined in the early 1990s within the Soil Inventory, Management and Conservation Programme (IGCS) and based on conventional soil mapping approaches. Now, small-scale soil map coverage of France has been almost achieved, soil data needs have evolved and DSM approaches have matured. The question therefore arises of what should be the future soil mapping strategy in France so as to foster soil mapping, better answer end-users needs and raise societal concern about soils. To answer this issue, we present in this paper a prospective analysis of the French national soil mapping strategy, which included i) a survey of the needs and difficulties expressed by producers, managers and users of soil data and ii) a foresight study of potential future scenarios for the development of soil mapping that takes advantage of DSM approaches. The survey indicated that soil information needs are high in terms of soil attributes, spatial resolution and accuracy and go beyond the data and maps presently available for France. The survey also showed that DSM methods remain little known outside the academic sector. The foresight study led to two main outputs. The first is to propose two complementary spatial sampling strategies for new data acquisition: i) upgrading the density of observed soil profiles to homogenize the accuracy of 1:250,000 soil maps for France and ii) improving the knowledge of local soil distribution patterns in the French regions by developing detailed mapping of reference areas, representative of the local soil patterns. The second output is a set of four possible scenarios for the development of soil mapping that differ according to the expected level of concern about soils that may exist in France in the future. The comparison of the scenarios led to several recommendations for favouring soil mapping, acquisition of new soil data and dissemination of soil knowledge. The recommendations include awareness raising about soil mapping and its potential for answering many environmental challenges, capacity building of soil surveyors and soil data users for DSM approaches, and improved quality assessment of soil maps to guide users and stimulate new investments of map producers. This certainly involves renewed public support before market development of soil mapping activities can take place and become the main support for soil mapping in France.

1. Introduction

The need for soil data has largely increased worldwide given the growing general concern about the maintenance and recovery of ecosystem resources and services (Harteminck and McBratney, 2008). The development of digital soil mapping (DSM) supported by the increased availability of spatial data (digital elevation model, satellite imagery) has been seen and promoted as a means for answering this demand (McBratney et al., 2003; Minasny and McBratney, 2016; Arrouays et al., 2020). Indeed, performance tests of DSM have shown a similar or higher performance of this approach compared to conventional soil mapping (Kempen et al., 2012; Collard et al., 2014), thanks

* Corresponding author at: INRAE, UMR LISAH, 2 Place Viala 34060, Montpellier, Cedex 1, France.
E-mail address: marc.voltz@inrae.fr (M. Voltz).

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especially to the use of data mining approaches and exploitation of many environmental covariates. Moreover, DSM has very attractive functionalities to enable quantitative predictions of soil classes and soil properties, uncertainty estimations, fine resolution mapping grids or to provide a reproducible quantitative spatial prediction model and the capacity to easily upgrade soil maps when new data become available. The *GlobalSoilMap* project (Sanchez et al., 2009; Arrouays et al., 2014) and now the Global Soil Partnership of FAO have stimulated the application of DSM at national, continental and global scales (e.g., Bui et al., 2006; Odgers et al., 2012; Adhikari et al., 2013; Hengl et al., 2015; Mulder et al., 2016; Viscarra Rossel et al., 2015, Padarian et al., 2017). These initiatives have already led to the production of digital soil maps over whole countries that estimate soil properties or soil classes at fine spatial resolutions ranging between 20 and 200 m. In addition, the production of digital soil maps has also emerged at regional and local scales (e.g., Grinand et al., 2008; van der Klooster et al., 2011; Lemercier et al., 2012; Vaysse and Lagacherie, 2015; Richer-de-Forges et al., 2017; Santra et al., 2017). Accordingly, Minasny and McBratney (2016) concluded in their paper about the history and future of DSM that it has now shifted from a research phase into operational use.

This shift is real but is not sufficient per se for enabling most demands for soil data and maps to be fulfilled in the near future, for which there are at least four challenges to be met.

First, it must be stressed that DSM techniques are still mostly led by scientific staff from universities, research institutes or state agencies, who represent only a small proportion of soil surveyors and staff involved in land resource management. To generalize soil mapping by DSM approaches and more largely to amplify soil mapping across the world, there is a need to attract as many land resource managers as possible to DSM, and it is therefore necessary to invest in training for building interest and capacity.

Second, the national digital soil maps produced over the last decade were often completed using the legacy soil data available in each country. Regardless of the intrinsic performance of DSM methods and the spatial resolution and accuracy of the auxiliary variables used, the accuracy of the mapped soil classes and properties ultimately depends largely on the available soil data that are used for training (Vaysse and Lagacherie, 2015; Somarathna et al., 2017). Because the density of the available legacy data is often low, typically from 1 per 800 km^2 (Hengl et al., 2017) to 1 per 30 km^2 (Mulder et al., 2016), many produced digital soil maps exhibit accuracy that limits their use essentially for planning purposes (e.g., Helmick et al., 2014; Ashketar et al., 2014; Samuel-Rosa et al., 2015; Vaysse and Lagacherie, 2015, 2017). Moreover, the type of data available does not cover the range of soil data needed (Richer-de-Forges et al., 2019; Samuel-Rosa et al., 2015; Arrouays et al., 2017; Zare et al., 2018). To meet the demand for soil data requested for many management purposes at field and local scales (e.g., Samuel-Rosa et al., 2015; Richer-de-Forges et al., 2019; Zare et al., 2018), the sole move from conventional mapping techniques to DSM is not enough in itself if it is not accompanied by prospects of acquiring new soil data that will increase the spatial density of soil information and the range of observed soil attributes (e.g., Arrouays et al., 2017; Zare et al., 2018; Farzamian et al., 2019).

Third, DSM basically depends on the development of soil and geographical information systems that can provide soil attributes and soil covariate data at satisfactory spatial density. Many efforts have already been made and are still under way (e.g., Hollis et al., 2006; Arrouays et al., 2017), but much must still be done to collect, harmonize and store the needed data to make them easily accessible and usable to all potential users of soil data at global, continental, national, regional or local scales.

Last, but not least, is the cost issue associated with DSM. Although the cost of conventional soil mapping approaches has been evaluated in the past (e.g., a series of papers by Bie and Beckett, 1970, 1971; Beckett and Burrough, 1971; and Burrough et al., 1971), the implementation cost of DSM has received little attention until now (Kempen et al., 2012; De Gruijter et al., 2016) and may be an obstacle to the dissemination of DSM. Ways to study this issue are not only to evaluate the costs but also to ask potential users of soil information whether they see economic value in soil information and are willing to pay for digital soil maps. Diafas et al. (2013) conducted a web-based survey of stakeholders at the European scale to evaluate their willingness to pay. The response rate was rather low but revealed that, among the respondents, significant willingness to pay increased with the resolution and accuracy of the maps. This finding is positive for DSM but certainly has to be confirmed because it may vary depending on the type of stakeholder and the current practices for environmental data acquisition and dissemination in each country.

For those countries that recognize that DSM has the potential for transforming and stimulating soil surveys and soil knowledge, the mentioned challenges, namely, disseminating DSM techniques, stimulating new data acquisition schemes, developing user-friendly and open soil information systems and evaluating the economic value of digital soil maps, need to be addressed in any national soil survey programme. If such programmes already exist and have been based on conventional soil mapping approaches, they certainly need now to be profoundly adapted. In France, the national soil mapping strategy has been defined within the Soil Inventory, Management and Conservation Programme (IGCS) that is driven by GIS Sol (Group of Scientific Interest for Soil, that includes research institutes and governmental bodies and agencies concerned with soil issues) and used to be based on conventional soil mapping approaches. The current strategy was defined in the early 1990s. Since that time, small-scale soil map coverage of France is now fairly well achieved, soil data needs have evolved, DSM approaches have matured and public funding for soil information has decreased in part. The question therefore arises of what should be the future soil mapping strategy in France so as to foster soil mapping, better answer end-users needs and raise societal concern about soils.

To answer this issue, in this paper, we present a prospective analysis of the French national soil mapping strategy. This analysis was recently completed under the auspices of GIS Sol, Ministry of Agriculture and Scientific Council of the IGCS programme, who mandated the authors of this paper, a group of soil scientists, including researchers and practitioners, to carry out a comprehensive analysis including i) a survey of the needs and difficulties expressed by producers, managers and users of soil data and, finally, ii) a prospective analysis of potential future scenarios for the development of soil mapping that take opportunity of DSM approaches and that are technically and economically sustainable. The results of the survey were fully presented in a report in French (Arrouays et al., 2018) and in part in an international journal paper (Richer-de-Forges et al., 2019), whereas the results of the whole analysis were presented in a report to the Ministry of Agriculture and to GIS Sol (Voltz et al., 2018) as well as at the joint workshop for digital soil mapping and Global Soil Map that was held in March 2019 in Santiago de Chile. Here, we report on the second step and discuss some of the conditions for the development and implementation of DSM in France. In the following, we first review the current state of the soil inventory programmes in France and examine, on the basis of the survey results, the present needs and concerns expressed by producers and users of soil data relating to the production, dissemination and use of maps. We then describe the technical options we elaborated for a new soil mapping programme in France in order to answer the surveyed needs. Eventually, we present and discuss a foresight exercise that produced four scenarios for the development of soil mapping that differ according to the level of concern about soil and to the socio-economical context that may prevail in France in the next two decades.

