Бюллетень Почвенного института им. В.В. Докучаева. 2018. Вып. 95.
Dokuchaev Soil Bulletin, 2018, 95

УДК 631.4

THE *GLOBALSOILMAP PROJECT*: PAST, PRESENT, FUTURE, AND NATIONAL EXAMPLES FROM FRANCE

© 2018 D. Arrouays[1], A. C. Richer-de-Forges[1], A. B. McBratney[2], A. E. Hartemink[3], B. Minasny[2], I. Savin[4,*], M. Grundy[5], J. G. B. Leenaars[6], L. Poggio[6], P. Roudier[7], Z. Libohova[8], N. J. McKenzie[5], H. van den Bosch[6], B. Kempen[6], V. L. Mulder[9], M. Lacoste[10], S. Chen[1, 11], N. P. A. Saby[1], M. P. Martin[1], M. Román Dobarco[1], I. Cousin[10], T. Loiseau[1], S. Lehmann[1], M. Caubet[1], B. Lemercier[11], C. Walter[11], E. Vaudour[12], C. Gomez[13], G. Martelet[14], P. Krasilnikov[15], P. Lagacherie [13]

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

[2]*University of Sydney, Sydney, Australia*

[3]*University of Wisconsin, Department of Soil Science, Madison, USA*

[4]*Dokutchaev Soil Science Institute, 119017 Moscow, Russia*

[5]*CSIRO, Australia*

[6]*ISRIC - World Soil Information, PO box 353, 6700 AJ, Wageningen, The Netherlands*

[7]*Landcare Research, Manaaki Whenua, New-Zealand*

[8]*US department of Agriculture, Natural Resources Conservation Services, Lincoln, Nebraska, USA*

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

[10]*URSOLS, INRA, 45075, Orléans, France*

[11]*UMR SAS, INRA-Agrocampus-Ouest, Rennes, Bretagne, France*

[12]*UMR ECOSYS, AgroParisTech, INRA, Université Paris-Saclay, 78850, Thiverval-Grignon, France*

[13]*INRA-IRD-Supagro, UMR Lisah, Montpellier, France*

[14]*BRGM, Direction des Géoressources, 45060 Orléans Cedex 2, France*

[15]*Lomonosov Moscow State University, Moscow 119991, Russia*

* *https://orcid.org/0000-0002-8739-5441, e-mail: savigory@gmail.com*

Received 10.11. 2018, *Revised* 15.11.2018, *Accepted* 15.11.2018

Soils have critical relevance to global issues, such as food and water security, climate regulation, sustainable energy, desertification and biodiversity protection. As a consequence, soil is becoming one of the top priorities for the global environmental policy agenda. Conventional soil maps suffer from large limitations, i.e. most of them are static and often obsolete, are often generated at coarse scale, and can be uneasy to handle. Digital Soil Mapping has been developed as a solution to generate high-resolution maps of soil properties over large areas. Two projects, *GlobalSoilMap* and SoilGrids, presently aim at delivering the first generation of global, high-resolution soil property fine grids. In this paper, we briefly describe the *GlobalSoilMap* history, its pre-sent status and present achievements, and illustrate some of these with (mainly) French examples. At given moment there is still an enormous potential for forthcoming research and for delivering products more helpful for end users. Key here is the continuous progress in available co-variates, in their spatial, spectral and temporal coverage and resolution through remote sensing products. All over the world, there is still a very large amount of point soil data still to be rescued and this effort should be pursued and encouraged. Statistically advances are expected by exploring and implementing new models. Especially relevant are spatial-temporal models and contemporary Artificial Intelligence for handling the complex big data. Advances should be made and research efforts are needed on estimating the uncertainties, and even on estimating uncertainties on uncertainties. Attempts to merge different model strategies and products (for instance deriving from different covariates, spatial extents, soil data sources, and models) should be made in order to get the most useful information from each of these predictions, and to identify how controlling factors may change depending on scales.

