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

Dominique Arrouays, Vera Leatitia Mulder, Anne C Richer-De-Forges

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

Dominique Arrouays[1*], Vera Leatitia Mulder[2], Anne C. Richer-de-Forges[1]

[1]*INRAE, InfoSol Unit, 45075, Orléans, France*

[2]*Soil Geography and Landscape group, Wageningen University, PO Box 47, 6700 AA Wageningen, The Netherlands*

[*]Corresponding author, dominique.arrouays@inrae.fr

Abstract

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

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

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

1. Introduction

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

The global Soil Security concept emerged from two seminal publications (Koch et al., 1013; McBratney et al., 2014), followed by numerous other publications, conferences and books addressing Soil Security from local to global scale (e.g. McBratney and Field, 2015; Kidd et al., 2015, 2018; Koch et al., 2015; Field et al., 2017; Huang et al., 2018; Allan, 2019; Bennett et al., 2019; McBratney et al., 2019; Murphy and Fogarty, 2019; Richer-de-Forges et al., 2019a; Bouma, 2020; Field, 2020). The emergence of this concept has been strengthened by three international conferences on Global Soil Security held in Texas A&M, USA, 2014, in Paris, France, 2016, in Sydney, Australia, 2018, and by the launching of the scientific journal "Soil Security" in 2020 (Morgan and McBratney, 2020). The main difference between Soil Security and previous concepts such as *soil care* (Yaalon, 1996; McBratney et al., 2017; Leonhardt et al., 1019), *soil quality* (Karlen et al., 1997, 2001), *soil health* (Doran et al., 1996; Doran and Ziess, 2000; Doran, 2002), among others, is that the other concepts mainly consider biophysical soil parameters and their changes. Soil Security considers this to be the *soil condition* and *capability*. Soil Security further adds three new dimensions to the framework namely the *soil capital*, *connectivity*, and *codification* (McBratney et al., 2014). These three additional dimensions add new essential criteria to assess Soil Security. The *soil capital* refers to the “production of human-demanded function and the attendant ecosystem services” (McBratney et al., 2019a). This way, it adds a value to soils (Costanza et al., 1997). *Soil condition* and *capacity* are mainly driven by the assessment of what soil can, or could, do; last three soil C’s (*soil capital*, *connectivity*, and *codification*) are taking into account the actions (at social, economic and policy levels) that are put in place guarantying the improvement of Soil Security. As stated in the Global Soil Security website (https://globalsoilsecurity.com/): “Yet an overarching concept that brings together these biophysical and socio-economic perspectives of soil is still lacking and this has led to the launch of the Soil Security concept”.

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

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

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

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

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

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

We first take as an example the country France and revisit their main aims and drivers of SM, DSM, SMS and the main evolutions in their objectives, progress, and settlement. We choose this country because it is a good illustration of some drastic changes that took place in SM, DSM and SMS strategies over time. Then, we make up the balance to which extent we have achieved assessing the five C's using existing examples from country to global scale, and identify pathways on how to improve Soil Security.

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

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

In the early 1960s, the challenge was to feed the growing post-war population and produce sufficient crop for human consumption and fodder. This was the early years of the Common Agricultural Policy (CAP) launched in 1962 (The European common policy at a glance: https://ec.europa.eu/info/food-farming-fisheries/key-policies/common-agricultural-policy/cap-glance-en). The objective was mainly tailored towards agricultural production rates. It was to develop new agricultural areas and to aim for maximum yields. The new agricultural areas that were developed, were mainly to the detriment of the forest and other natural areas which were cleared for this purpose only. It was the era of the development of large land-use planning companies, involving many soil mapping activities. Consequently, it also involved deforestation, drainage, liming, fertilization and cultivation of large areas (see, for example, Legros, 1996). This tendency was amplified both by technology (mechanization, fertilizers and pesticides use and progress in plant breeding) and by war conflicts (the need for new arable lands due to the massive return from Algeria of French colonial farmers, Journal officiel de la République française, 1961). This period clearly focused on improving *soil capability* and *soil condition* with the aim of increasing agricultural production. In other words, it mainly focused on only one soil ecosystem services – food security.

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

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

In the mid-1980s, the EU faced agricultural overproduction. To guarantee prices, policies were put in place. These were the policies of quotas and those of set-aside, falsely called fallows and which for some, like bare fallows, were environmental aberrations (Balesdent and Arrouays, 1999; Tonitto et al., 2006), nevertheless imposed because they were easier to control. Thus, the French priority changed from maximizing yields to maximizing farmer’s incomes, by a better assessment of soil *capability* and *condition* and a better reasoning of agricultural inputs. Some soil mapping programs at 1:50,000 scale were put in place by agricultural development bodies to accompany these changes (Richer-de-Forges at al., 2014). These maps clearly increased soil *connectivity* (the 4th Soil C) with farmers who better adapted their practices to their soils. Note, however, that these maps were rather detailed and were not “broad-scale” maps (each map covering about 600 km^2) which facilitated the *connectivity* with local farmers.

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

After 30 years of pushing towards increasing yields and optimizing farmers income, changes were imminent. An increased awareness for natural declines and environmental concerns took over in the 1990s, with the Kyoto protocol (UNFCCC, 1997) and the other Rio conventions (United Nations, 1992; UNCDD, 1994). These began to give insight into the global aspect towards the problems of the global soil resource: carbon storage and climate change, biodiversity conservation, protection against erosion and desertification. In Europe and in France, this resulted in agri-environmental policies and the emergence of the concept of eco-conditionality of CAP aid (European Parliament, 2003). Slowly, but progressively, this led France to adopt some agro-environmental legal constraints for soil management, and to develop 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 end of the 1990s, a review of the national soil monitoring system was conducted by the European Environmental Agency. Among the main results, were the large discrepancies between EU countries, and the need for a transboundary harmonization (Arrouays et al., 1998). For France, it was concluded that it performed very poorly in comparison to other EU countries in terms of soil monitoring development. This outcome, together with the increasing need of monitoring the soil *condition*, led to the launch of the French soil monitoring network in 2001. This clearly added a new priority that was to monitor the 2nd C (*condition*). During the 1990s, the available digital data drastically increased (digital terrain models, satellite data, digitized map data of climate, vegetation, geology, etc.). Meanwhile, the computing power of the computers increased rapidly. Therefore, French research in soil mapping gradually moved from a model of tacit knowledge of the soil expert (conventional soil mapping) to formalized and quantified models (pedometrics and DSM). In the 1990s, some French papers already dealt with DSM, although they most often focused on local applications (e.g. Lagacherie and Depraetere, 1991; Lagacherie et al., 1995; Arrouays et al., 1995, 1998; Bourennane et al., 1996; Voltz et al., 1997). At the end of the 1990s, five main technical decisions influenced SM, DSM and SMS in France:

i) all the points and areal data gathered in regional and national SM programs should be rescued and stored in a national database,

ii) the highest SM priority will be given to the achievement of a 1:250,000 soil geographical database,

iii) more detailed maps and data will be gathered to provide soil data to environmental and agronomical purposes and calibration areas for DSM,

iv) soil analysis ordered by farmers will be centralized in a common database, and

v) a soil monitoring network will be implemented for the entire mainland territory of France.

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

In the 2000s, the notion of ecosystem services emerged, particularly due to the Millennium Ecosystem Assessment (MEA, 2005). Though the need for soil maps became more and more evident, France was still among the less advanced EU countries concerning its national soil mapping program. Finally, during the mid-2010s, France was asked by the EU to contribute to the delineation of agricultural areas subject to natural constraints, i.e. ‘Agricultural Areas with Natural Handicaps’ (Jones et al., 2014), by making use of existing soil maps to assess the biophysical criteria for this delineation. The French policy-makers suddenly realized that data was still missing in some critical regions. Consequently, it could imply they may lose an enormous amount of agricultural EU subsidies. This resulted in a fantastic boosting of the French program of soil mapping at 1:250,000 scale, the funding quadrupled in only few years.

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

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

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

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

The situation improved substantially with the release of the new Soilgrids2.0 product (Poggio et al., 2021) for several reasons. The number of calibration points was much larger compared to the first versions. This new version also provides an estimate of the uncertainty of predictions, which is helpful to estimate the confidence of the predicted values and to indicate where calibration data density should be improved. This therefore provides better information on some current properties related to soil *capability* and *condition*. However, we still need to find ways to identify *shifts* in *capability* or *condition* compared to this reference state. Indeed, this product by itself is not able to inform the impact of changes in management practices. This will require the settlement of long-term SMS, or coupling DSM predictions with modeling which may lead to large error propagation. As suggested by Heuvelink (2014), for modelers, the ideal product would be a map providingng for each cell the probability distribution function (PDF) of soil properties or even the joint PDF of several soil properties.

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

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

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

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

Finally, the response to the question “Do the SM, DSM and SMS over large areas contribute the two first C’s (*capability* and *condition*) of soil security?” is partly yes. SM, DSM and SMS can provide the basis for assessing soil *capability* and *condition* over large areas, especially if we assume that *capability* mainly depends on rather stable soil attributes. However, we are still missing much information if we want to better map and monitor the wide variety of soil functions that are connected to Soil Security (McBratney et al., 2014). Soil physico-chemical and biotic data are lacking about changes in e.g. nutrient status, biota, compaction, soil structure, soil hydrological parameters.