2. Present state and issues of the French soil inventory programme IGCS

2.1. Achievements of IGCS

The IGCS programme has inventoried soils at various scales by applying mainly conventional soil survey approaches. Its main outputs are a cartographic representation of the spatial distribution of soils, in the form of soil mapping units (Arrouays et al., 2004), and a national soil information storage system, DoneSol, managed by the French national soil data centre InfoSol in Orléans. The IGCS programme has 3 sub-programmes defined according to the scale of the soil survey. The first is the Regional Pedological Reference Framework (RRP), which aims to obtain an exhaustive knowledge of soils at a 1:250,000 scale (Laroche et al., 2014). The second is the Pedological Knowledge of France (CPF) sub-programme, which focuses on medium scales (1:100,000 to 1:50,000) and aims to improve knowledge of soil diversity and distribution laws on the basis of their formation factors (Richer-de-Forges et al., 2014). Finally, the third is the Reference Area (SR) sub-programme, which aims to carry out large-scale soil studies (approximately 1/10,000) over small reference areas to address agricultural or environmental issues at the local level, with the possibility of extrapolating the acquired soil knowledge to the small regions surrounding the reference areas (Favrot, 1989).

These three sub-programmes have several features in common:

(i) a coordination by INRAE InfoSol of a set of regional partners, from the academic and research sectors or from the agricultural or environmental sectors, having soil survey expertise and ensuring the implementation of soil surveys at the local level;
(ii) a harmonized approach to data acquisition, described in detail by Arrouays et al. (2004);
(iii) capitalization of all data collected in a single national information system, called DoneSol (Grolleau et al., 2004), which now includes approximately 70,000 soil profiles and 97,000 soil auger descriptions;
(iv) scientific coherence and consistency ensured by the National Scientific Council of the IGCS programme (CS IGCS).

For two decades, the priority of funding has been given to the completion of exhaustive coverage of the French territory at the 1:250,000 scale. As shown in Fig. 1, the RRP programme is nearly complete. All maps and related soil information have been made available through the national soil information system on the web and are regularly utilized. However, given the small scale of the RRP, there is a growing need for more detailed soil data. In this respect, it must be recognized that the two other sub-programmes are far from the entire coverage of France because the CPF and SR programmes cover only approximately 37% and 17% of France, respectively. Moreover, it is not possible to consider that these programmes will be achieved in a reasonable time period given the expected future public funding. A new agenda has therefore to be defined that remains reasonable in cost, identifies new funding sources, takes advantage of new methodologies and, eventually, allows us to answer as closely as possible the present soil data needs for end users.

2.2. Main results of a survey of soil data producers and end users

The survey consisted of two questionnaires, one sent to map producers and the other to current or potential end users (Richer-de-Forges et al., 2019; Arrouays et al., 2018). The questionnaires included a broad range of questions (up to 92 for map producers and 67 for end users) that covered practical, technical, scientific and economic issues. A total of 875 surveys were sent to people from 676 different organizations; 271 people responded (52 producers and 219 end users). We briefly report the results of the survey that are important to consider when designing future soil mapping programmes in France.

Concerning the practical, technical and scientific results of the survey, a detailed presentation was made by Richer-de-Forges et al. (2019); therefore, we only present the main conclusions that emerged:

- The spatial resolution and accuracy provided by available conventional soil maps are not fine enough for the needs of many users. DSM approaches are therefore desirable to develop fine resolution mapping grids of soil attributes. Accordingly, map producers agree that the existing soil geographical databases need to be extended and densified.
- The list of soil attributes currently available in geographical soil databases needs to be expanded. A larger number of attributes relating to soil structure and soil water behaviour are requested, whether obtained by measurements or by pedo transfer functions. Information about soil depth when deeper than the usual auger depth is considered important for many uses. The need for soil biodiversity attributes was also cited. Eventually, a need to move from maps predicting soil "capability" to maps predicting changes in soil "condition" emerged. Note that soil capability and soil condition concepts were defined by McBratney et al. (2014).
- DSM methods have spread in the academic sector but remain little or not known in the state agencies and private sectors. Although

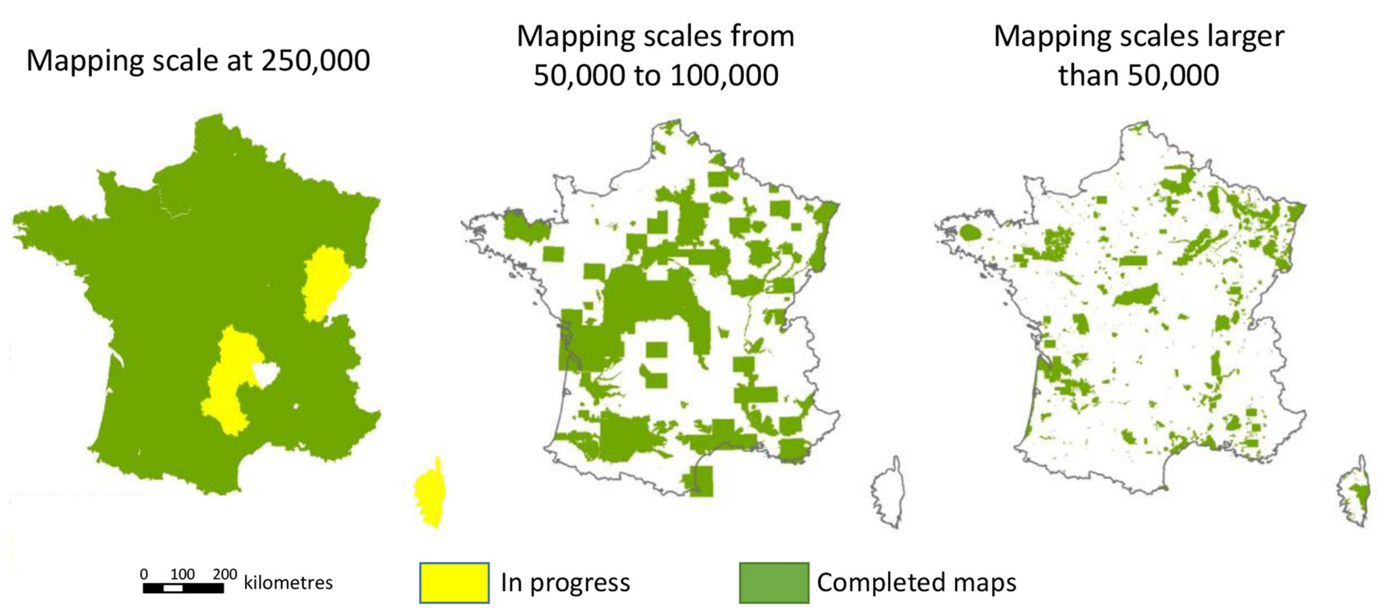

Fig. 1. Status of progress of soil mapping in mainland France and Corsica according to the mapping scales (established in August 2019).

most producers and users of soil data declare to be interested in DSM methods, the majority of them understand neither how exactly they work nor their potentials and limits. Awareness raising and capacity building are clearly prerequisites for putting DSM into real operational use in France.

- End users, and even some map producers, are confused about uncertainty issues. The implicit link between spatial resolution and uncertainty is frequently wrongly made. Many feel that if the size of the support is finer, then it will include more reliable and accurate semantic information. Furthermore, map producers do not always communicate about the uncertainty of their maps, and many end users simply do not know how to use uncertainty or how to communicate it. The development of methods for estimating uncertainties is therefore essential but also of methods for communicating about mapping uncertainties and for using them in modelling and decision making.

Concerning economic issues, the survey attempted to analyse what soil map producers and users had in mind as business models for stimulating the production of new data and the use of available data. For example, Fig. 2 shows the answers to the question "Who should be in charge of the production of soil data and maps in the future?". The result was similar for map producers and users. A clear majority considered that the public sector with public funding should be in charge, and only a very few expressed the idea that the commercial sector should invest in soil mapping given potential economic returns. In line with these results, users did express a rather small willingness to pay for the different kinds of works related to soil surveys (see Fig. 3). In summary, the survey shows that certain conservatism exists towards the current economic model of soil data production in France, which is dominated by public funding. According to the comments that accompanied the survey, this apparent economic conservatism is also justified by the fear of the risk of privatization of soil data, considered de facto as a public good, and by the risk of non-sustainability of soil information systems if the production and management of soil data were entrusted to the commercial sector. Thus, an exclusively commercial model is unanimously rejected. Nevertheless, producers plan and wish that the processing of soil data, and in some cases, the provision of data, should be subject to a charge.