Key words: digital soil mapping, geostatistics

DOI: 10.19047/0136-1694-2018-95-3-23

INTRODUCTION

Soils have critical relevance to global issues, such as food and water security, climate regulation, sustainable energy, desertification and biodiversity protection (Montanarella et al., 2016). As a consequence, soil is becoming one of the top priorities for the global environmental policy agenda (Hartemink and McBratney, 2008; McBratney et al., 2014; Amundson et al., 2015). Although sustainable soil management is a global issue, appropriate actions from soil users (land use planners, farmers) require high-resolution data about soil properties. Conventional soil maps suffer from large limitations, i.e. most of them are static and often obsolete (Rossiter, 2018), are often generated at coarse scale, and can be uneasy to handle. Also, they are most often non quantitative, based upon very simplified level of soil classification, and most of them lack any quantitative estimates of soil properties. Digital Soil Mapping (DSM) (McBratney et al., 2003; Lagacherie et al., 2006; Arrouays et al., 2017a, Rossiter, 2018) has been developed as a solution to generate high-resolution maps of soil properties over large areas. Two projects, *GlobalSoilMap* (Arrouays et al., 2014b) and SoilGrids (Hengl et al., 2014, 2017), presently aim at delivering the first generation of global, high-resolution soil property fine grids. The former relies in a bottom-up approach (from country to globe), while the latter uses a top-down approach (a global model that predicts properties for every country). As acquiring new soil data is laborious and expensive, both projects promote the use of existing legacy and heritage soil survey data available across the world. These data are being rescued, compiled and processed into a common, consistent and harmonized dataset of relevant soil properties covering the planet's land surface (Arrouays et al., 2017b). The resulting data are then used for spatial prediction of soil attributes using ancillary spatial information.

The resulting maps are essential for scientific communities from climate and environmental modeling to decision making and sustainable resources management at a scale that is relevant to soil management. From a global policy point of view, these initiatives could bring a major contribution to the implementation of the priorities of the United Nations' Global Soil Partnership, Pillar 4, one objective of which is to deliver fine grids of soil properties all over the planet. The *GlobalSoilMap* initiative brings together some world scientific leaders involved in both projects. We believe that the full utilization potential of can only be realized by creating a strong link to a public policy framework to ensure meeting quality, reliability, continuity, coherence and usability requirements. In this paper, we briefly describe the *GlobalSoilMap* history, its present status and present achievements, and illustrate some of these with (mainly) French examples. We cite some other examples of achievements and finally discuss the future and prospects of this project, including the scientific issues still to be solved and the necessary collaboration between projects aiming at delivering similar products.

OBJECTIVES OF *GLOBALSOILMAP*

The *GlobalSoilMap* initiative aims at developing and transferring methods to improve the prediction accuracy of soil properties and their associated uncertainty, by using legacy soil data and ancillary spatial information. The objective of the *GlobalSoilMap* project is to provide a scientific framework to deliver fine grids of soil attributes as a consistent, spatially explicit and continuous database freely available for all. The fine grids of soil attributes will be delivered at high spatial resolution, thus applicable to both global and local applications. The specifications of the *GlobalSoilMap* products have been discussed collegially by a scientific consortium, and written into a detailed document based on peer-review. The specified product includes predicted values of selected key soil properties at 6 standard depth intervals (0–5, 5–15, 15–30, 30–60, 60–100 and 100–200 cm), at a global scale on a 3 arc-second support grid (approximately 90 × 90 m) along with their uncertainties. The key primary soil properties include the clay, silt and sand contents, coarse fragments, pH in water, soil organic carbon (**SOC**) content, effective cation exchange capacity (**ECEC**), soil depth to bedrock and effective root zone depth. Additional key properties, mainly derived using pedotransfer functions (PTF, see a review from, Minasny and Hartemink, 2011), include bulk density and plant-available water holding capacity. This minimal dataset may be supplemented by other soil attributes on an *ad-hoc* basis (e.g., P, N and S contents, electric conductivity, soil type, presence of diagnosis horizons, trace elements contents). Predictions are generated using state-of-the-art Digital Soil Mapping (**DSM**) techniques (McBratney et al., 2003; Grunwald et al., 2001; Minasny and McBratney, 2016; Arrouays et al., 2017a; Rossiter, 2018). The final *GlobalSoilMap* product aims to be outcome soil information product that can be updated iteratively, i.e. when new or additional soil profile data or environmental co-variates are available either at a country-based or a world-based scale, updated soil maps can be quickly produced thus continuously improving the accuracy of this collaborative product. Hereby, we support data science for informed policy making by providing up to date, high-resolution soil information for practical support of planning and environmental policy frameworks.