Therefore, one major challenge is to enlarge the range of soil properties that we are currently predicting and monitoring. McBratney et al. (2014) outlined the dimensions of soil security and suggested that soil biota in the future may be a significant and broad indicator of the soil's *condition* (Zak et al., 2003; Barrios, 2007). In recent years, the soil biology science has substantially increased our knowledge on the synergies and tradeoffs of how the soil biological *condition* and *capability* (i.e. soil organisms) contribute to sustainable land management and the delivery of ecosystem services (Pulleman et al., 2012; Vazquez et al., 2021) and how soil organisms play an important role in water regulation, nutrient cycling, soil fertility and biological control, among other services (Creamer et al., 2016; Zwetsloot et al., 2021). Studies showed that there are strong similarities between the soil biodiversity and pedodiversity (Chu et al., 2020; Martiny et al., 2006). This knowledge has subsequently been used to create some of the first maps on soil biota such as bacteria, nematodes and earthworms from the national to global scale (Karimi et al., 2018; Phillips et al., 2019; Rutgers et al., 2019; van den Hoogen et al., 2020). One of the most limiting factors for producing accurate maps on the soil’s biological *condition* is data availability. Fortunately, more and more soil biological data is becoming available, e.g. through collaborations such as proposed by Smith et al. (2019), where they call for a collaboration for building a global database of soil microbial biomass and function. With initiatives like this, pedometricians can seek out collaborations with soil biologists in the near future to create reliable digital soil maps of the soil biological *condition* and *capability*. With that, we are one step closer to the suggestion of McBratney et al. (2014) that soil biota may be a significant and broad indicator of the soil's *condition*.

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

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

Repeated DSM, or long-term SMS are some responses to monitor changes in soil *condition* with time. The oldest long-term broad-scale established SMS in England and Wales already demonstrated its efficiency (Bellamy et al., 2005; Kirk et al., 2010). Preferably, repeated DSM and SMS should be able not only report on mean, total changes and locations where they occur, but also to test new hypothesis on the causes of these changes (Wadoux and McBratney, 2021) or to even bring new data knowledge discovery in soil science (Wadoux et al., 2021). A challenge here is also to differentiate between actual changes in the soil over time and uncertainty around the measured soil property. Van Leeuwen et al. (2021) showed that even laboratory measurements in wet chemistry soil data can be very uncertain and thus affect the monitoring of changes over time. Hence, we must keep in mind though that improving soil *condition* and enhancing soils to their maximum *capability* requires local actions. Supporting these local actions will require more detailed-scale assessment of soil *capacity* and *condition*. For example, Soil Navigator DSS, a the decision Support System for Assessment and Management of Soil Functions (Debeljak et al., 2019) was developed for assessing soil functions in the delivery of various ecosystem services. This DSS works well at the field-scale and can be a great tool for farmers to improve the soil *condition* and *capability*. Moreover, if DSS like the Soil Navigator can be coupled with DSM and land management information, it may become a great tool for large farm holders having diverse abiotic conditions and crops on their farms, or even regional or national stakeholders may use the toolkit for assessing soil functions at larger scales. Thus, supporting these local actions will also largely depend on some aspects of the 4^{th} C, the *connectivity* dimension of soil security, e.g. how to raise soil awareness, education, and the adoption of good soil management practices of local actors (farmers, farmers' advisers, land-use planners, local decision makers, etc.).

Finally, the main question related to this section was 'How do broad-scale SM, DSM and SMS contribute to the 1^{st} and 2^{nd} C's of Soil Security, the soil *capability* and *condition*?

- With respect to soil *capability* it can be concluded that broad-scale SM, DSM and SMS have not yet fully achieved the provision of information concerning the delivery of soil functions and soil-based ecosystem services. Some broad-scale estimates about soil based ecosystem services have been produced using such broad-scale products, e.g. Soil Organic Carbon (SOC) storage, dynamics (Bellamy et al., 2005; van Wesemael et al., 2010; Meersmans et al., 2011; Stockmann et al., 2015) and sequestration potential (Martin et al., 2021), agricultural production (Panagos et al., 2018). However a lot of other functions and ecosystem services still need to be estimated, and often at more detailed scale than broad areas.

- The *condition* of the soil is concerned with the current state of the soil but also refers to the shift in *capability* compared to the reference state. Some long-term SMS (Bellamy et al., 2005) or repeated DSM of which some rely on remote sensing time series (Meersmans et al., 2011; Kempen et al., 2012; Liu et al., 2013; Ivushkin et al., 2019) attempted to quantify these shifts over large areas, but in most cases SMS don't have yet a long enough track record to answer these questions. Another challenge is forecasting the changes in soil *condition* and *capability*. It will often need coupling soil data with models, which raises the question the uncertainty of these predictions.
- One major challenge is to enlarge the range of soil properties that we are currently predicting and monitoring, by adding several soil physico-chemical and biotic such as hydraulic properties, soil structure, soil biota, among others. For instance, monitoring soil biota may be a significant and broad indicator of the soil's *condition*.

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

In this section, we analyze how broad-scale SM, DSM and SMS and the derived spatial soil information progressed valuing soil services and evaluating the *capital dimension of soil security*, i.e. the 3rd dimension of Soil Security. Placing monetary values on natural resources allows people to better understand their significance (McBratney et al., 2019a, 2019b). Soil is part of a natural capital defined as the "stock of materials of information contained within an ecosystem" (Costanza et al., 1997). The stocks contained within the soil include, for instance, SOC stocks, available water for plants, nutrients, material for building, areas available for different land uses. This capital, however, does not necessarily have to be converted into financial or market values. The concept of *soil capital* can be distinguished between the five principal forms being: financial, manufactured, human, social and natural capital. When Sanderman et al. (2017) estimated the soil carbon debt of 12,000 years of human land-use, they evidenced very large historical losses, but did not put any monetary value on them. They just showed regions of the world where the largest losses occurred, and elaborated on the feasibility and the time needed to recover part of this debt for climate change mitigation. Nevertheless, some monetary values can be put on SOC stocks, they can be derived from the price of carbon-exchange markets, or even, indirectly, from the potential loss or increase of agricultural yields these stocks could generate (e.g. Lal, 2006, 2020; Soussana et al., 2019).

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

Soil sealing by urban and infrastructures sprawls are major issues in many parts of the planet (FAO-ITPS, 2015). A rather straightforward way to monitor them could be using high-resolution remote sensing data. This should allow to provide quantitative estimates, both in time and space of soils that become impervious. This is, however, not trivial to implement in a consistent way. In a review paper, Reba and Seto (2020) concluded that that an overwhelming majority of all studies identify only one urban class. This is very worrying if we want to distinguish impervious areas from others, and to take into account services provided by soil, such as water infiltration or hot-spot temperature regulation. This also often results in a confusion between soil sealing by impervious materials, soil consumption, or land-take. Nevertheless, most attempts to evaluate broad-scale *soil capital* losses due to these processes are mainly restricted to the loss of land for agricultural production and related yields (e.g. Gardi et al., 2015, 2021; Bren d'Amour et al., 2017; Wang et al., 2021; Nickayin et al., 2021). Similarly, soil contamination is often accounted as a loss of suitable lands for agriculture and/or as a loss of food and fodder due to their contamination (see for instance, Liu et al., 2013). Although restricted in their estimates of *soil capital* changes, these approaches have the advantage to convert part of these changes in monetary values.

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

This brief review shows that there are several ways to estimate *soil capital*. This can be done by estimating quantities of soil and related elements, by evaluating the ecosystem services they render, or by transforming their capital or their services into monetary values. Concerning soil stocks capital, Robinson et al. (2017) advocated that with LUCAS Soil and other EU monitoring programs, Europe is well placed to develop pan-European accounts including resources such as soil. In a correspondence to Nature, Obst (2015) writes that Integrating information on soil resources with other measures of natural capital and economic activity remains one of the least developed areas of the United Nations System of Environmental Economic Accounting (SEEA).

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

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

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

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

Let us take the example of global issues like soil organic carbon (SOC) change, climate change and food security. Most the citizens and the policy makers are now well aware about the deleterious effects that climate change can have on humanity. However, how many of them made the relationships with soil management before the magic *4 per mille* “slogan” emerged in the political sphere? Historically, this slogan came from a rough calculation made by Balesdent and Arrouays (1999). They used it because they were looking for a striking figure which raised awareness on the importance of SOC for climate change mitigation. This figure came from simply dividing the world anthropogenic C emissions in 1998 by a rough estimate of total SOC down to 1-m made by Batjes (1996) which was mainly based on the combination of a world soil map, available soil profiles with SOC data, and vegetation biomes. It took nearly 16 years of lobbying until this slogan was picked up by the French Ministry of Agriculture who subsequently launched this initiative at the Paris COP21 in 2015 (Minasny et al., 2017; Soussana et al., 2019; Martin et al., 2021).