3. Technical specifications for a new soil inventory programme and related costs

The development of technical options for a new soil inventory programme identifies several possible ambitions for improving soil mapping knowledge in France and assesses their technical implementation costs. This is based on two main choices that we assume critical to answer the needs of end users in terms of soil attributes, resolution and accuracy:

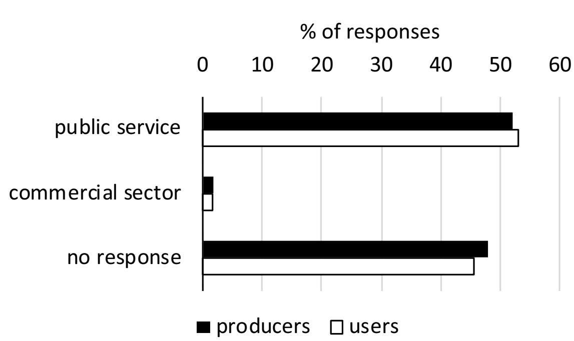

Fig. 2. Responses to the question 'Who should be in charge of the production of soil data and maps in the future?'.

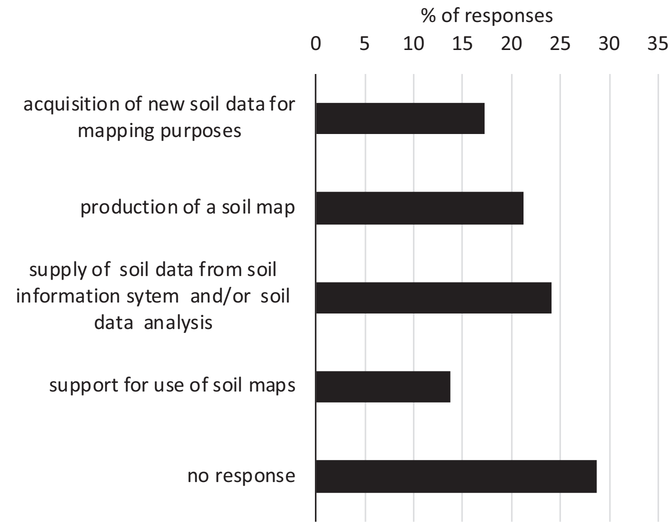

Fig. 3. Responses of end users to the multiple choice question: 'For which of these works would you be willing to pay?'.

- The intensity of characterization of the soil profiles that will be used for mapping.
- The spatial sampling design of new soil profiles.

It is expected that digital soil mapping will be the main mapping approach in any future soil inventory programme and will take advantage of both the available legacy data and new soil data. The choice among DSM methods is not considered a critical choice to be included in the technical specifications of a national inventory programme. Indeed, the choice is large and expanding, and it has to be made specifically for each mapping area according to the nature of its pedological variability and the availability of soil data and of soil covariates. Moreover, although the application of digital mapping methods has a cost, we assume that it is not going to vary too much according to the method used and will not have an impact on the differences in cost between the technical options.

3.1. New specifications for soil characterization

The new specifications were defined with several objectives: (i) to be compatible with the specifications of the *GlobalSoilMap* project (Arrouays et al., 2014), (ii) to meet users' needs in terms of soil properties as expressed in the survey, and (iii) to take into account the technical and economic feasibility of observing the targeted properties. As a result, soil characterization depths have been defined, up to 2 m deep where possible, to estimate property values for the 6 standard *GlobalSoilMap* depths but also for the soil horizons identified when describing the soil profile. The final list of target soil properties includes the 12 main *GlobalSoilMap* properties (see Table 3.2 in Arrouays et al., 2014) as well as total calcium and nitrogen contents and extractable and total phosphorus contents. All these new specifications go beyond those currently being implemented in the IGCS programme. The cost of characterizing a profile was estimated based on the current costs of profile excavation, soil description, sampling and analysis that are underway in France (Table 1). It is estimated to amount on average to 2000 €, including taxes, per soil profile.

3.2. New spatial sampling strategies

Two main complementary spatial sampling strategies were considered. The first aims at ensuring complete coverage of France with soil maps of known and similar accuracy that can serve for studies at

Table 1
Total cost estimate for one soil profile (in €).

		Duration in hours	Costs of working hours*	Direct costs (without VAT)	Total costs
1	**Before digging the soil profile**				
1,1	Contacting the farmer and/or the landowner	1	85		85
1,2	Preparing the material and logistics	1	85		85
2	**Profile digging, description and sampling**				
2,1	Travel and mission expenses	2	170	200	370
2,2	Locating and digging the soil pit using an excavator machine	1	85	300	385
2,3	Soil profile description and sampling	2	170		170
3	**Posterior operations**				
3,1	Managing, preparing and sending samples	1	85	30	115
3,2	Entering data into the soil information system	2	170		170
3,3	Chemical analyses**			419	419
4	**TOTAL without VAT**		**850**	**949**	**1799**

* On the basis of a man-day cost of 680 € (i.e., 85€/h).
** Estimate based upon an average of 4 horizons per profile and applying standard analytical costs according to INRA Central laboratory rates in 2018.

national or sub-national scales. The second aims at providing precise soil knowledge at fine scales throughout France for local soil management.

3.2.1. Standardizing and upgrading the spatial density of soil data in France

This first strategy intends to standardize the accuracy of mapping between French regions and increase the average accuracy currently provided by the 1:250,000 soil maps. It will provide the opportunity to develop more precise DSM approaches than those carried out to date at national or regional levels.

To grossly estimate the total number of new soil profile observations that would be necessary for standardization, we computed for all French small agricultural regions (SAR) the number of additional profiles needed to meet a fixed minimal spatial density of soil data in each region. In doing so, we assume that the stratification of France in SAR represents approximately the variation in elementary spatial soil patterns, which should benefit each of a minimum density of soil observations. The SAR are agricultural census units that combine several districts that are supposed to have the same agricultural production systems and rather homogeneous soil scapes. They were defined by the French Ministry of Agriculture. Their number is 713, and their average agricultural area is 355 km^2, whereas their average total area is 576 km^2. Thus, the limits of SAR are close to those of small pedological regions, which should ideally be considered but for which there is no national map yet. It must be noted that standardizing the density of soil profiles does not ensure the standardization of mapping accuracy because the variability of soils clearly differs between regions. However, because the local patterns of soil are not known everywhere, standardizing the density is currently a first step towards accuracy standardization.

To compute the number of new profiles, we considered two soil properties whose observation densities were at the extremes of the observation densities of the main soil properties stored in the DoneSol national soil database: organic carbon (OC) and cation exchange capacity (CEC). Over mainland France, OC exhibits approximately 50,000 measurements for topsoil and 16,000 for 30–60 cm layers, whereas CEC has been measured for approximately 27,000 topsoils and 18,000 30–60 cm layers. To illustrate the differences in observation densities between the two soil properties and between the SAR, Table 2 gives the basic statistics of the density of observations for the two soil properties between the SAR. Note that the density is computed by the number of ha in a region divided by the number of available soil observations at a given depth, which in turn leads to a density expressed as a number of ha per soil observation. For organic carbon, the densities in the SAR range between less than 20 ha/soil observation for topsoils to more than 145,000 ha/soil observation at 60 cm depth, whereas for cation exchange capacity, they range from 56 ha/observation for topsoils to almost no data at all at 60 cm depth. Fig. 4a shows the number of additional soil profiles to be sampled and observed for a given targeted minimal sampling density in all SAR for the two soil properties and two soil depths, whereas Fig. 4b shows the cost of acquiring these additional soil profiles to reach a given minimal density.

It is important to note the considerable effort required to bring the entire French territory to the minimum densities that are requested to assign the best quality levels to the 1:250,000 soil maps, namely, 4000 ha per soil profile for the "advanced level" and 2000 ha per soil profile for the "optimum level". These levels are the potential two targets we chose for the standardization strategy. Their costs amount to 15 M€ and 36 M€, respectively. They both represent significant steps towards improving soil knowledge at national and regional scales.

3.2.2. Investing in detailed mapping of reference areas in small agricultural regions

For users concerned with soil management at plot-scale or farm-scale resolution, it is important to know the local variability of soils. This requires, in principle, large-scale soil maps and/or high-density soil data. None of these is currently available throughout France. As shown in Fig. 1, in many areas in France, there is no medium- or large-scale soil mapping. Moreover, even if the option of standardizing soil data density over French SAR to a minimum of 1 soil profile per 2000 ha is implemented in the future, it is far from the requested densities for high-accuracy and high-resolution digital soil mapping. For example, Somarathna et al. (2017) showed in a nice example over a study site of a few tens of km^2 in New South Wales that to capture and map with optimal accuracy the local variation in soil organic carbon, the training of most DSM models required a minimum of 15 samples per square kilometre, that is, a density of more than 1 sample per 7 ha. Clearly, the entire coverage of France with large-scale maps and high-density soil data is out of reach from operational and economical perspectives. One possible solution is to build on an approach proposed by Favrot (1981) in which reference sub-areas of a given region are identified to represent the main soil distribution patterns (Lagacherie and Voltz, 2000). These reference areas of small spatial extent can be subject to detailed soil mapping and high-density soil sampling. In terms of conventional soil mapping approaches, the reference areas enable us to define the main soil classes of the regions with limited cost with their discriminating criteria and their properties. It is then possible to allocate any site within the region to the predefined soil classes by simple observations of the soil at the site (Favrot, 1989). The assumption has been found to be reasonable in several test regions (Favrot, 1989; Lagacherie et al., 1995). In terms of digital soil mapping, the reference areas may provide relevant data sets for training DSM models to be applied over the whole region. Preliminary tests were already performed for mapping soil classes (Lagacherie et al., 1995; Lagacherie and Holmes, 1997; Bui and Moran, 2003; Henrique et al., 2016; Abbaszadeh et al., 2018) or soil properties (Voltz et al., 1997;

Table 2
Basic statistics of the density of observations, expressed as ha/soil observation, of organic carbon and cation exchange capacity in the topsoil and at 60 cm depth between the French small agricultural regions.