GLOBALSOILMAP BRIEF HISTORY

A brief history of the *GlobalSoilMap* initiative is summarized in table 1. The initial idea came from a meeting of the International Union of Soil Sciences (IUSS) DSM Working Group in Rio de Janeiro, Brazil, 2006. Further meetings and conferences led to the publication of the first version of the specifications in 2008. In continuation, a great impulse to the project was provided by a 18 M$ grant from the Bill&Melinda Gates foundation (mainly dedicated to actions to undertake in Africa), and by the publication of a highly cited seminal paper in *Science* (Sanchez et al., 2009). In 2012, some changes of governance were decided during a business meeting on the occasion of another IUSS DSM Working Group in Sydney, Australia. Later that same year, a dedicated *GlobalSoilMap* workshop on uncertainty assessment was held in Lincoln, USA. Indeed, there are many ways to assess uncertainty, and even uncertainty on uncertainty, and this workshop led to refining the ways of assessing uncertainties of predicted values and to define four tiers level for *GlobalSoilMap* products. These four tiers, and other refinements of the specifications, were discussed in detail in 2013 during the first *GlobalSoilMap* conference held in Orléans, France and then incorporated into the 2nd version of the specifications.

One of the most productive years was 2014; with the organization of a dedicated symposium and a business meeting during the IUSS World Congress of Soil Sciences (WCSS) in Jeju, Korea; the publication of the book of the first *GlobalSoilMap* conference (Arrouays et al., 2014a), and of a very detailed and highly cited paper (Arrouays et al., 2014b); and finally an invited keynote talk in a dedicated session and open discussion organized during the IUSS DSM WG conference in Nanjing, China. This year was also characterized by the beginning of countrywide releases of products (table 1). Indeed, from 2013 to 2018, the number of national or sub-national products progressively increased, including e.g. products from Denmark, Nigeria, Scotland, continental USA, Chile and France. Significant progress (but not yet complete products) were also obtained for example in Madagascar (Ramohiarivo et al., 2017); Mexico (Guerrero et al., 2014), Canada (Mansuy et al., 2104), Korea (Young Hong, 2013), Indonesia (Sulaeman et al., 2013), and in numerous smaller test areas of the world (Lelyk et al., 2014; Vaysse and Lagacherie, 2015; Santra et al., 2017; Chagas et al., 2017; Chartin et al., 2017).

Table 1. Pivotal Moments for *GlobalSoilMap* and Soil Science from 2006 to now

Date	Events	Location	Products	Papers	Books
2006	2nd IUSS Working Group for Digital Soil Mapping Conference	Rio de Janeiro, Brazil	Initial idea		
2006	18th Working Group for Digital Soil Mapping business meeting	Philadelphia, USA	Work on specifications		
2006	Planning meeting and naming of the project GlobalSoilMap.net	New York, USA	Presentations, formation of nodes		
2008	3rd IUSS Working Group for Digital Soil Mapping	Logan, USA	1st version of the specifications	1st version of the specifications	
2009	Bill & Melinda Gates' foundation grant (18M$). Most of which for Africa	New-York USA	Launch, financial support		
2009	launch of the Africa Soil Information System	Nairobi, Kenya	Official launch for Africa		
2009	Publication of the initial paper		Seminal paper	Sanchez et al., 2009	
2012	5th IUSS Working Group for Digital Soil Mapping Conference	Sydney, Australia	Business meeting, changes of governance		
2012	Uncertainty workshop	Lincoln, USA	Refinement of uncertainties estimates according to 4 tiers		