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

Hence, demonstrating the need for SMS is useful for convincing stakeholders, funding agencies, and policy makers at all levels (from sub-national to international). It might, however, be a source of fear for those having intensive or industrial farming systems. They might be afraid that new binding regulations will prevent them to manage their soils as they want, or will generate new controls, new declarations to fill, or even fees. What we have to do with farmers, is to talk about the risk of degrading their main patrimony and production resource, and how improving their soil’s “health” will be beneficial for them, for the environment, and for their children and grandchildren. Moreover, we need to ensure that when we talk about specific terminology with farmers that we have an equal understanding of the meaning of the terminology used and understand the importance of socioeconomics. Take for example ‘Land suitability’. Traditionally, soil surveys would assess to which extent the land qualities and land characteristics of a field would match the requirements of e.g. specific land use types or crop requirements (Verheye et al., 1982). However, Møller et al. (2021) assessed the added value of machine learning for agricultural land suitability assessment in Denmark, allowing the integration of both environmental and socioeconomic processes for assessing the suitability of agricultural land. They found that socioeconomic factors play a role at the farmers’ decisions which crops to grow rather than solely the land qualities and land characteristics. Consequently, the land suitability assessment was more considered a socioeconomic suitability rather than an ecological suitability assessment. This may very well have been often the case in many of the assessments that we have done so far, yet we have hardly ever considered the socioeconomic value in decision making. In order to improve Soil Security, we need to bridge the gap between the socioeconomic side of decision making and ecological land suitability.

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

There is a great potential of broad-scale SM, DSM and SMS to increase soil *connectivity*, simply because maps and temporal changes are easily understandable and speak for themselves. Our main challenge is to adapt our language and our communication tools to the target audience. There is work to do beyond the soil science community. We should not talk vaguely about the importance of soils. We should communicate according the target audience interests. We should avoid using too much scientific jargon. We should also avoid communicating about the intense scientific debates we have on some definitions. Soil science has been criticized for a long time because soil scientists could not even agree on how to classify or give a common understandable name to the same pedon. There are recurrent scientific debates or even disputes on new concepts as soon as they emerge. Related to the topic of our paper, examples of opinion papers and letters to the editor about the concepts of “Soil Quality”, “Soil Health”, and, unavoidably, now, “Soil Security” are numerous. These are scientific discussions and we do not blame them. New concepts do need to withstand thorough scientific debate prior to a general acceptance by the scientific community yet they should remain constructive. Moreover, exacerbating these debates outside of our community is counter-productive. A real question is “should we communicate only on what is scientifically defined and agreed”? We may have to wait for years. Who will decide that a concept is “scientifically defined and agreed”? We are afraid that it is not a good practice for communication. In this sense, we agree with White and Andrew (2019) when they write “…soil scientists have failed to communicate effectively with the public, the media and policymakers to gain recognition for their achievements and to encourage the investment […]. Soil science needs communication champions with credible stories to tell.” We are also surprised about the debates on “soil health” which are still ongoing, though already largely used for communication by the US, the FAO, and the EU. This word simply speaks to people. No matter if its scientific definition or its measurement standardization exist. We agree with Lehmann et al. (2020) when they write “Scientists should embrace soil health as an overarching principle that contributes to sustainability goals, rather than only a property to measure.” Though there also some debates about Soil Security concept (Allan, 2019), we also agree with the rather similar statement written on the Global Soil Security website “Yet an overarching concept that brings together these biophysical and socio-economic perspectives of soil is still lacking and this has led to the launch of the Soil Security concept”.

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

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

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

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

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

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

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

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

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

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

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

One main concern of some scientists is to which degree these international endorsements and EU policies will enable a sustainable management of soils and be translated into national policies? There are, for instance, at this moment, no real global concerted actions at EU level for improving soil *codification* (Panagos and Montanarella, 2018; Montanarella and Panagos, 2021a). Glæsner et al. (2014) reviewed the European policies that prevent soil threats and support soil Functions. They concluded that there is currently no legislation at the European level that focuses exclusively on soil conservation. They argued that addressing soil functions individually in various directives fails to account for the multifunctionality of soil. Kutter et al. (2011) stated that only a few EU Member States have enacted comprehensive national soil legislation and although some EU legislation and guidelines are integrated into national laws and programmes, the content and implementation of these policies can differ greatly among the countries. This disparity was also shown by comparing the content and implementation of agricultural contractual policies between France and the Netherlands (Daniel and Perraud, 2009). In a recent comparative analysis of the different approaches adopted by EU Member States, Ronchi et al. (2019) revealed the absence of a common EU strategy to address soil protection and insisted on the inefficacy of the subsidiary principle in the sustainable management of soil resources. This is why in a recent paper, Montanarella and Panagos (2021a) concluded that "binding legal framework is a necessary condition for assuring soil security for the EU and protecting this natural resource from further degradation processes".

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

7. Reflection and Conclusion

How do broad-scale SM, DSM and SMS contribute to the 1st and 2nd dimension of Soil Security, the soil *capability and condition*? Our review shows that SM, DSM and SMS can provide the basis for assessing soil *capability* and *condition* over large areas, especially if we assume that *capability* mainly depends on rather stable soil attributes. Repeated DSM or SMS are appropriated tool to monitor changes in soil *condition* with time at these scales. In case of some drastic changes, they may even allow to map changes in soil *capability*. However, broad-scale SM, DSM and SMS had not yet fully achieved the provision of information concerning the delivery of some soil functions and soil-based ecosystem services. Thus, we must enlarge the range of soil properties that we are monitoring. Physico-chemical and biotic soil data are lacking about changes in nutrient status, biota, compaction, soil structure, soil hydrological parameters, among others. We must also keep in mind that improving soil *capability* and *soil condition* needs local actions*.* Therefore, we also need to provide SM, DSM and SMS methods and products which are relevant at the local scale.

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

How does the development of SM, DSM and SMS contribute to the *soil connectivity*? Does it enable an increase in soil *connectivity* and awareness, and to which target audiences? We show that there is a great potential of broad-scale SM, DSM and SMS to increase soil *connectivity*. One of the best ways to communicate and educate on issues related to soil degradation and to the need for good soil management practices is to provide maps, or easy to understand figures or fact sheets, showing how soil *condition* is changing rapidly, and alerting about the consequences and impacts that the most severe soil degradation have. Our main challenge is to adapt our language and our communication tools to the target audience. Exacerbating some scientific debates outside of the soil science community may be counter-productive.

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

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

Aknowledgements

We thank the editors of "Soil Security" for encouraging us to write this paper. D.A. is coordinator, V.L.M. is member and A.C.R.d.F. is collaborator of the Research Consortium GLADSOILMAP, supported by LE STUDIUM Loire Valley Institute for Advanced studies.

References

Allan, C., 2019. The Opportunities and Risks of the Soil Security Metaphor: A Review. Sustainabitity. 11, 16, DOI10.3390/su11164464

Amundson, R., Berhe, A.A., Hopmans, J.W., Olson, C., Sztein, A.E., Sparks, D.L., 2015. Soil and human security in the 21st century. Science. 348, 6235. https://doi.org/10.1126/science.1261071

Arrouays, D., Daroussin, J., Kicin, J.L., Hassika, P., 1998. Improving topsoil carbon storage prediction using a digital elevation model in temperate forest soils of France. Soil Science. 163, 103-108.

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, M.d.L., 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. Advances in Agronomy. 125, 93-134. https://doi.org/10.1016/B978-0-12-800137-0.00003-0

Arrouays, D., Lagacherie, P., Hartemink, A.E., 2017b. Digital soil mapping across the globe. Geoderma Regional. 9, 1-4. https://doi.org/10.1016/j.geodrs.2017.03.002

Arrouays, D., Leenaars, J., Richer-de-Forges, A.C., Adhikari, K., Ballabio, C., Greve, M.H., Grundy, M., Guerrero, E., Hempel, J., Hengl, T., Heuvelink, G.B.M., Batjes, N.H., 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.J., Vasques, G., Mulder, V.L., Minasny, B., Montanarella, L., Odeh, I., Padarian, J., Poggio, L., Roudier, P., Saby, N., Savin, I., Searle, R., Stolbovoy, V., Thompson, J.A., Smith, S., Sulaeman, Y., Vintila, R., Viscarra Rossel, R., Wilson, P., Zhang, G.-L., Swerts, M., van 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., Kayusuki, Y., Mansuy, N., Panagos, P., van Liedekerke, M., Skalsky, R., Sobocka, J., Kobza, J., Eftekhari, K., Kazem Alavipanah, S., Moussadek, R., Badraoui, M., da Silva, M., Paterson, G., da Conceição Gonçalves, M., Theocharopoulos, S., Yemefack, M., Tedou, S., Vrscaj, B., Grob, U., Kozak, J., Boruvka, L., Dobos, E., Taboada, M., Moretti, L., Rodriguez, D., 2017a. Soil legacy data rescue via GlobalSoilMap and other international and national initiatives. GeoRes J. 14, 1-19. https://doi.org/10.1016/j.grj.2017.06.001

Arrouays, D., Marchant B.P., Saby N.P.A., Meersmans, J., Orton, T.G., Martin, M.P., Bellamy, P.H., Lark R.M., Kibblewhite, M., 2012. Generic issues on broad scale soil monitoring schemes: A review. Pedosphere. 22(4), 456-469.