	Depth	Mean	Minimum	Maximum
Organic carbon	Topsoil	2,785	19	42,721
	60 cm	10,366	46	144,270
Cation exchange capacity	Topsoil	10,564	56	361,206
	60 cm	14,242	76	361,206

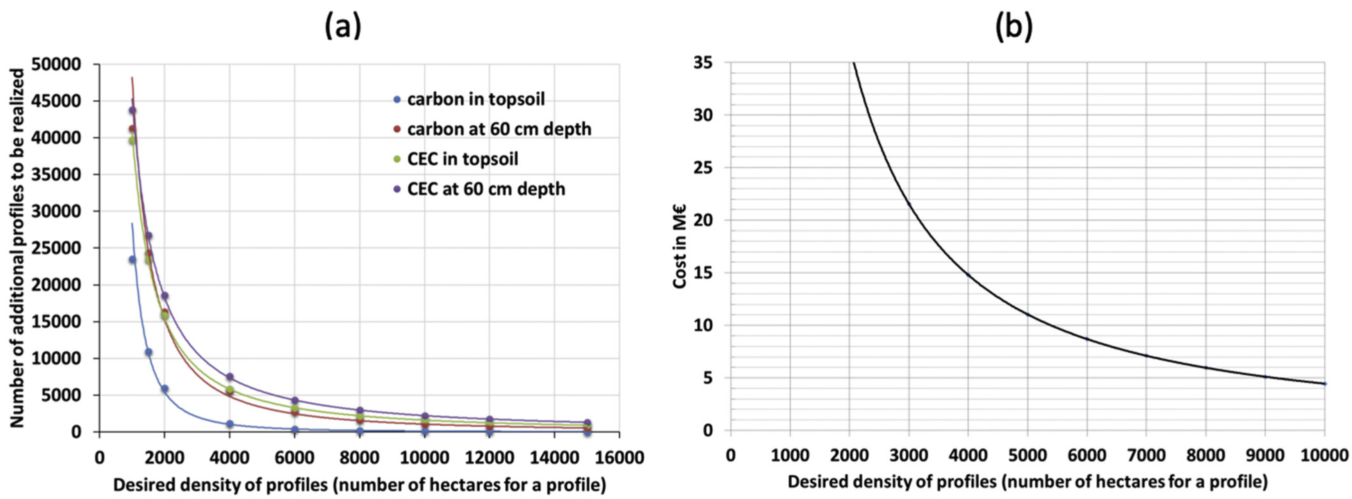

Fig. 4. Additional sampling effort to be done for achieving a minimal sampling density in all small agricultural regions in France: a) number of additional profiles for organic carbon and cation exchange capacity in the topsoil and at 60 cm depth, b) estimated average costs in euros. Note that power law models were adjusted to the number of profiles as a function of required minimum observation density.

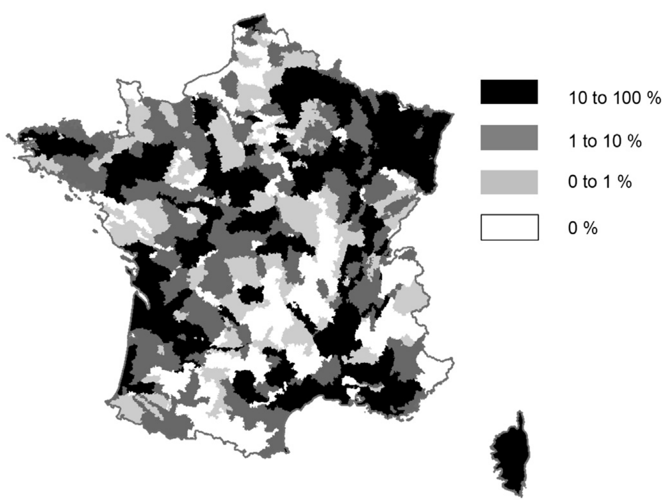

Fig. 5. Map of the percentage of area covered by soil maps at scales larger than 1:50,000 in the French small agricultural regions.

Lagacherie and Voltz, 2000). We therefore hypothesize that the reference area approach can be a relevant technical strategy to deliver at reasonable cost high-accuracy and high-resolution soil maps. Indeed, further research must be performed to study how DSM models can take advantage of large data sets over small reference areas and whether the desired accuracy is attained.

The implementation of this strategy requires new sampling and mapping of soils in regions where no detailed soil maps and soil databases are already available. The map in Fig. 5 shows the percentage of each small agricultural region that exhibits soil maps at scales larger than 1:50,000. As a rule of thumb, Favrot (1989) suggested that to represent the soil distribution pattern in a given region, a reference area should cover at least 1% of its surface. Accordingly, new detailed reference area mapping needs to be performed at least in all SARs with less than 1% detailed soil maps, namely, 336 SAR out of 713. However, because we do not know whether the available detailed maps properly sample the actual soil distribution of the SAR, it is likely that reference area mapping must be extended to a larger number of SAR. If we consider a threshold of 10% instead of 1%, then 490 SAR require reference area mapping. The cost of implementation of a reference area, including soil mapping and soil profile characterization, was estimated by the average cost of detailed mapping over 1000 ha with one soil profile per 35 ha. This amounts to 98,640 euros per reference area, which leads to overall costs between 33 M€ and 48 M€ for the number of SAR ranging from 336 to 490.

4. Scenarios for soil mapping development in France

To develop soil mapping in France and answer more closely the needs of end users, we assumed that the IGCS programme had to change and should have new aims and support. In this respect, it is not enough to define technical strategies; it is also essential to foresee how the interaction between stakeholders, producers and users of soil maps should take place and what could be the funding and business model of the programme.

Given the current state of available information and the uncertainty of future economic and legal conditions, it seemed difficult to foresee a single and robust scenario to support the production and dissemination of soil mapping data in France. Accordingly, we chose to explore several contrasting scenarios and to evaluate their consequences rather than to propose a unique scenario that could very quickly become obsolete depending on the evolution of the socio-economic context and the positioning of the various stakeholders concerned. An advantage of studying multiple scenarios is the ability to analyse the actions to be taken to:

- support the best development of soil mapping under any scenario that may emerge,
- identify ways to favour one scenario over the others,
- collect the additional information necessary to identify the most appropriate and realistic scenarios.

To identify contrasting scenarios, we followed a qualitative forecasting approach that was inspired, with simplifications, by a prospective study conducted recently on vineyard under climate change (France Agrimer, 2016). Following this approach, a panel of experts, namely the authors of this paper:

- defined a common representation of the soil mapping “system” in France and a set of contrasting hypotheses about the future of its key components.
- developed the scenarios by choosing and linking in a consistent way the hypotheses of the key factors of the system.

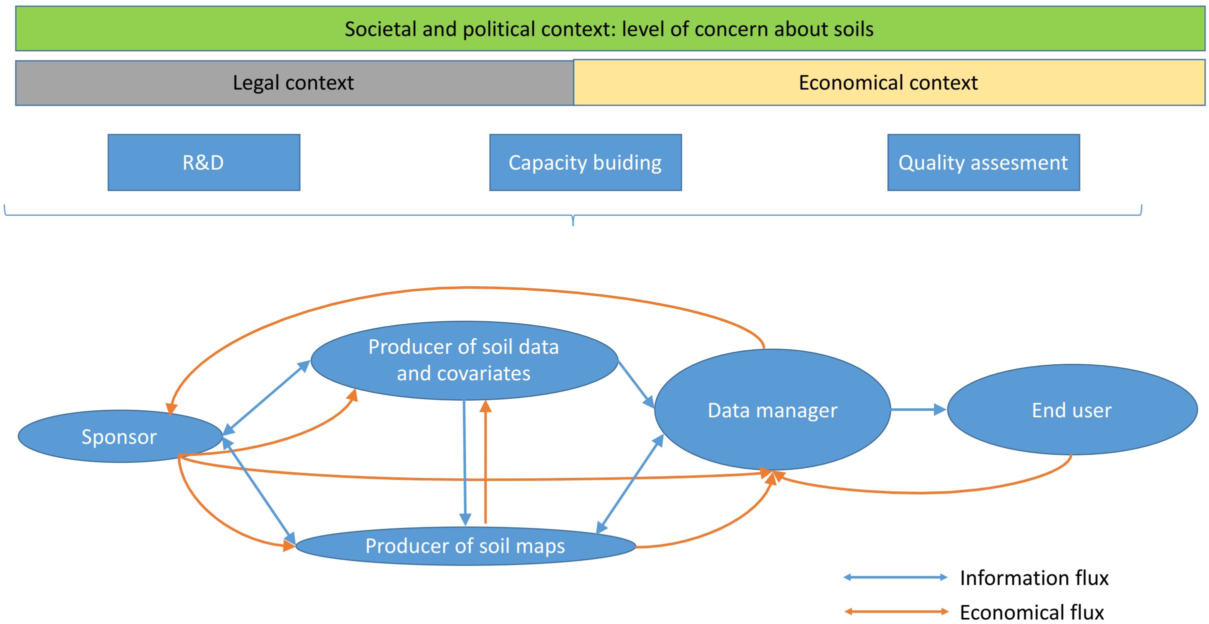

Fig. 6. Schematic representation of the soil mapping system.