Date	Events	Location	Products	Papers	Books
2012	First Africa-wide legacy soil dataset released	Wageningen	Dataset & report (Leenaars, 2012)		
2013	First Africa-wide soilgrids released at 1km	Wageningen	Dataset (ISRIC, 2013)		
2013	First *GlobalSoilMap* Conference	Orléans, France	Discussions and presentations	2nd version of the specifications	
2014	Publication of the book from the Orléans conference	Orléans, France	Book		Arrouays et al., 2014a
2014	WCSS symposium on *GlobalSoilMap* + business meeting	Jeju, Korea	Discussions and presentations	3rd version of the specifications	
2014	Publication of a second high level paper		Full paper	Arrouays et al., 2014b	
2014	IUSS Working Group for Digital Mapping Conference	Nanjing, China	Keynote paper, and dedicated session on *GlobalSoilMap*		
2014-2015	Release of complete products (USA, Australia)	USA, Australia	Data bases and papers	Grundy et al., 2015, Viscarra Rossel et al., 2015	Nauman et al., 2012
2015	*GlobalSoilMap* business meeting	Ottawa, Canada	Willingness of new countries to join the initiative		
2013 to 2018	Publications of numerous scientific papers	Mainy journals	Papers	Padarian et al. 2017, Akpa et al., 2014, Adhikari et al.,	

Date	Events	Location	Products	Papers	Books
				2013, Poggio,Gimona. 2014, 2017, Mulder et al 2016	
2016	*GlobalSoilMap* business meeting during the IUSS Working Group Conference	Aarhus, Denmark	Decision to propose a dedicated WG to the IUSS, under de commission 1.5 pedometrics		
2016	Intercongress IUSS meeting, proposal presented by D. Arrouays	Rio de Janeiro, Brazil	the IUSS endorses the *GlobalSoilMap* WG	IUSS report	
2016	*GlobalSoilMap* receives the honorable mention awarded to data rescue effort	Vienna, EGU	Certificate delivered to D. Arrouays and J. Leenaars on behalf of all contributors to C		
2017	Publication of a review paper on soil data rescuing		Review paper	Arrouays et al., 2017b	
2017	Global Soil Parnership (GSP-FAO) Plenary Assembly	FAO, Rome, Italy			
2017	2nd *GlobalSoilMap* Conference	Moscow, Russian Federation	Keynotes, presentations, business meetings		

Date	Events	Location	Products	Papers	Books
2017	Publication of the book from the 2nd *GlobalsoilMap* Conference	CRCS Press, Taylor& Francis, London	Books		Arrouays at al., 2018
2018	Various keynotes on *GlobalSoilMap*	Bahrein, Philippines, Thailand, India, Belgium, France, Korea, Brazil	Keynotes presentations	Mainly done by Arrouays et al., and Lagacherie et al.	
2018	Joint business meeting of the Digital Soil Mapping and *GlobalSoilMap* Working Groups Rio de Janeiro, Brazil	Rio de Janeiro, Brazil	Proposal about governance, discussion with GSP-FAO, JRC, and ISRIC		
2018	Proposal for better integration FAO GSP and IUSS *GlobalSoilMap* IUSS Working Group	To be discussed in the Tcheck Republic and in Roma	Proposal of a draft agreement	Drafted and sent by D. Arrouays	
2019 (forthcoming)	Joint Conference between the DigitalSoilMapping and *GlobalSoilMap* Working Groups, March 2019	Puerto Varas, Chile	Book and/or papers. Re-organization of the governance	To be written	To be written

In parallel, similar global products were released at the world level (Hengl et al., 2014; 2017), and at continental level (ISRIC, 2013; Hengl et al., 2015; Toth et al., 2013; Gardi, Yigini, 2012; Ballabio et al., 2016; Leenaars et al., 2018). The product line for sub-Saharan Africa is complete in terms of targeted soil properties. Although, these were often delivering different attributes or layer depths and a bit coarser resolution (1 km to 250 m). In 2015, the complete product for Australia was released (Grundy et al., 2015; Viscarra Rossel et al., 2015) and a new business meeting was organized in Ottawa, Canada. This business meeting showed the willingness of some new countries to join the project.