Arrouays, D., Poggio, L., Salazar Guerrero, O., Mulder, V.L. 2020a. Digital Soil Mapping and GlobalSoilMap. Main advances and ways forward. Geoderma Regional, 21. e000265. https://doi.org/10.1016/j.geodrs.2020.e00265

Arrouays, D., Richer-de-Forges, A.C., Héliès, F., Mulder, V.L., Saby, N.P.A., Chen, S., Martin, M.P., Roman Dobarco, M., Follain, S., Jolivet, C., Laroche, B., Cousin, I., Lacoste, M., Ranjard, L., Toutain, B., Le Bas, C., Eglin, T., Bardy, M., Antoni, V. Meersmans J, Ratié C., Bispo, A., 2020b. Impacts of Digital Soil Mapping programs in France at national scale. Geoderma Regional. 23, e00337. https://doi.org/10.1016/j.geodrs.2020.e00337

Arrouays, D., Vion, I., Kicin, J.L., 1995. Spatial analysis and modeling of topsoil carbon storage in forest humic loamy soils of France. Soil Sci. 159, 191–198. https://doi.org/10.1097/00010694-199515930-00006

Arrouays, D., Vogel, H., Eckelmann, W., Armstrong-Brown, S., Loveland, P., Coulter, B., 1998 Soil monitoring networks in Europe. A review 16th World Congress of Soil Science, Montpellier, France, August 1998.

Ausseil, A.-G.E., Jamali, H., Clarkson, B.R., Golubiewski, N.E. 2015. Soil carbon stocks in wetlands of New Zealand and impact of land conversion since European settlement. Wetlands Ecology and Management. 23, 947–961. https://doi.org/10.1007/s11273-015-9432-4

Balesdent, J., Arrouays, D., 1999. Usage des terres et stockage de carbone dans les sols du territoire français. Une estimation des flux nets annuels pour la période 1900-1999. C.R. Acad. Agric. Fr. 85, 265–277.

Barrios, E., 2007. Soil biota, ecosystem services and land productivity. Ecological Economics. 64, 269–285. https://doi.org/10.1016/j.ecolecon.2007.03.004

Batjes, N.H., 1996. Total carbon and nitrogen in the soils of the world. Eur J Soil Science. 47, 151–163. https://doi.org/10.1111/j.1365-2389.1996.tb01386.x

Batjes, N.H., 2016. Harmonized soil property values for broad-scale modelling (WISE30sec) with estimates of global soil carbon stocks. Geoderma. 269, 61–68. https://doi.org/10.1016/j.geoderma.2016.01.034

Bellamy, P.H., Loveland, P.J., Bradley, R.I., Lark, R.M., Kirk, G.J.D., 2005. Carbon losses from all soils across England and Wales 1978-2003. Nature. 437, 245–248. https://doi.org/10.1038/nature04038

Bennett, J.M., McBratney, A.B., Field, D.J., Stockmann, U., Liddicoat, C., Grover, S., 2019. Soil Security for Australia. Sustainability. 11(12), 3416. DOI10.3390/su11123416

Bennett, J.M., Roberton, S.D., Ghahramania, A., McKenzie, D.C., 2021. Operationalising soil security by making soil data useful: Digital soil mapping, assessment and return-on-investment. Soil Security. 4, 100010. https://doi.org/10.1016/j.soisec.2021.100010

Boulaine, J.J., 1983. V. V. Dokouchaev et les débuts de la pédologie. Revue d'histoire des sciences. 36(3-4), 285-306. [in French]. doi : https://doi.org/10.3406/rhs.1983.1942

Bouma, J., 2019. How to communicate soil expertise more effectively in the information age when aiming at the UN Sustainable Development Goals. Soil Use Manage. 35, 32-38. https://doi.org/10.1111/sum.12415

Bouma, J., 2020. Soil security as a roadmap focusing soil contributions on sustainable development agendas. Soil Security. 1, Article 100001. https://doi.org/10.1016/j.soisec.2020.100001

Bouma, J., Montanarella, L., 2016. Facing policy challenges with inter- and transdisciplinary soil research focused on the UN sustainable development goals. Soil. 2, 135–145. https://doi.org/10.5194/soil-2-135-2016

Bourennane, H., King, D., Chéry, P., Bruand, A., 1996. Improving the kriging of a soil variable using slope gradient as external drift. Eur. J. Soil Sci. 47 (4), 473–483. https://doi.org/10.1111/j.1365-2389.1996.tb01847.x

Brady, M.V., Hristov, J., Wilhelmsson, F., Hedlund, K., 2019. Roadmap for Valuing Soil Ecosystem Services to Inform Multi-Level Decision-Making in Agriculture. Sustainability. 11(19), Article Number5285, DOI10.3390/su11195285

Bren d'Amour, C., Reitsma, F., Baiocchi, G., Barthel, S., Guneralp, B., Erb, K.H., Haberl, H., Creutzig, F., Seto, K.C., 2017. Future urban land expansion and implications for global croplands. PNAS. 114(34), 8939-8944. DOI10.1073/pnas.1606036114

Brus, D.J., 2014. Statistical sampling approaches for soil monitoring: Sampling for soil monitoring. European Journal of Soil Science. 65, 779–791. https://doi.org/10.1111/ejss.12176

Brus, D.J., 2021. Statistical approaches for spatial sample survey: Persistent misconceptions and new developments. European Journal of Soil Science. 72(2), 686-703. DOI10.1111/ejss.12988

Carré, F., McBratney, A.B., Mayr, T., Montanarella, L., 2007. Digital soil assessments: Beyond DSM. Geoderma. 142(1-2), 69-79. DOI10.1016/j.geoderma.2007.08.015

Caubet, M., Roman Dobarco, M., Arrouays, D., Minasny, B., Saby, N., 2019. Merging country, continental and global predictions of soil texture: Lessons from ensemble modelling in France. Geoderma. 337, 99-110. https://doi.org/10.1016/j.geoderma.2018.09.007

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

Chen, S., Mulder, V.L., Heuvelink, G.B.M., Poggio, L., Caubet, M., Román Dobarco, M., Walter, C., Arrouays, D., 2020. Model averaging for mapping topsoil organic carbon in France. Geoderma. 366, 114237. https://doi.org/10.1016/j.geoderma.2020.114237

Costanza, R., d'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R.V., Paruelo, J., Raskin, R.G., Sutton, P., van den Belt, M., 1997. The value of the world's ecosystems services and natural capital. Nature. 387, 253-260. https://doi.org/10.1038/387253a0

CPCS., 1967. Commission de Pédologie et de Cartographie des Sols. Classification des sols. Laboratoire de Géologie et de Pédologie, Ecole Nationale Supérieure d'Agronomie, Paris-Grignon, France, 87 p. [in French].

Creamer, R.E., Hannula, S.E., Leeuwen, J.P.V., Stone, D., Rutgers, M., Schmelz, R.M., Ruiter, P.C. de, Hendriksen, N.B., Bolger, T., Bouffaud, M.L., Buee, M., Carvalho, F., Costa, D., Dirilgen, T., Francisco, R., Griffiths, B.S., Griffiths, R., Martin, F., Silva, P.M. da, Mendes, S., Morais, P.V., Pereira, C., Philippot, L., Plassart, P., Redecker, D., Römbke, J., Sousa, J.P., Wouterse, M., Lemanceau, P., 2016. Ecological network analysis reveals the inter-connection between soil biodiversity and ecosystem function as affected by land use across Europe. Applied Soil Ecology. 97, 112–124. https://doi.org/10.1016/j.apsoil.2015.08.006

Daniel, F.J., Perraud, D., 2009. The multifunctionality of agriculture and contractual policies. A comparative analysis of France and the Netherlands. Journal of environmental management. 90, Supplement 2, S132-S138. DOI10.1016/j.jenvman.2008.11.015

DAWE, 2021. National Soil Strategy. Department of Agriculture, Water and the Environment, Canberra, Australia. https://www.agriculture.gov.au/sites/default/files/documents/awe.gov.au/publications (last access: 07/31/2021)

Debeljak, M., Trajanov, A., Kuzmanovski, V., Schröder, J., Sandén, T., Spiegel, H., Wall, D.P., Van de Broek, M., Rutgers, M., Bampa, F., Creamer, R.E., Henriksen, C.B., 2019. A Field-Scale Decision Support System for Assessment and Management of Soil Functions. Front. Environ. Sci. 7, 115. https://doi.org/10.3389/fenvs.2019.00115

Delmas, M., Cerdan, O., Cheviron, B., Mouchel, J.M., Eyrolle, F., 2012. Sediment export from French rivers to the sea. Earth Surface Processes and Landforms. 37(7), 754-762. DOI10.1002/esp.3219

Doran, J.W., 2002. Soil health and global sustainability: translating science into practice. Agriculture, Ecosystems & Environment. 88, 119–127. https://doi.org/10.1016/S0167-8809(01)00246-8

Doran, J.W., Sarrantonio, M., Liebig, M.A., 1996. Soil Health and Sustainability, in: Advances in Agronomy. Elsevier, pp. 1–54. https://doi.org/10.1016/S0065-2113(08)60178-9

Doran, J.W., Zeiss, M.R., 2000. Soil health and sustainability: managing the biotic component of soil quality. Applied Soil Ecology. 15, 3–11. https://doi.org/10.1016/S0929-1393(00)00067-6

Droogers, P., Bouma, J., 1997. Soil survey input in exploratory modelling of sustainable soil management practices. Soil Sci. Soc. Am. J. 61, 1704-1710. https://doi.org/10.2136/sssaj1997.03615995006100060023x

ESDAC (European Soil Data Centre) 2021. European Soil Data Centre. Joint Research Centre, Ispra [WWW document]. URL http://esdac.jrc.ec.europa.eu/ [accessed on 22 July 2021].