- evaluated the developed scenarios according to their capacity to intensify soil mapping in terms of territorial coverage, accuracy and range of soil descriptors, as well as their ability to facilitate the use of the mapped soil data by end users.

The first three steps were completed through panel discussions, whereas the evaluation was done individually by each expert to avoid the biases from group dynamics, where participants may stick to stated or leader opinions. It should be noted that the output of the forecasting exercise is closely linked to the diversity of backgrounds of the panel experts. Here, the absence of experts from the economic and social sciences certainly reduced the field of possibilities (number of hypotheses and combinations of hypotheses) that served to build the scenarios.

4.1. Representation of the soil mapping system and hypothesis identification

Fig. 6 presents the main stakeholders of the soil mapping process and the information and economic fluxes between them. One can note that producers of soil data are distinguished from producers of soil maps. Conventional soil surveyors often do both, but with the development of digital soil mapping, the two functions may be separated and taken on by different specialists, i.e., soil surveyors on one hand and spatial data modellers on the other. The figure also identifies several drivers of soil mapping. Some directly influence the vitality of soil mapping. Research and development provide new and more efficient soil mapping methods, such as DSM. Capacity building helps soil mappers to improve their technical skills; quality assessment stimulates soil mappers to increase their mapping performance and provides insight to end users about the potentials and limits of the produced soil maps. Other drivers, such as legal regulation or economical context, relate to the overall societal context and exert an indirect but still very significant influence.

For each component of the figure, stakeholder or drivers, panel discussions led to the formulation of two or more contrasting assumptions about the possible state of the component in the future. In all, this led to 35 assumptions. For capacity building in soil mapping, for example, assumptions were about who is in charge of it and what would be the level of training costs. Three options were defined: public sector with small costs for trainees; private sector with higher training costs; sharing between private and public sector with variable costs. For the producers of maps, assumptions distinguished between an option where a national soil data centre with qualified staff manages most mapping applications and another option where there is a large number of independent public or private consultancy offices with varying qualifications that manage soil mapping on request. The set of hypotheses is described in detail in Voltz et al. (2018).

4.2. The four forecasted scenarios

The scenarios were developed by starting from a main assumption on the level of concern about soils that may exist in France in the future, which we believe to be the major driver, though not the only one. Four levels of concern were distinguished, and accordingly, four scenarios were developed by choosing for each component of the soil mapping system in France the assumption that was the most consistent with the level of concern chosen and the assumptions made about the other components. In Table 3, we present a summary view of the four scenarios and their main assumptions. Hereafter, we present the rationale behind each scenario.

Scenario SO1, called “Business as usual”, maintains the current state of concern and investment about soils in France. Soil knowledge is recognized as necessary to manage some well-targeted societal issues (protection of drinking water plants, protection of agricultural land against urbanization, waste management, etc.), but soil resources are not a priority for public authorities on the same level as other resources such as water. Accordingly, there is no change in the legal framework for soil data, and many data cannot be freely disseminated because they belong to those who collected them or fall within the framework of the European Directive 2016/680 for the protection of individuals. Future soil mappings are mainly financed by public funds from different sources (Government, European programmes, Water Agencies, local authorities, etc.), which remain limited. Standard specifications for soil mapping and quality assessment procedures are maintained at the national level by the IGCS programme and are mandatory only for publically funded maps. Soil data collected with public funding are stored in the DoneSol national soil database but cannot all be freely

Table 3
The four scenarios developed in the qualitative forecasting study.

	SO1	SO2	SO3	SO4
Socio-political context level of concern about soils	Business as usual	Soil is a common resource (EU soil framework directive)	Soil is a private resource	Soil is private but also of common interest
Legal context/soil data	Open in part	Fully open data	Private data	Private data
Funding	= Public funding	↗ Public funding	No public funding	↘ Public funding
Dissemination of soil data	National data centre	National data centre reinforced	No national soil data centre	National data centre
Capacity building (DSM)	Public support	Public support	No public support	Public support
National regulation	Quality assessment (mandatory)	Quality assessment (mandatory)	No quality assessment	Quality assessment (optional)
New data acquisition				
↗ Homogenisation	4000 ha per profile	2000 ha per profile	No	No
↗ Reference areas	Yes	Yes	Yes	Yes

disseminated. Capacity building will be mainly managed by academic groups in universities and by InfoSol.

In this scenario, it is expected that the target of 1 soil profile per 4000 ha can be met for France and that a significant number of reference areas could be launched by local authorities and, to a lesser extent, by the commercial sector. However, the full coverage of the French territory with reference areas will be hardly attainable within a reasonable delivery time because funding is expected only in small regions that will have short-term soil survey needs.

Scenario SO2, called “Soil is a common resource”, considers that new and strong public policies are being put into place to support the development of soil knowledge and its integration into societal issues and to promote private initiative. In this scenario, a Soil Framework Directive for protecting soils (see Directive proposal (CEC, 2006)) would have eventually been adopted by the European Commission. In France, a law is passed that recognizes soil as a public good and makes it mandatory to carry out soil studies prior to any land-use planning project, as well as to characterize the soil when there is a change in land use or ownership. The principle of capitalizing soil data in a national database in a standardized format is affirmed. The legal context concerning soil data has changed and establishes the pre-eminence of the public interest in these data over their confidential nature, which makes it possible to freely disseminate and transfer them. An important programme for standardizing and improving the mapping accuracy of French soils is launched. Standard specifications and quality assessment procedures are defined and promoted for all soil mappings performed in France, whether funded by public authorities or by private individuals. Soil data stored in the DoneSol National Soil Data Centre increase drastically and are freely disseminated. Capacity building is reinforced by establishing a national soil resource centre that not only manages the national soil data centre but also provides support and training to all soil surveyors and soil mappers in France and coordinates an intensive R&D programme for developing DSM methods.

In this scenario, it is expected that the target of 1 soil profile per 2000 ha can be met for France and that all SAR without high-resolution maps, including those that will not have short-term needs in the soil survey, will benefit from reference area mapping.

Scenario SO3, called “Soil is a private resource”, corresponds to a low level of concern about soil security in French society. Therefore, no public policy is defined for the knowledge and consideration of soil in societal issues, and the pre-eminence of the confidential nature of soil data over their public interest prevails. Public funds for developing and organizing soil mapping in France progressively disappear. No incentive is given for capitalizing new data in the national soil data centre or for disseminating standard specifications and quality assessment procedures for soil mapping. In the same way, capacity building and R&D on soil mapping are not supported and remain only in a few academic groups. In practice, this means that the IGCS programme is suppressed.

In this scenario, it is expected that no progress in the standardization of soil data density will be achieved at the national scale but that medium- or high-resolution maps will still be produced and that there will be potential economic return of soil information or its interest for local authorities, but will neither be shared nor capitalized.

Scenario SO4, called “Soil is a private resource but also of common interest”, is an intermediate scenario between scenarios SO2 and SO3. As in SO3, no new public policy is defined for the knowledge and consideration of soil in societal issues, and only private initiative is promoted. However, as in SO2, public regulation is still implemented to ensure the transparency and quality of mapping operations as well as the maintenance of possibilities for capitalizing on new data and maps acquired. This means that the IGCS programme is focused on the maintenance of the national soil data centre and the elaboration and implementation of quality insurance procedures.

In this scenario, as in SO3, no significant progress in the standardization of soil data density at the national level is expected; only medium- or high-resolution maps are expected to be ordered by local stakeholders. However, capitalization of soil data will continue, and end users will be informed about the existence and quality of the soil maps produced.

4.3. Evaluation of the scenarios

The multi-criteria evaluation, presented in Table 4, is essentially qualitative in nature. It evaluates the adequacy of the different scenarios for the objective of improving spatialized soil knowledge and its appropriation by users. The evaluation was done by personal judgment by each expert. The numbers in Table 4 correspond to the average rating of the experts for each criteria. We considered two types of criteria: i) those measuring progress in spatial soil knowledge and ii) those expressing the level of appropriation and concern about soil issues by end users and society.