The next *GlobalSoilMap* business meeting took place during the IUSS DSM Working Group Conference in Aarhus, Denmark, 2016. During this meeting, it was decided that a core group (D. Arrouays, P. Roudier, A. McBratney, Z. Libohova) would prepare a motion to propose the creation of a new IUSS WG 'GlobalSoilMap', under Division 1 and Commission 1.5 of the IUSS. D. Arrouays defended this motion during the IUSS inter-congress council meeting in Rio de Janeiro (Brazil, November, 2016) and it was unanimously accepted and endorsed by the IUSS Council. In 2016, the *GlobalSoilMap* initiative officially received the 'honorable mention' for the international data rescue award in geosciences delivered by the Interdisciplinary Earth Data Alliance (IEDA) and Elsevier. This award was followed by an international review publication about soil data rescuing efforts in the world, involving 89 co-authors from all continents (Arrouays et al., 2017b).

In July 2017, the *GlobalSoilMap* international conference was organized by the V.V. Dokuchaev Soil Science Institute (Moscow, Russian Federation) and the Agrarian Technological Institute of RUDN University (Moscow, Russian Federation) under the umbrella of the IUSS, and the Soil Science Society named after V.V. Dokuchaev, with financial support from the Russian Science Foundation (Grant N°15-16-30007). This conference was very well organized and successful and stimulated the development of the project and the delivery of products in all parts of the world, especially in the former USSR republics where scientific activity in DSM is rapidly emerging. During this conference, the IUSS *GlobalSoilMap* WG was officially launched and had its first formal business meeting. The second book on *GlobalSoilMap* 'GlobalSoilMap.

Digital Soil Mapping from Country to Globe' was rapidly published (Arrouays et al., 2018).

During 2018, *GlobalSoilMap* was presented at various invited conferences around the world (e.g. Bahrein, Philippines, Thailand, India, Belgium, France, Korea, Brazil). A first joint business meeting of the DSM and *GlobalSoilMap* IUSS Working Groups was held during the WCSS in Rio de Janeiro, Brazil. During this business meeting, we decided to organize a next joint DSM and *GlobalsoilMap* WG conference in Chile, in March 2019. We had also sound discussions about the need to consolidate relations between the IUSS *GlobalSoilMap* WG and more policy-related initiatives that have a common aim, including the activities carried out under the Pillar 4 of the Global Soil Partnership (GSP) that was created under the auspices of the Food and Agricultural Organization (FAO) of the United Nations. In 2018, a large number of countries aggregated their 90-m *GlobalSoilMap* SOC predictions to a 1 km grid in order to give a country bottom-up input to the Global Soil Organic Carbon map initiative of the GSP.

EXAMPLES FROM FRANCE

Here, we briefly describe the development and delivery of *GlobalSoilMap* products for mainland France and in some specific French regions.