European Commission, 2019. COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE EUROPEAN COUNCIL, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS The European Green Deal - COM/2019/640 final. European Commission, Brussels. https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en (last access: 07/31/2021)

European parliament, 2003. European Parliament legislative resolution on the proposal for a Council regulation on establishing common rules for direct support schemes under the common agricultural policy and support schemes for producers of certain crops (COM(2003) 23 – C5-0040/2003 – 2003/0006(CNS)) (No. P5_TA(2003)0256). European parliament - 5th parliamentary term.

FAO, 2015. Revised World Soil Charter. Food and Agriculture Organization of the United Nations. Rome. Italy. 7p.

FAO, 2017. Voluntary Guidelines for Sustainable Soil Management. Food and Agriculture Organization of the United Nations. Rome, Italy. 16p.

FAO/IIASA/ISRIC/ISS-CAS/JRC, 2008. Harmonized World Soil Database (version 1.0). FAO, Rome, Italy and IIASA, Laxenburg, Austria. 37 p. http://www.fao.org/uploads/media/Harm-World-Soil-DBv7cv_1.pdf (last access 06/28/2021)

FAO-ITPS, 2015. Status of the World's Soil Resources (SWSR). Main Report. Food and Agriculture Organization of the United Nations and Intergovernmental Technical Panel on Soils. Rome, Italy.

Field, D.J., 2020. Sustaining agri-food systems framed using soil security and education. International journal of agriculture and natural resources. 47, 3, 249-260. DOI10.7764/ijanr.v47i3.2289.

Field, D.J., Morgan, C.L.S., McBratney, A.B., (eds). 2017 Global Soil Security. Progress in Soil Science, Springer, 463 p. 42 chapters. DOI10.1007/978-3-319-43394-3_1

Gardi, C., Florczyk, A.J., Scalenghe, R., 2021. Outlook from the soil perspective of urban expansion and food security. Heliyon. 7(1), e05860. DOI10.1016/j.heliyon.2020.e05860

Gardi, P., Panagos, P., Van Liedekerke, M., Bosco, C., De Brogniez, D., 2015. Land take and food security: assessment of land take on the agricultural production in Europe. Journal of Environmental Planning and Management. 58, 5, 898-912. https://doi.org/10.1080/09640568.2014.899490

Glæsner, N., Helming, K., de Vries, W., 2014. Do Current European Policies Prevent Soil Threats and Support Soil Functions? Sustainability. 6, 12, 9538-9563. DOI10.3390/su6129538

Gray, J.M., Bishop, T.F.A., 2016. Change in Soil Organic Carbon Stocks under 12 Climate Change Projections over New South Wales, Australia. Soil Science Society of America Journal. 80(5), 1296-1307. DOI10.2136/sssaj2016.02.0038

Grønlund, A., Hauge, A., Hovde, A., Rasse, D.P., 2008. Carbon loss estimates from cultivated peat soils in Norway: a comparison of three methods. Nutrient Cycling in Agroecosystems. 81, 157–167. https://doi.org/10.1007/s10705-008-9171-5

Grunwald, S., Thompson, J.A., Boettinger, J.L., 2011. Digital soil mapping and modeling at continental scales: Finding solutions for global issues. Soil Science Society of America Journal. 75, 1201–1213. https://doi.org/10.2136/sssaj2011.0025

Harms, B., Brough, D., Philip, S., Bartley, R., Clifford, D., Thomas, M., Willis, R., Gregory, L., 2015. Digital soil assessment for regional agricultural land evaluation. Glob. Food Sec. 5, 25–36. https://doi.org/10.1016/j.gfs.2015.04.001

Hartemink, A.E., McBratney, A.B., 2008. A soil science renaissance. Geoderma. 148,123–129. https://doi.org/10.1016/j.geoderma.2008.10.006

Hengl, T., de Jesus, J.M., Heuvelink, G.B.M., Gonzalez, M.R., Kilibarda, M., Blagotic, A., Shangguan, W., Wright, M.N., Blagotic, A., Geng, X.Y., 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., 2017a. SoilGrids250m: global gridded soil information based on Machine Learning. PLoS ONE. 12(2), e0169748. https://doi.org/10.1371/journal.pone.0169748

Hengl, T., de Jesus, J.M., MacMillan, R.A., Batjes, N.H., Heuvelink, G.B.M., Ribeiro, E., Samuel-Rosa, A., Kempen, B., Leenaars, J.G.B., Walsh, M.G., Gonzalez, M.R., 2014. SoilGrids1km-Global Soil Information Based on Automated Mapping. PLoS ONE. 9(8), e105992. DOI10.1371/journal.pone.0105992

Hengl, T., Heuvelink G.B.M., Kempen, B., Leenaars J.G.B., Walsh, M.G., Shepherd, K., Sila, A., MacMillan, R.A., de Jesus, J.M., 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. https://doi.org/10.1371/journal.pone.0125814

Hengl, T., Leenaars, J.G.B., Shepherd, K.D., Walsh, M.G., Heuvelink, G.B.M., Mamo, T., Tilahun, H., Berkhout, E., Cooper, M., Fegraus, E., Wheeler, I., Kwabena, N.A., 2017b. Soil nutrient maps of Sub-Saharan Africa: assessment of soil nutrient content at 250 m spatial resolution using machine learning. Nutr Cycl Agroecosyst. 109, 77–102. https://doi.org/10.1007/s10705-017-9870-x

Heuvelink, G.B.M., 2014. Uncertainty quantification of *GlobalSoilMap* products. In: *GlobalSoilMap*: Basis of the global spatial soil information system. Arrouays, D., McKenzie, N.J., Hempel, J., Richer-de-Forges, A.C., McBratney, A.B., (eds). pp. 335-340. CRC Press-Taylor & Francis, Boca Raton, FL. USA.

Hewitt, A., Dominati, E., Webb, T., Cuthill, T., 2015. Soil natural capital quantification by the stock adequacy method. Geoderma. 241, 107-114. DOI10.1016/j.geoderma.2014.11.014

Huang, J.Y., McBratney, A.B., Malone, B.P., D.J. Field, D.J., 2018. Mapping the transition from pre-European settlement to contemporary soil conditions in the Lower Hunter Valley Australia. Geoderma. 329, 27-42, 10.1016/j.geoderma.2018.05.016

Ivushkin, K., Bartholomeus, H.,Bregt, A.K., Pulatov, A., Kempen, B., de Sousa, L., 2019. Global mapping of soil salinity change. Remote Sensing Env. 231, 111260. DOI10.1016/j.rse.2019.111260

Jamagne, M., 1967. Bases et techniques d'une cartographie des sols. Annales Agronomiques. 18, numéro hors-série. 142 p. [in French].

Jamagne, M., 1973. Contribution à l'étude pédogénétique des formations loessiques du Nord de la France. PhD Thesis, Fac. Sci. Agron. Gembloux. France. 475 p. [In French]

Jamagne, M., 1978. Les processus pédogénétiques dans une séquence évolutive progressive sur formations limoneuses en zone tempérée froide et humide. C. R. Acad. Sci. 286(17), 25-27. [In French]

Jamagne, M., Bornand, M., Hardy, R., 1989. La cartographie des sols en France à moyenne échelle. Programmes en cours et évolution des démarches. Science du sol. 27, 301–318. [In French]

Jamagne, M., De Coninck, F., Robert, M., Maucorps, J., 1984. Mineralogy of the clay fractions of some soils in northern France. Geoderma. 33, 319-342. https://doi.org/10.1016/0016-7061(84)90032-6

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

Journal officiel de la République française., 1961. Loi n° 61-1489 du 26 décembre 1961 relative à l'accueil et à la réinstallation des Français d'outre-mer. In: Journal officiel de la République française. Lois et décrets, n° 0304, 11996-11997. [in French]. https://www.legifrance.gouv.fr/jorf/id/JORFTEXT000000508788 (last accessed, 07/30/2021).

Karimi, B., Terrat, S., Dequiedt, S., Saby, N.P.A., Horrigue, W., Lelièvre, M., Nowak, V., Jolivet, C., Arrouays, D., Wincker, P., Cruaud, C., Bispo, A., Maron, P.-A., Bouré, N.C.P., Ranjard, L., 2018. Biogeography of soil bacteria and archaea across France. Sci. Adv. 4, eaat1808. https://doi.org/10.1126/sciadv.aat1808

Karlen, D.L., Andrews, S.S., Doran, J.W., 2001. Soil quality: Current concepts and applications, in: Advances in Agronomy. Elsevier, pp. 1–40. https://doi.org/10.1016/S0065-2113(01)74029-1

Karlen, D.L., Mausbach, M.J., Doran, J.W., Cline, R.G., Harris, R.F., Schuman, G.E., 1997. Soil Quality: A Concept, Definition, and Framework for Evaluation (A Guest Editorial). Soil Science Society of America Journal. 61, 4–10. https://doi.org/10.2136/sssaj1997.03615995006100010001x

Keesstra, S.D., Bouma, J., Wallinga, J., Tittonell, P., Smith, P., Cerdà, A., Montanarella, L., Quinton, J.N., Pachepsky, Y., Van Der Putten, W.H., Bardgett, R.D., Moolenaar, S., Mol, G., Jansen, B., Fresco, L.O., 2016. The significance of soils and soil science towards realization of the United Nations sustainable development goals. Soil. 2, 111–128.