Scenario SO1 is evaluated as providing only a slow progression of soil knowledge. It builds on the progress of the current IGCS programme. It would not allow response to many requests of the end users and would not have a new leverage effect to raise societal awareness of the importance of protecting soil resources. Indeed, it would also not solve the difficulties concerning the dissemination of data, the weakness of the available soil expertise, and the gap between the need for high resolution and accurate soil data and the available data.

Scenario SO2 is obviously the scenario perceived as the most favourable for the progression of soil knowledge. It involves a higher public investment at the national level but should also encourage significant additional private or public investment at the local level, motivated by regulations that promote soil characterization and data capitalization. This scenario is expected to lead to significant progress in terms of systematic knowledge of the soils of France.

Scenario SO3 is the one that is judged most negatively. In terms of soil data acquisition, mapping accuracy and use and appropriation of the soil issue by society. The perception of this scenario is, however, only slightly lower than that of SO1 because it is expected that the private sector may compensate in part through funding and initiatives. However, the fact that in this scenario, the driving force for improving soil knowledge depends strongly on local initiatives, whether public or private, raises serious concerns about a lack of capitalization and dissemination of soil knowledge, which may lead to a less dynamic presence of France in international soil programmes. It can be noted that in financial terms, the overall effort of this scenario is estimated to be similar to that of SO1 but with a major contribution from the private sector.

Scenario SO4 corresponds to a version of SO3 with national regulation. It is therefore judged more favourably for many criteria than SO3. Regulation is supposed to enhance the quality of maps and soil data capitalisation and dissemination at the national level. However, regulation alone is not expected to strongly correct the risks of territorial imbalances in soil knowledge and difficulties in participation in international programmes.

5. Discussion

Hereafter, we discuss several main issues raised in the survey of producers and users of soil data and maps in light of the potentials and limits of DSM and of the forecasted scenarios.

5.1. Match and mismatch between available soil data and end users' needs

Hartemink and McBratney (2008) noted a massive demand and need for soil information. The survey of end users of soil data we conducted in France confirms this. In their analysis of the survey, Richer-de-Forges et al. (2019) indicated that the current soil information that has already been acquired during past soil surveys and is available in the French national soil data infrastructure meets a number of the needs of end users. However, there are a number of other needs that are not satisfied. Among them are many soil attributes that have been little or not observed up to now, a better spatial resolution and accuracy of soil maps, and the move from predicting the potential functionalities of soils to predicting their current functional conditions. DSM will undoubtedly help to facilitate and develop soil mapping, increase mapping accuracy, and move from the soil class to soil attribute predictions (Minasny and McBratney, 2016; Arrouays et al., 2017). However, it cannot compensate for a lack of data in terms of spatial density (e.g., Somarathna et al., 2017) or a range of soil attributes. This should be made very clear to land managers and end users of soil data to stimulate their investment in both adopting and training in DSM approaches and gathering new data. This is all the more necessary in France because the survey has revealed that awareness and understanding of soil mapping approaches, whether digital or conventional, and soil data infrastructures, are still low. Thus, contrary to the very positive Australian experience in the dissemination of DSM techniques (Minasny and McBratney, 2016), awareness raising about soil mapping and its potential for helping to answer the numerous environmental challenges facing us is still a pre-requisite for any new soil inventory programme in France. In this respect, public support is certainly necessary as in scenarios SO1 and SO2.

5.2. Quality assessment of digital soil maps

Estimation and release of uncertainty measures of soil maps appear to be essential issues according to both the survey and the forecasted scenarios. This is due to several reasons. First, the survey showed that uncertainty measures are not fully understood by soil surveyors and end users, especially in the case of digital soil mapping. Second, knowing the uncertainty of soil maps is becoming even more crucial because with DSM approaches, it is possible now to have several competing digital maps for the same territory at similar spatial grid resolutions (e.g., Caubet et al., 2019). Thus, the users of soil data will need to have criteria to select the map that is the best for their own usage and to know what they pay for if the maps are produced by the commercial sector. In addition, if soil map quality is not assessed, there is no incentive to produce precise maps. This is why we anticipated that quality assessment should be part of national regulation of soil mapping in the scenario forecasting exercise.

5.3. Capacity building

There is a consensus among the DSM community that training is a key factor in the dissemination of digital soil mapping (Minasny and McBratney, 2016; Arrouays et al., 2017). Our survey supports this opinion in several aspects. Capacity building should be directed to both soil surveyors for mastering DSM and new proximal sensing techniques but also to end users for understanding the scientific and economic value of soil maps.

5.4. Business model for soil mapping in France

According to our estimation, investment needed to homogenize soil data density across France and to make reference area maps available in all SAR amounts between 48 and 84 M€. Costs related to data treatment, data management and capacity building can be foreseen as large as the soil survey and sampling costs (Voltz et al., 2018). Regardless of the prospective scenario, public funding from governmental bodies cannot be expected to answer all of these investment needs. During the last few years, public funding decreased at times due to difficult economic conditions and also due to a general trend to transfer part of the central government missions to the commercial sector that is assumed to provide better economic growth or to local authorities in accordance with the subsidiarity principle. However, there is no clear view of the current and potential investments at local levels, from public or commercial sectors, for developing soil mapping. Indeed, there are many crucial land management issues faced by local stakeholders that require better knowledge of soil capability and condition. However, are the stakeholders aware of the economic value of soil information and are they willing to pay for this? The development of soil mapping depends on the answer, which so far remains unknown. Diafas et al. (2013) performed a choice experiment in a European survey that revealed a significant willingness to pay for high-resolution and high-accuracy maps. This positive result is, however, different from the conclusions of our survey, which can be explained by the type of respondents in the choice experiment of Diafas et al., who were predominantly, up to 89%, from public administrations, universities and research organizations, with only a few (9%) from private companies (i.e., the number of respondents). We therefore believe that more thorough market studies would be beneficial to identify the possibilities and exact conditions for market development of soil mapping, especially for local stakeholders. In the scenarios, it is assumed that regulation of soil mapping by fixing standards and assessing quality may be one lever for adding value to soil maps and in turn for stimulating investments from public and private sectors.

The development of DSM is an opportunity to favour new investments in soil mapping because it is flexible, easy to apply and cost-effective (Kempen et al., 2012). Nevertheless, renewal of mapping techniques is not everything; new stakeholders should take part in soil mapping, and former stakeholders must adapt to end users and to commercially oriented soil mapping activities. To initiate these changes, a number of actions must be implemented: awareness raising, capacity building, developing reliable and user-friendly soil data infrastructures, and defining quality assessment procedures. All these actions are already more or less promoted by public stakeholders, academic groups or some government agencies, but they are still too limited to have a

Table 4
Multi-criteria evaluation of the four forecasting scenarios. The rating of each criterion follows the following principle: 2 to 3, very good progression; 1 to 2, good progression; 0 to 1, weak or no progression; −1 to 0 regression; −2 to −1 strong regression. Rating numbers in italics indicate high variability, i.e., greater than two classes, between assessors.

Scenario	SO1	SO2	SO3	SO4
Indicators measuring progress in spatial soil knowledge				
Number of soil data points per ha	1...3	2..8	1..8	1..5
Range of mapped soil properties	2..1	2..9	0..6	1..5
Accuracy and resolution of soil maps	1..1	2..8	0..9	1..3
Homogeneity of soil mapping coverage of France	1.....4	2..3	*−0..4*	*−0..1*
Amount of soil data stored in the national soil data infrastructure	1..3	2..5	*−0..9*	*0..6*
Indicators expressing the level of appropriation and concern about soil issues by end users and society				
Number of jobs in the soil mapping sector	1..1	2..6	1..3	1..4
Ease of soil data access	1..3	2..6	−1.0	0.1
Intensity of use of soil knowledge in main societal issues	1..3	2..9	0..7	1..1
Level of concern of soil security issues in societal issues	1..3	2..9	0..8	0..8
Presence of French soil mapping initiatives in international programmes	1..6	2..6	−1..1	−0..4

real leverage effect. Scenario SO2, and in part, scenarios SO1 and SO4, can support these actions in the future.

6. Concluding remarks

In this study, we obtained the opinion of soil mappers and of soil data users about their needs and difficulties and completed a forecasting exercise for the conditions of development of soil mapping in France based on an extensive implementation of DSM techniques. We considered a set of four scenarios that basically differed following the level of societal concern about soil security issues. It is not our expertise to identify which scenario is the most likely and the most realistic. However, by examining the four forecasted scenarios and their positive and negative aspects, it is possible to recommend a number of actions that should be part of a renewed soil inventory programme in France:

- Supporting new soil data acquisition by standardizing spatial data density in the national Soil Information System and developing fine-resolution soil mapping through the reference area approach focused on local user needs.
- Improving the networking of soil mapping activities at the national scale by building a national organization of soil surveyors and soil data managers, reinforcing the national soil data centre, developing capacity building in DSM and setting up a national regulatory body.
- Developing a market of soil data services by studying conditions for market access.
- Supporting several research needs, namely:
  - extending DSM applications to reference area extrapolation to produce high-resolution and high-accuracy maps of soil properties,
  - studying sampling designs for new data acquisition and for optimal application of DSM,
  - developing proximal and remote soil sensing and enlarging the range of mapped soil properties,
  - studying the ways of expressing uncertainty estimates so they become understandable and usable by end users.