The years 2013 and 2014 were mainly dedicated to rescuing and harmonizing all soil point data available for the country, and to gathering and resampling all the co-variates that were meaningful and exhaustively available over the territory to the 90-m resolution needed for the final products. Then, the soil profile properties were harmonized according to the *GlobalSoilMap* specifications (e.g., by using spline functions, Bishop et al., 1999)), and various prediction models were evaluated. The first available products were SOC (Mulder el al., 2016a) and total soil depth (Lacoste et al., 2016). A much more complete set of 'primary' data was then produced leading to a 2nd version of *GlobalSoilMap* France (Mulder et al., 2016b). We also assessed how the relief (and mainly the slope) could affect the assessment of stocks on a regular square grid (Chen, Arrouays, 2018). As many secondary data (e.g., bulk density, available water capacity) had very scarce *in situ* georeferenced measurements, we then focused on developing pedo-transfer functions to predict them using more easily available data (e.g., for bulk density, Chen et al., 2018a; for available water capacity, Román Dobarco et al., 2019) We also used the *GlobalSoilMap* products to derive new products (e.g., Chen et al, 2018b; Román Dobarco et al. submitted) which are more directly usable by end users. We are now finalizing the AWC and BD products, and we are beginning to test new approaches for prediction of censored soil properties such e.g. soil depth.

At more regional or even local scales, we tested if the use of other methods could also be used to predict other soil attributes, such as, for instance, the presence of diagnosis horizons (Richer-de-Forges et al., 2017). The use of DSMART (Odgers et al., 2014) as a tool for disaggregating/downscaling soil maps was tested in Brittany (Vincent et al., 2016), and new methods, such as Quantile Random Forest (QRF) were tested to use point data for *GlobalSoilMap* products in the south of France (Vaysse and Lagacherie, 2017). In the western Paris croplands, a bootstrap resampling procedure provided estimations for the uncertainty regionally and for each sample location, using a criterion of pointwise RMSE (Zaouche et al. 2017).We also explored the potential of new airborne gamma-ray measurements in some regions, and the potential of a large range of spatial and spectral resolutions of Visible and Near Infrared (400-2500 nm) imagery data (Vaudour et al., 2016; Gomez et al., 2012, 2018). Finally, we are also convinced that extending the list of *GlobalSoilMap* attributes will be a future necessity, and thus we have been exploring the possibility to predict new ones (e.g. soil type, phosphorus (Delmas et al., 2015), soil contaminants (Villanneau et al., 2013; Orton et al., 2013; Marchant et al., 2017), and inorganic carbon (Marchant et al., 2015)).

The French teams that are active in producing DSM methods have been grouped since 2016 into a federative project (CES Theia “Digital Soil mapping”, https://www.sol-theia.org) for producing methodological advances on critical aspects of DSM (e.g. the use remote sensing data in DSM, calibration and validation procedures), promoting and diffusing DSM approaches and, in the near future, accompanying the users of GSM products.

FUTURE AND PROSPECTS

In this final section, we recap the main prospects we see for the development of *GlobalSoilMap* products.

From a 'technical and scientific' point of view:

– There is still an enormous potential for forthcoming research and for delivering products more helpful for end users. Key here is the continuous progress in available co-variates, in their spatial, spectral and temporal coverage and resolution through remote sensing products.

– All over the world, there is still a very large amount of point soil data still to be rescued and this effort should be pursued and encouraged.

– Statistically advances are expected by exploring and implementing new models. Especially relevant are spatial-temporal models and contemporary Artificial Intelligence for handling the complex big data.

– Advances should be made and research efforts are needed on estimating the uncertainties, and even on estimating uncertainties on uncertainties (Lagacherie et al., 2019).

– Attempts to merge different model strategies and products (for instance deriving from different covariates, spatial extents, soil data sources, and models) should be made in order to get the most useful information from each of these predictions, and to identify how controlling factors may change depending on scales (Román Dobarco et al., 2017, 2019; Caubet et al., 2019).