Keesstra, S.D., Munkholm, L., Cornu, S., Visser, S.M., Faber, J., Kuikman, P., Thorsoe, M., de Haan, J., Vervuurt, W., Verhagen, J., Neumann, M., Fantappie, M., van Egmond, F., Bispo, A., Wall, D., Berggreen, L., Barron, J., Gascuel, C., Granjou, C., Gerasina, R., Chenu, C., 2021. Roadmap of the European Joint Programme SOIL (EJP SOIL Report, deliverable 2.4.).

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(6), 2097-2115. DOI10.2136/sssaj2011.0424

Kidd, D., Field, D.J., McBratney, A.B., Webb, M., 2018. A preliminary spatial quantification of the soil security dimensions for Tasmania. Geoderma. 322, 184-200. DOI10.1016/j.geoderma.2018.02.018

Kidd, D., Webb, M., Malone, B., Minasny, B., McBratney, A., 2015. Digital soil assessment of agricultural suitability, versatility and capital in Tasmania, Australia. Geoderma Reg. 6, 7–21. https://doi.org/10.1016/j.geodrs.2015.08.005

King, D., Daroussin, J., Tavernier, R., 1994. Development of a soil geographic database from the soil map of the European Communities. CATENA. 21(1), 37-51.

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

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

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

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

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

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

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

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

Lal, R., 2006. Enhancing crop yields in the developing countries through restoration of the soil organic carbon pool in agricultural lands. Land Degrad. Dev. 17, 197-209. https://doi.org/10.1002/ldr.696

Lal, R., 2020. Managing soils for negative feedback to climate change and positive impact on food and nutritional security. Soil Sci. Plant Nutr. 66, 1–9. https://doi.org/10.1080/00380768.2020.1718548

Leenaars, J.G.B., 2014. ISRIC Report 2012/03. Africa Soil Information Service (AfSIS) project. Wageningen, The Netherlands: ISRIC - World Soil Information. 148p.

Leenaars, J.G.B., Claessens, L., Heuvelink, G.B.M., Hengl, T., Ruiperez González, M., van Bussel, L.G.J., Guilpart, N., Yang, H., Cassman, K.G., 2018. Mapping rootable depth and root zone plant-available water holding capacity of the soil of sub-Saharan Africa. Geoderma. 324, 18–36. https://doi.org/10.1016/j.geoderma.2018.02.046

Leenaars, J.G.B., Kempen, B., van Oostrum, A.J.M., Batjes, N.H., 2014a. Africa soil profiles database: a compilation of georeferenced and standardised legacy soil profile data for Sub-Saharan Africa. In: Arrouays, D., McKenzie, N.J., Hempel, J.W., Richer-de-Forges, A.C., McBratney, A.B., (eds). *GlobalSoilMap*: basis of the global soil information system. CRC Press-Taylor & Francis, Boca Raton, FL. USA. pp. 51–57.

Leenaars, J.G.B., van Oostrum, A.J.M., Ruiperez Gonzalez, A.J.M., 2014b. ISRIC report 2014/01. Africa Soil Information Service (AfSIS) project. Wageningen, The Netherlands: ISRIC - World Soil Information.

Legros, J.-P., 1996. Cartographies des sols: de l’analyse spatiale à la gestion des territoires, 1. éd. ed, Collection Gérer l’environnement. Presses Polytechniques et Univ. Romandes, Lausanne. [in French]

Legros, J.P., Bonneric, P., 1979. Modélisation informatique de la répartition des sols dans le Parc Régional Naturel du Pilat. Ann. Univ. Savoie. 63–68. [in French]

Lehmann, J., Bossio, D.A., Kogel-Knabner, I., Illig, M.C., 2020. The concept and future prospects of soil health. Nature Reviews Earth & Environment. 1, 10, 544-553. DOI10.1038/s43017-020-0080-8

Leonhardt, H., Penker, M., Salhofer, K., 2019. Do farmers care about rented land? A multi-method study on land tenure and soil conservation. Land Use Policy. 82, 228–239. https://doi.org/10.1016/j.landusepol.2018.12.006

Liu Y., Wen, C., Liu, X., 2013. China's Food Security Soiled by Contamination. Science. 339, 6126, 1382-1383. DOI: 10.1126/science.339.6126.1382-b

Louis, B.P., Saby, N.P.A., Orton, T.G., Lacarce, E., Boulonne, L., Jolivet, C., Ratié, C., Arrouays, D., 2014. Statistical sampling design impact on predictive quality of harmonization functions between soil monitoring networks. Geoderma. 213, 133–143. https://doi.org/10.1016/j.geoderma.2013.07.018

Martin M.P., Dimassi, B., Roman Dobarco, M., Guenet, B., Arrouays, D., Angers, D.A., Soussana, J.F., Pellerin, S. 2021. Feasibility of the 4 per 1000 aspirational target for soil carbon. A case study for France. Global Change Biology. 27(11), 2458-2477. doi: 10.1111/GCB.15547.

Martiny, J.B.H., Bohannan, B.J.M., Brown, J.H., Colwell, R.K., Fuhrman, J.A., Green, J.L., Horner-Devine, M.C., Kane, M., Krumins, J.A., Kuske, C.R., Morin, P.J., Naeem, S., Øvreås, L., Reysenbach, A.-L., Smith, V.H., Staley, J.T., 2006. Microbial biogeography: putting microorganisms on the map. Nat. Rev. Microbiol. 4, 102–112. https://doi.org/10.1038/nrmicro1341

McBratney, A.B., Field, D.J., 2015. Securing our soil. Soils Science and Plant Nutrition. 61, 4, 587-591. DOI10.1080/00380768.2015.1071060.

McBratney, A.B., Field, D.J., Jarrett, L.E., 2017. General Concepts of Valuing and Caring for Soil, in: Field, D.J., Morgan, C.L.S., McBratney, A.B. (Eds.), Global Soil Security, Progress in Soil Science. Springer International Publishing, Cham, pp. 101–108. https://doi.org/10.1007/978-3-319-43394-3_9

McBratney, A.B., Field, D.J., Koch, A., 2014. The dimensions of soil security. Geoderma. 213, 203-213. https://doi.org/10.1016/j.geoderma.2013.08.013

McBratney, A.B., Field, D.J., Morgan, C.L.S., Huang, J., 2019a. On Soil Capability, Capacity, and Condition. Sustainability. 11(12), Article Number3350. DOI10.3390/su11123350

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., Moyce, M., Field, D.J., Bryce, E., 2019b. The concept of soil security. In: Richer-de-Forges, A.C., Carré, F., McBratney, A.B., Bouma, J., Arrouays, D., (eds). Global Soil Security. Towards more science-society interfaces. CRC Press, Taylor & Francis, London. pp. 11-17.

MEA (Millenium Ecosystem Assessment), 2005. Ecosystems and human well-being: biodiversity synthesis. Washington D.C., World Resources Institute.

MEDDE and Gis Sol, 2013. Guide pour l'identification et la délimitation des sols de zones humides. Ministère de l'Écologie, du Développement Durable et de l'Énergie. Groupement d'Intérêt Scientifique Sol. 63p. [in French].

Meersmans, J., van Wesemael, B., Goidts, E., van Molle, M., De Baets, S., De Ridder, F., 2011. Spatial analysis of soil organic carbon evolution in Belgian croplands and grasslands, 1960-2006. Global Change Biology, 17(1), 466-479. DOI10.1111/j.1365-2486.2010.02183.x

Minasny, B., Berglund, O., Connolly, J., Hedley, C., de Vries, F., Gimona, A., Kempen, B., Kidd, D., Lilja, H., Malone, B., McBratney, A.B., Roudier, P., O'Rourke, S., Rudiyanto, Padarian, J., Poggio, L., ten Caten, A., Thompson, D., Tuve, C., Widyatmanti, W., 2019. Digital mapping of peatlands - A critical review. Earth-Science Reviews. 196, DOI10.1016/j.earscirev.2019.05.014

Minasny, B., Malone, B.P., McBratney, A.B., (eds), 2012. Digital Soil Assessments and Beyond. CRC Press, Taylor & Francis, Boca Raton, FL. USA. 446 p. + CD.