Declaration of Competing Interest

None.

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References

Abbaszadeh, A.F., Ayoubi, S., Jafari, A., 2018. The extrapolation of soil great groups using multinomial logistic regression at regional scale in arid regions of Iran. Geoderma 315, 36–48.

Adhikari, K., Kheir, R.B., Greve, M.B., Bøcher, P.K., Malone, B.P., Minasny, B., McBratney, A.B., Greve, M.H., 2013. High-resolution 3-D mapping of soil texture in Denmark. Soil Sci. Soc. Am. J. 77, 860–876.

Agrimer, France, 2016. Une prospective pour le secteur vignes et vins dans le contexte du changement climatique. Les synthèses d'Agrimer, N° 40 (22 pages).

Arrouays, D., Hardy, R., Schnebelen, N., Le Bas, C., Eimberck, M., Roque, J., Grolleau, E., Pelletier, A., Doux, J., Lehmann, S., Saby, N., King, D., Jamagne, M., Rat, D., Stengel, P., 2004. Le programme inventaire gestion et conservation des sols de France. Etude et Gestion des Sols 11 (3), 187–197.

Arrouays, D., Grundy, M.G., Hartemink, A.E., Hempel, J.W., Heuvelink, G.B.M., Hong, S.Y., Lagacherie, P., Lelyk, G., McBratney, A.B., McKenzie, N.J., Mendonça-Santos, MdL, Minasny, B., Montanarella, L., Odeh, I.O.A., Sanchez, P.A., Thompson, J.A., Zhang, G.-L., 2014. GlobalSoilMap: towards a fine-resolution global grid of soil properties. Adv. Agron. 125, 93–134.

Arrouays, D., Leenaars, J.G.B., Richer-de-Forges, A.C., Adhikari, K., Ballabio, C., Greve, M., Grundy, M., Guerrero, E., Hempel, J., Hengl, T., Heuvelink, G.B.M., Batjes, N., Carvalho, E., Hartemink, A.E., Hewitt, A., Hong, S.Y., Krasilnikov, P., Lagacherie, P., Lelyk, G., Libohova, Z., Lilly, A., McBratney, A.B., McKenzie, N., Vasquez, G.M., Mulder, V.L., Minasny, B., Montanarella, L., Odeh, I., Padarian, J., Poggio, L., Roudier, P., Saby, N.P.A., Savin, I., Searle, R., Solbovoy, V., Thompson, J., Smith, S., Sulaeman, Y., Vintila, R., Rossel, R.V., Wilson, P., Zhang, G.-L., Swerts, M., Oorts, K., Karklins, A., Feng, L., Ibelles Navarro, A.R., Levin, A., Laktionova, T., Dell'Acqua, M., Suvannang, N., Ruam, W., Prasad, J., Patil, N., Husnjak, S., Pásztor, L., Okx, J., Hallet, S., Keay, C., Farewell, T., Lilja, H., Juilleret, J., Marx, S., Takata, Y., Kazuyuki, Y., Mansuy, N., Panagos, P., Van Liedekerke, M., Skalsky, R., Sobocka, J., Kobza, J., Eftekhari, K., Alavipanah, S.K., Moussadek, R., Badraoui, M., Da Silva, M., Paterson, G., Gonçalves, M.D.C., Theocharopoulos, S., Yemefack, M., Tedou, S., Vrscaj, B., Grob, U., Kozák, J., Boruvka, L., Dobos, E., Taboada, M., Moretti, L., Rodriguez, D., 2017. Soil legacy data rescue via GlobalSoilMap and other international and national initiatives. GeoResJ 14, 1–19.

Arrouays, D., Richer-de-Forges, A., Voltz, M., Bardy, M., Bispo, A., Lagacherie, P., Laroche, B., Lemercier, B., Michalski, J., Sauter, J., 2018. Enquête sur les perspectives d'évolution de la cartographie des sols en France: synthèse des résultats. INRA, Paris, France 48p. Available online:. http://www.gissol.fr/publications/la-cartographie-des-sols-en-france-etat-des-lieux-et-perspectives-4629 (accessed on 25 February 2019).

Arrouays, D., McBratney, A.B., Bouma, J., Libohova, Z., Richer-de-Forges, A.C., Morgan, C., Roudier, P., Poggio, L., Mulder, V.L., 2020. Impressions of digital soil maps: the good, the not so good, and making them ever better. Geoderma Reg. 20, e00255. https://doi.org/10.1016/j.geodrs.2020.e00255.

Ashketar, J.M., Owens, P.R., Brown, R.A., Winzeler, H.E., Dorantes, M., 2014. Digital soil mapping of soil properties and associated uncertainties in the llanos Orientales, South America. In: Arrouays, D., McKenzie, N.J., Hempel, J.W., Richer-de-Forges, A.C., McBratney, A.B. (Eds.), GlobalSoilMap. Basis for the Global Spatial Soil Information System. CRC Press Balkema, pp. 367–372.

Beckett, P.H.T., Burrough, P.A., 1971. The relation between cost and utility in soil survey: V. The cost-effectiveness of different soil survey procedures. J. Soil Sci. 22, 481–489. https://doi.org/10.1111/j.1365-2389.1971.tb01632.x.