Minasny, B., Malone, B.P., McBratney, A.B., Angers, D.A., Arrouays, D., Chambers, A., Chaplot, V., Chen, Z.-S., Cheng, K., Das, B.S., Field, D.J., Gimona, A., Hedley, C.B., Hong, S.Y., Mandal, B., Marchant, B.P., Martin, M., McConkey, B.G., Mulder, V.L., O'Rourke, S., Richer-de-Forges, A.C., Odeh, I., Padarian, J., Paustian, K., Pan, G., Poggio, L., Savin, I., Stolbovoy, V., Stockmann, U., Sulaeman, Y., Tsui, C.-C., Vågen, T.-G., van Wesemael, B., Winowiecki, L., 2017. Soil carbon 4 per mille. Geoderma 292, 59–86. https://doi.org/10.1016/j.geoderma.2017.01.002

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

Ministry of Infrastructure and Water Management, 2013. Soil Protection Act. The Netherlands. https://rwsenvironment.eu/subjects/soil/legislation-and/ (last access: 07/31/2021)

Møller, A.B., Mulder, V.L., Heuvelink, G.B.M., Jacobsen, N.M., Greve, M.H., 2021. Can We Use Machine Learning for Agricultural Land Suitability Assessment? Agronomy. 11, 703. https://doi.org/10.3390/agronomy11040703

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

Montanarella, L., Panagos, P., 2021a. Soil Security for the European Union. Soil Security. 4, 100009. https://doi.org/10.1016/j.soisec.2021.100009

Montanarella, L., Panagos, P., 2021b. The relevance of sustainable soil management within the European Green Deal. Land Use Policy. 100, 104950. https://doi.org/10.1016/j.landusepol.2020.104950

Montanarella, L., Pennock, D.J., McKenzie, N.J., Badraoui, M., Chude, V., Baptista, I., Mamo, T. Yemefack, M., Singh Aulakh, M., Yagi, K., Young Hong, S., Vijarnsorn, P., Zhang, G.-L., Arrouays, D., Black, H., Krasilnikov, P., Sobocká, J., Alegre, J., Henriquez, C.R., Mendonça-Santos, M.d.L., Taboada, M., Espinosa-Victoria, D., AlShankiti, A., AlaviPanah, S.K., Elsheikh, E.A.E., Hempel, J., Camps-Arbestain, M., Nachtergaele, F., Vargas, R., 2016. World's soils are under threat. Soil. 2, 79-82. https://doi.org/10.5194/soil-2-79-2016

Morgan, C.L.S., McBratney, A.B., 2020. Editorial: Widening the disciplinary study of soil. Soil Security. 1, 100003. https://doi.org/10.1016/j.soisec.2020.100003

Morvan, X.P.P., Saby, N.P.A., Arrouays, D., Le Bas, C., Jones R.J.A., Verheijen, F.G.A, Bellamy P.H., Stephens, M., Kibblewhite, M.G., 2008. Soil monitoring in Europe: a review of existing systems and requirements for harmonisation. Sci. Tot. Env. 391, 1-12. https://doi.org/10.1016/j.scitotenv.2007.10.046

Mulder, V.L., van Eck, C.M., Friedlingstein, P., Arrouays, D., Regnier, P., 2019. Controlling factors for land productivity under extreme climatic events in continental Europe and the Mediterranean Basin. CATENA. 182, 104124. https://doi.org/10.1016/j.catena.2019.104124

Murphy, B., Fogarty, P., 2019. Application of the Soil Security Concept to Two Contrasting Soil Landscape Systems-Implications for Soil Capability and Sustainable Land Management. Sustainability. 11(20), Article Number5706. DOI10.3390/su11205706

Nickayin, S.S., Perrone, F., Ermini, B., Quaranta, G., Salvia, R., Gambella, F., Egidi, G., 2021. Soil Quality and Peri-Urban Expansion of Cities: A Mediterranean Experience (Athens, Greece). Sustainability. 13(4), 2042. DOI10.3390/su13042042

Obst, C.G., 2015. Economics: Account for soil as natural capital. Nature. 527, 165–165. https://doi.org/10.1038/527165b

Orgiazzi, A., Ballabio, C., Panagos, P., Jones, A., Fernández-Ugalde, O., 2018. LUCAS Soil, the largest expandable soil dataset for Europe: a review. European Journal of Soil Science. 69, 140–153, https://doi.org/10.1111/ejss.12499

Padarian, J., McBratney, A.B., 2020. A new model for intra- and inter-institutional soil data sharing. SOIL. 6(1), 89-94. DOI10.5194/soil-6-89-2020

Padarian, J., Minasny, B., McBratney A.B., 2019. Online machine learning for collaborative biophysical modelling. Environmental Modelling & Software. 122, 104548. https://doi.org/10.1016/j.envsoft.2019.104548

Panagos, P., Borrelli, P., Poesen, J., Ballabio, C., Lugato, E., Meusburger, K., Montanarella, L., Alewell, C., 2015. The new assessment of soil loss by water erosion in Europe. Environmental Science & Policy. 54, 438-447. DOI10.1016/j.envsci.2015.08.012

Panagos, P., Montanarella, L., 2018. Soil Thematic Strategy: an important contribution to policy support, research, data development and raising the awareness. Curr. Opin. Environ. Sci. Health. 5, 38-41. https://doi.org/10.1016/j.coesh.2018.04.008

Panagos, P., Standardi, G., Borrelli, P., Lugato, E., Montanarella, L., Bosello, F., 2018. Cost of agricultural productivity loss due to soil erosion in the European Union: from direct cost evaluation approaches to the use of macroeconomic models. Land Degrad. Dev. 29, 471-484. https://doi.org/10.1002/ldr.2879

Panagos, P., Van Liedekerke, M., Jones, A., Montanarella, L., 2012. European Soil Data Centre: Response to European policy support and public data requirements. Land Use Policy. 29 (2), 329-338. doi:10.1016/j.landusepol.2011.07.003

Phillips, H.R.P., Guerra, C.A., Bartz, M.L.C., Briones, M.J.I., Brown, G., Crowther, T.W., Ferlian, O., Gongalsky, K.B., van den Hoogen, J., Krebs, J., Orgiazzi, A., Routh, D., Schwarz, B., Bach, E.M., Bennett, J.M., Brose, U., Decaëns, T., König-Ries, B., Loreau, M., Mathieu, J., Mulder, C., van der Putten, W.H., Ramirez, K.S., Rillig, M.C., Russell, D., Rutgers, M., Thakur, M.P., de Vries, F.T., Wall, D.H., Wardle, D.A., Arai, M., Ayuke, F.O., Baker, G.H., Beauséjour, R., Bedano, J.C., Birkhofer, K., Blanchart, E., Blossey, B., Bolger, T., Bradley, R.L., Callaham, M.A., Capowiez, Y., Caulfield, M.E., Choi, A., Crotty, F.V., Crumsey, J.M., Dávalos, A., Diaz Cosin, D.J., Dominguez, A., Duhour, A.E., van Eekeren, N., Emmerling, C., Falco, L.B., Fernández, R., Fonte, S.J., Fragoso, C., Franco, A.L.C., Fugère, M., Fusilero, A.T., Gholami, S., Gundale, M.J., López, M.G., Hackenberger, D.K., Hernández, L.M., Hishi, T., Holdsworth, A.R., Holmstrup, M., Hopfensperger, K.N., Lwanga, E.H., Huhta, V., Hurisso, T.T., Iannone, B.V., Iordache, M., Joschko, M., Kaneko, N., Kanianska, R., Keith, A.M., Kelly, C.A., Kernecker, M.L., Klaminder, J., Koné, A.W., Kooch, Y., Kukkonen, S.T., Lalthanzara, H., Lammel, D.R., Lebedev, I.M., Li, Y., Jesus Lidon, J.B., Lincoln, N.K., Loss, S.R., Marichal, R., Matula, R., Moos, J.H., Moreno, G., Morón-Ríos, A., Muys, B., Neirynck, J., Norgrove, L., Novo, M., Nuutinen, V., Nuzzo, V., Mujeeb Rahman P95, Pansu, J., Paudel, S., Pérès, G., Pérez-Camacho, L., Piñeiro, R., Ponge, J.-F., Rashid, M.I., Rebollo, S., Rodeiro-Iglesias, J., Rodríguez, M.Á., Roth, A.M., Rousseau, G.X., Rozen, A., Sayad, E., van Schaik, L., Scharenbroch, B.C., Schirrmann, M., Schmidt, O., Schröder, B., Seeber, J., Shashkov, M.P., Singh, J., Smith, S.M., Steinwandter, M., Talavera, J.A., Trigo, D., Tsukamoto, J., de Valença, A.W., Vanek, S.J., Virto, I., Wackett, A.A., Warren, M.W., Wehr, N.H., Whalen, J.K., Wironen, M.B., Wolters, V., Zenkova, I.V., Zhang, W., Cameron, E.K., Eisenhauer, N., 2019. Global distribution of earthworm diversity. Science. 366, 480–485. https://doi.org/10.1126/science.aax4851

Poggio, L., de Sousa, L.M., Batjes, N.H., Heuvelink, G.B.M., Kempen, B., Riberio, E., Rossiter, D., 2021. SoilGrids 2.0: producing quality-assessed soil information for the globe. SOIL. 7(1), 217-240. DOI10.5194/soil-7-217-2021

Pulleman, M., Creamer, R., Hamer, U., Helder, J., Pelosi, C., Pérès, G., Rutgers, M., 2012. Soil biodiversity, biological indicators and soil ecosystem services—an overview of European approaches. Current Opinion in Environmental Sustainability. 4, 529–538. https://doi.org/10.1016/j.cosust.2012.10.009

Reba, M., Seto, K.C., 2020. A systematic review and assessment of algorithms to detect, characterize, and monitor urban land change. Remote Sensing of Environment. 242, 111739. DOI10.1016/j.rse.2020.111739

Richer-de-Forges., A.C., Arrouays, D., Bardy, M., Bispo, A., Lagacherie, P., Laroche, B., Lemercier, B., Sauter, J., Voltz, M., 2019b. Mapping of Soils and Land-Related Environmental attributes in France: analysis of end-users' needs. Sustainability. 11, 2940. doi:10.3390/su11102940.

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., 2014b. La cartographie des sols à moyennes échelles en France métropolitaine. Etude et Gestion des sols. 21, 25–36. [in French].

Richer-de-Forges, A.C., Carré, F., McBratney, A.B., Bouma, J., Arrouays, D., (eds)., 2019a. Global Soil Security. Towards more science-society interfaces. CRC Press, Taylor & Francis, London. 137 p. 19 chapters.

Robinson, D.A., Panagos, P., Borrelli, P., Jones, A., Montanarella, L., Tye, A., Obst, C.G., 2017. Soil natural capital in Europe; a framework for state and change assessment. Sci. Rep. 7 (1), 1-14. https://doi.org/10.1038/s41598-017-06819-3

Ronchi, S., Salata, S., Arcidiacono, A., Piroli, E., Montanarella, L., 2019. Policy instruments for soil protection among the EU member states: a comparative analysis. Land Use Policy. 82, 763-780. https://doi.org/10.1016/j.landusepol.2019.01.017

Rossiter, D.G., Bouma, J., 2018. A new look at soil phenoforms - Definition, identification, mapping. Geoderma. 314, 113-121. DOI10.1016/j.geoderma.2017.11.002

Rutgers, M., van Leeuwen, J.P., Vrebos, D., van Wijnen, H.J., Schouten, T., de Goede, R.G.M., 2019. Mapping Soil Biodiversity in Europe and the Netherlands. Soil Syst. 3, 39. https://doi.org/10.3390/soilsystems3020039

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, M.d.L., 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. https://doi.org/10.1126/science.1175084

Sanderman, J., Hengl, T., Fiske, G.J., 2017. Soil carbon debt of 12,000 years of human land use. PNAS. 114(36), 9575-9580. DOI10.1073/pnas.1706103114

Sartori, M., Philippidis, G., Ferrari, E., Borrelli, P., Lugato, E., Montanarella, L., Panagos, P., 2019. A linkage between the biophysical and the economic: assessing the global market impacts of soil erosion. Land Use Policy. 86, 299-312. https://doi.org/10.1016/j.landusepol.2019.05.014

Smith, G.R., Crowther, T.W., Eisenhauer, N., van den Hoogen, J., 2019. Building a global database of soil microbial biomass and function: a call for collaboration. Soil Organisms. 91(3), 139–142. https://doi.org/10.25674/SO91ISS3PP140

Soussana, J.-F., Lutfalla, S., Ehrhardt, F., Rosenstock, T., Lamanna, C., Havlík, P., Richards, M., Wollenberg, E., Chotte, J.-L., Torquebiau,E., Ciais, P., Smith, P., Lal, R., 2019. Matching policy and science: Rationale for the '4 per 1000 - soils for food security and climate' initiative. Soil and Tillage Research. 188, 3-15. https://doi.org/10.1016/j.still.2017.12.002

Stockmann, U., Padarian, J., McBratney, A.B., Minasny, B., de Brogniez, D., Montanarella, L., Hong, S. Y., Rawlins, B. G., Field, D. J., 2015. Global soil organic carbon assessment, Global Food Security. 6, 9–16. https://doi.org/10.1016/j.gfs.2015.07.001

Stoorvogel, J.J., Bakkenes, M., Temme, A.J.A.M., Batjes, N.H., ten Brink, B.J.E., 2017. S-World: A Global Soil Map for Environmental Modelling. Land Degradation & Development. 28(1), 22-33. DOI10.1002/ldr.2656

Stoorvogel, J.J., Mulder, V.L., 2021. A Comparison, Validation, and Evaluation of the S-world Global Soil Property Database. Land. 10, 544. https://doi.org/10.3390/land10050544

The European common policy, n.d. The European common policy at a glance [WWW Document]. URL https://ec.europa.eu/info/food-farming-fisheries/key-policies/common-agricultural-policy/cap-glance_en (accessed 7.28.21).

Tifafi, M., Guenet, B., Hatte, C., 2018. Large Differences in Global and Regional Total Soil Carbon Stock Estimates Based on SoilGrids, HWSD, and NCSCD: Intercomparison and Evaluation Based on Field

Data From USA, England, Wales, and France. Global Biogeochemical Cycles. 32, 42–56. https://doi.org/10.1002/2017GB005678

Tonitto, C., David, M.B., Drinkwater, L.E., 2006. Replacing bare fallows with cover crops in fertilizer-intensive cropping systems: A meta-analysis of crop yield and N dynamics. Agriculture, Ecosystems & Environment. 112, 58–72. https://doi.org/10.1016/j.agee.2005.07.003

UNCCD (United Nations Convention to Combat Desertification), 1994. Elaboration of an international convention to combat desertification in countries experiencing serious drought and/or desertification, particularly in Africa. Final text of the Convention. http://www.unccd.int/Lists/SiteDocumentLibrary/conventionText/conv-eng.pdf (last access, 07/30/2021)

UNFCCC, 1997. Kyoto Protocol to the United Nations Framework Convention on Climate Change adopted at COP3 in Kyoto, Japan, on 11 December 1997. %20http://unfccc.int/resource/docs/cop3/07a01.pdf Website: https://www.eea.europa.eu/data-and-maps/indicators/primary-energy-consumption-by-fuel/unfccc-1997-kyoto-protocol-to (last access 07/30/2021)

United Nations, 1992. Convention on Biological Diversity. https://www.cbd.int/doc/legal/cbd-en.pdf (last access 07/31/2021)

USDA RCA Interagency Working Group Members, 2011. RCA Appraisal - Soil and Water Resources Conservation Act. USDA RCA Interagency Working Group Members. https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/nra/rca/ (last access: 07/31/2021)

van den Hoogen, J., Geisen, S., Wall, D.H., Wardle, D.A., Traunspurger, W., de Goede, R.G.M., Adams, B.J., Ahmad, W., Ferris, H., Bardgett, R.D., Bonkowski, M., Campos-Herrera, R., Cares, J.E., Caruso, T., de Brito Caixeta, L., Chen, X., Costa, S.R., Creamer, R., da Cunha e Castro, J.M., Dam, M., Djigal, D., Escuer, M., Griffiths, B.S., Gutiérrez, C., Hohberg, K., Kalinkina, D., Kardol, P., Kergunteuil, A., Korthals, G., Krashevska, V., Kudrin, A.A., Li, Q., Liang, W., Magilton, M., Marais, M., Martín, J.A.R., Matveeva, E., Mayad, E.H., Mzough, E., Mulder, C., Mullin, P., Neilson, R., Nguyen, T.A.D., Nielsen, U.N., Okada, H., Rius, J.E.P., Pan, K., Peneva, V., Pellissier, L., da Silva, J.C.P., Pitteloud, C., Powers, T.O., Powers, K., Quist, C.W., Rasmann, S., Moreno, S.S., Scheu, S., Setälä, H., Sushchuk, A., Tiunov, A.V., Trap, J., Vestergård, M., Villenave, C., Waeyenberge, L., Wilschut, R.A., Wright, D.G., Keith, A.M., Yang, J., Schmidt, O., Bouharroud, R., Ferji, Z., van der Putten, W.H., Routh, D., Crowther, T.W., 2020. A global database of soil nematode abundance and functional group composition. Sci. Data. 7, 103. https://doi.org/10.1038/s41597-020-0437-3

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

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

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

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

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

Voltz, M., Arrouays, D., Bispo, A., Lagacherie, P., Laroche, B., Lemercier, B., Richer-de-Forges, A.C., Sauter, J., Schnebelen, N., 2020. Possible futures of soil mapping in France. Geoderma Regional. 23, e00334. https://doi.org/10.1016/j.geodrs.2020.e00334

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 (1), 19–30. https://doi.org/10.1111/j.1365-2389.1997.tb00181.x

Wadoux, A.M.J-C., Román-Dobarco, M., McBratney, A.B., 2021. Perspectives on data-driven soil research. European Journal of Soil Science. 72(4), 1675-1689. DOI10.1111/ejss.13071

Wadoux, A.M.J-C., McBratney, A.B., 2021. Hypotheses, machine learning and soil mapping. Geoderma. 383, 114725. DOI10.1016/j.geoderma.2020.114725

Wang, M., Xu, Q.C., Fan, Z.M., Sun, X.F., 2021. The Imprint of Built-Up Land Expansion on Cropland Distribution and Productivity in Shandong Province. Land. 10(6), 639. DOI10.3390/land10060639

White, R.E., Andrew, M., 2019. Orthodox Soil Science versus Alternative Philosophies: A Clash of Cultures in a Modern Context. Sustainability. 11(10), 2919. https://doi.org/10.3390/su11102919

Yaalon, D.H., 1996. Soil science in transition: soil awareness and soil care research strategies. Soil Science. 161, 3–8. https://doi.org/10.1097/00010694-199601000-00002

Zak, D.R., Holmes, W.E., White, D.C., Peacock, A.D., Tilman, D., 2003. Plant diversity, soil microbial communities, and ecosystem function: are there any links? Ecology. 84, 2042–2050. https://doi.org/10.1890/02-0433

Zwetsloot, M.J., Leeuwen, J., Hemerik, L., Martens, H., Simó Josa, I., Broek, M., Debeljak, M., Rutgers, M., Sandén, T., Wall, D.P., Jones, A., Creamer, R.E., 2021. Soil multifunctionality: Synergies and trade-offs across European climatic zones and land uses. Eur J Soil Sci. 72, 1640–1654. https://doi.org/10.1111/ejss.13051