Bie, S.W., Beckett, P.H.T., 1970. The costs of soil survey. Soils Fert. 33, 203–217.
Bie, S.W., Beckett, P.H.T., 1971. Quality control in soil survey: II. The costs of soil survey. J. Soil Sci. 22, 453–465. https://doi.org/10.1111/j.1365-2389.1971.
Bui, E.N., Moran, C.J., 1971. A strategy to fill gaps in soil survey over large spatial extents: An example from the Murray-Darling Basin of Australia. Geoderma 111, 21–44. https://doi.org/10.1016/S0016-7061(02)00238-0.
Burrough, P.A., Beckett, P.H.T., Jarvis, M.G., 1971. The relation between cost and utility in soil survey (I–III). J. Soil Sci. 22, 359–394. https://doi.org/10.1111/j.1365-2389.
Caubet, M., Román Dobarco, M., Arrouays, D., Minasny, B., Saby, N.P.A., 2019. Merging country, continental and global predictions of soil texture: Lessons T from ensemble modelling in France. Geoderma 337, 99–110. https://doi.org/10.1016/j.geoderma.2018.09.007.
CEC, 2006. Proposal for a Directive of the European Parliament and of The Council Establishing a Framework for The Protection of Soil and Amending Directive 2004/35/EC. https://esdac.jrc.ec.europa.eu/ESDB_Archive/Policies/Directive/com_2006_0232_en.pdf.
Collard, F., Kempen, B., Heuvelink, G.B.M., Saby, N.P.A., Richer-de-Forges, A.C., Lehmann, S., Nehlig, P., Arrouays, D., 2014. Refining a reconnaissance soil map by calibrating regression models with data from the same map (Normandy, France). Geoderma Reg. 1, 21–30.
De Gruijter, J., McBratney, A.B., Minasny, B., Wheeler, I., Malone, B., Stockmann, U., 2016. Farm-scale carbon auditing. Geoderma 265, 120–130.
Farzamian, M., Paz, M.C., Paz, A.M., Castanheira, N.L., Goncalves, M.C., Santos, F.A.M., Triantafilis, J., 2019. Mapping soil salinity using electromagnetic conductivity imaging-a comparison of regional and location-specific calibrations. Land Degrad. Dev. 30 (12), 1393–1406.
Favrot, J.C., 1981. Pour une approche raisonnée du drainage agricole en France: la méthode des secteurs de référence. C.R. Acad. Agric. France 716–723 (séance du 6 mai).
Favrot, J.C., 1989. Une stratégie d'inventaire cartographique à grande échelle: la méthode des secteurs de référence. Sci. Sol. 27 (44), 351–368.
Grinand, C., Arrouays, D., Laroche, B., Martin, M.P., 2008. Extrapolating regional soil landscapes from an existing soil map: sampling intensity, validation procedures, and integration of spatial context. Geoderma 143, 180–190.
Grolleau, E., Bargeot, L., Chafchafi, A., Hardy, R., Doux, J., Beaudou, A., Le Martret, H., Lacassin, J.-C., Fort, J.-L., Falipou, P., Arrouays, D., 2004. Le système d'information national sur les sols: DoneSol et les outils associés. Etude et Gestion des Sols 11 (3), 255–269.
Harteminck, A.E., McBratney, A., 2008. A soil science renaissance. Geoderma 148, 123–129.
Helmick, H., Nauman, T.W., Thompson, J.A., 2014. Developing and assessing prediction intervals for soil property maps derived from legacy databases. In: Arrouays, D., McKenzie, N.J., Hempel, J.W., Richer-de-Forges, A.C., McBratney, A.B. (Eds.), GlobalSoilMap. Basis for The Global Spatial Soil Information System. CRC Press, Balkema, pp. 359–366.
Hengl, T., Heuvelink, G.B.M., Kempen, B., Leenaars, J.G.B., Walsh, M.G., Shepherd, K., Sila, A., MacMillan, R.A., Mendes de Jesus, J., Tamene, L., Tondoh, J.E., 2015. Mapping soil properties of Africa at 250 m resolution: random forests significantly improve current predictions. PLoS One 10 (6), e0125814.
Hengl, T., De Jesus, J.M., Heuvelink, G.B.M., Gonzalez, M.R., Kilibarda, M., Blagotić, A., Shangguan, W., Wright, M.N., Geng, X., Bauer-Marschallinger, B., Guevara, M.A., Vargas, R., MacMillan, R.A., Batjes, N.H., Leenaars, J.G.B., Ribeiro, E., Wheeler, I., Mantel, S., Kempen, B., 2017. SoilGrids250m: global gridded soil information based on machine learning. PLoS One 12, 1–40.
Henrique, S., Silva, G., Duarte, M., Menezes, D., Ray, P., Curi, N., 2016. Retrieving pedologist ' s mental model from existing soil map and comparing data mining tools for re fining a larger area map under similar environmental conditions in Southeastern Brazil. Geoderma 267, 65–77.
Hollis, J.M., Jones, R.J.A., Marshall, C.J., Holden, A., Van de Veen, J.R., Montanarella, L., 2006. SPADE-2: The Soil Pro-File Analytical Database for Europe, Version 1.0. European Soil Bureau Research Report No. 19, EUR 22127 ENOffice for official publications of the European Communities, Luxembourg 38pp.
Kempen, B., Brus, D.J., Stoorvogel, J.J., Heuvelink, G.B.M., de Vries, F., 2012. Efficiency comparison of conventional and digital soil mapping for updating soil maps. Soil Sci. Soc. Am. J. 76, 2097–2115.
van der Klooster, E., van Egmond, F.M., Sonneveld, M.P.W., 2011. Mapping soil clay contents in Dutch marine districts using gamma-ray spectrometry. Eur. J. Soil Sci. 62, 743–753. https://doi.org/10.1111/j.1365-2389.2011.01381.x.
Lagacherie, P., Holmes, S., 1997. Addressing geographical data errors in a classification tree for soil unit prediction. Int. J. Geogr. Inf. Sci. 11, 183–198.
Lagacherie, P., Voltz, M., 2000. Predicting soil properties over a region using sample information from a mapped reference area and digital elevation data: a conditional approach. Geoderma 97, 187–208.
Lagacherie, P., Legros, J.P., Burfough, P.A., 1995. A soil survey procedure using the knowledge of soil pattern established on a previously mapped reference area. Geoderma 65, 283–301.
Laroche, B., Richer-de-Forges, A., Leménager, S., Arrouays, D., Schnebelen, N., Eimberck, M., Toutain, B., Lehmann, S., Tientcheu Nguenkam, M.-E., Héliès, F., Chenu, J.-P., Parot, S., Desbourdes, S., Girot, G., Voltz, M., Bardy, M., 2014. Le programme inventaire gestion conservation des sols de France: volet référentiel régional pédologique. Etude et Gestion des Sols 21, 125–140.
Lemercier, B., Lacoste, M., Loum, M., Walter, C., 2012. Extrapolation at regional scale of local soil knowledge using boosted classification trees: a two-step approach. Geoderma 171–172, 75–84. https://doi.org/10.1016/j.geoderma.2011.03.010.
McBratney, A.B., Mendonça Santos, M.L., Minasny, B., 2003. On digital soil mapping. Geoderma 117, 3–52. https://doi.org/10.1016/S0016-7061(03)00223-4.
McBratney, A.B., Field, D.J., Koch, A., 2014. The dimensions of soil security. Geoderma 213, 203–213.
Somarathna, P.D.S.N., Minasny, B., Malone, B.P., 2017. More data or a better model? Figuring out what matters most for the spatila prediction of soil carbon. Soil Sci. Soc. Am. J. 81, 1413–1426.
Minasny, B., McBratney, A.B., 2016. Digital soil mapping: a brief history and some lessons. Geoderma 264, 301–311. https://doi.org/10.1016/j.geoderma.2015.07.017.
Mulder, V.L., Lacoste, M., Richer-de-Forges, A.C., Arrouays, D., 2016. *GlobalSoilMap* France: high-resolution spatial modelling the soils of France up to two meter depth. Sci. Total Environ. 573, 1352–1369. https://doi.org/10.1016/j.scitotenv.2016.07.066.tb01630.x.
Odgers, N.P., Libohova, Z., Thompson, J.A., 2012. Equal-area spline functions applied to a legacy soil database to create weighted-means maps of soil organic carbon at a continental scale. Geoderma 189, 153–163.
Padarian, J., Minasny, B., McBratney, A.B., 2017. Chile and the Chilean soil grid: a contribution to *GlobalSoilMap*. Geoderma Reg. 9, 17–28.
Diafas, I., Panagos, P., Montanarella, L., 2013. Willingness to pay for soil information derived by digital maps: a choice experiment approach. Vadose Zone J. https://doi.org/10.2136/vzj2012.0198.
Richer-de-Forges, A.C., Baffet, M., Berger, C., Coste, S., Courbe, C., Jalabert, S., Lacassin, J.-C., Maillant, S., Michel, F., Moulin, J., Party, J.-P., Renouard, C., Sauter, J., Scheurer, O., Verbèque, B., Desbourdes, S., Héliès, F., Lehmann, S., Saby, N.P.A., Tientcheu, E., Jamagne, M., Laroche, B., Bardy, M., Voltz, M., 2014. La cartographie des sols à moyennes échelles en France métropolitaine. Etude et Gestion des sols 21, 25–36.
Richer-de-Forges, A.C., Saby, N.P.A., Mulder, V.L., Laroche, B., Arrouays, D., 2017. Probability mapping of iron pan presence in sandy podzols in South-West France, using digital soil mapping. Geoderma Reg. 9, 39–46.
Richer-de-Forges, A.C., Arrouays, D., Bardy, M., Bispo, A., Lagacherie, P., Laroche, B., Lemercier, B., Sauter, J., Voltz, M., 2019. Mapping of soils and land-related environmental attributes in France: analysis of end-users' needs. Sustainability 11, 2940.
Samuel-Rosa, A., Heuvelink, G.B.M., Vasques, G.M., Anjos, L.H.C., 2015. Do more detailed environmental covariates deliver more accurate soil maps? Geoderma 243–244, 214–227.
Sanchez, P.A., Ahamed, S., Carré, F., Hartemink, A.E., Hempel, J.W., Huising, J., Lagacherie, P., McBratney, A.B., McKenzie, N.J., Mendonça-Santos, MdL, Minasny, B., Montanarella, L., Okoth, P., Palm, C.A., Sachs, J.D., Shepherd, K.D., Vagen, T.G., Vanlauwe, B., Walsh, M.G., Winowiecki, L.A., Zhang, G.-L., 2009. Digital soil map of the world. Science 325 (5941), 680–681.
Santra, P., Kumar, M., Panwar, N., 2017. Digital soil mapping of sand content in arid western India through geostatistical approaches. Geoderma Reg. 9, 56–72.
Vaysse, K., Lagacherie, P., 2015. Evaluating digital soil mapping approaches for mapping GlobalSoilMap soil properties from legacy data in Languedoc-Roussillon (France). Geoderma Reg. 4, 20–30.
Vaysse, K., Lagacherie, P., 2017. Using quantile regression forest to estimate uncertainty of digital soil mapping products. Geoderma 291, 55–64.
Viscarra Rossel, R., Chen, C., Grundy, M., Searle, R., Clifford, D., Campbell, P., 2015. The Aus tralian three-dimensional soil grid: Australia's contribution to the GlobalSoilMap project. Soil Res. 53 (8), 845–864.
Voltz, M., Lagacherie, P., Louchart, X., 1997. Predicting soil properties over a region using sample information from a mapped reference area. Eur. J. Soil Sci. 48, 19–30.
Voltz, M., Arrouays, D., Bispo, A., Lagacherie, P., Laroche, B., Lemercier, B., Richer-de-Forges, A.C., Sauter, J., Schnebelen, N., 2018. La cartographie des sols en France: Etat des lieux et perspectives. INRA, Paris, France 112 pages.
Zare, E., Beucher, A., Huang, J., Boman, A., Mattback, S., Greve, M.H., Triantafilis, J., 2018. Three-dimensional imaging of active acid sulfate soil using a DUALEM-21S and EM inversion software. J. Environ. Manag. 212, 99–107.