From a 'policy and scientific' point of view:

We are now in the situation where there is a global consensus about the specifications for gridded soil information products. We have a very advanced science and technology. The technology to support the development of high resolution grids, such as IT solutions to deal with large datasets and to support fast calculation, is quickly increasing. *GlobalSoilMap* is now institutionalized as the IUSS WG on *GlobalSoilMap* supporting considerable progress on DSM methodology and on improving the specifications. At the same time, the Global Soil Partnership which has been endorsed by the FAO member countries, provides an efficient policy mechanism to engage countries to deliver products. We believe that the full utilization potential can only be realized by creating a strong link to a public policy framework to ensure meeting quality, reliability, continuity, coherence and usability requirements. Hereby, we can support data science for informed policy making by providing up to date, high-resolution soil information for practical support of planning and environmental policy frameworks from the national to global scale. The IUSS *GlobalSoilMap* Working Group, and the Global Soil Partnership Pillar 4 should collaborate intimately for improving the specifications and make scientific advances, but also for capacity development for the less advanced countries.

This provides a unique opportunity to deliver sound and standardized national and global soil information products We should not miss this unique opportunity; it would be a terrible error for the future of our soils and for the world safety.

ACKNOWLEDGMENTS

We would like to thank the IUSS Council for endorsing the *GlobalSoilMap* WG and to thank the Global Soil Partnership plenary assembly to have endorsed the *GlobalSoilMap* specifications for delivering fine grids if soil properties. The *GlobalSoilMap* activities of the INRA InfoSol Unit are partly funded by the Environment & Agronomy department of the National Institute for Agronomic Research (INRA). Testing the added value of remote sensing data is partly worked in the CES Theia Digital Soil mapping project funded by the French national center of space studies (CNES 160102 agreement). Most of the French point soil data has been collected or rescued thanks to funding from national ‘Groupement d’Intérêt Scientifique Sol’ involving the French Ministry of Ecology, the French Ministry of Agriculture, the French Environment and Energy Management Agency (ADEME), the French Institute for Research and Development (IRD), the Institute for National geographic and Forest Information (IGN) and the INRA. In most cases, these national funding were complemented by French Regions or more local agencies. We thank all the people involved in sampling the sites and populating the database. Songchao Chen received the support of China Scholarship Council for three years’ Ph.D. study in INRA and Agrocampus Ouest (under grant agreement no. 201606320211). We also thank the Russian Science Foundation (Grant N°15-16-30007) for his support to the *GlobalSoilMap* Moscow’s conference.

REFERENCES

1. Adhikari K., Kheir R.B., Greve M.B., Bocher P.K., Malone B.P., Minasny B., A. McBratney, Greve M.H. High-Resolution 3-D Mapping of Soil Texture in Denmark, *Soil Sci. Soc. Am. J.*, 2013, V. 77, No. 3, pp. 860–876
2. Akpa S.I.C., Odeh I.O.A., Bishop T.F.A., Hartemink A.E. Digital soil Mapping of soil particle-size fractions in Nigeria, *SSSAJ*, 2014, V. 78, No. 6, pp. 1953-1966.
3. Amundson R., Berhe A.A., Hopmans J.W., Olson C., Sztein A.E., Sparks D.L. Soil and human security in the 21st century, *Science*, 2015, 348(6235).
4. Arrouays D., McKenzie N.J., Hempel J.W., Richer-de-Forges A.C., McBratney A.B. (eds). *GlobalSoilMap: Basis of the global spatial soil information system.* 1st ed. CRC Press Taylor & Francis Group, 2014a, 478 p.
5. 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 Md.L., Minasny B., Montanarella L., Odeh I.O.A., Sanchez P.A., Thompson J.A., Zhang G.-L. GlobalSoilMap: towards a fine-resolution global grid of soil properties, *Advances in Agronomy*, 2014b, V. 125, No. 93, pp. 134.
6. Arrouays D., Lagacherie P., Hartemink A. Digital soil mapping across the globe, *Geoderma Regional*, 2017a, V. 9, pp. 1-4.
7. Arrouays D., Leenaars J., Richer-de-Forges A.C., Adhikari K., Ballabio C., Greve M., Grundy M., Guerrero E., Hempel J., Hengl T., Heuvelink G., Batjes N., Carvalho E., Hartemink A., Hewitt A., Suk-Young Hong, Krasilnikov P., Lagacherie P., Lelyk G., Libohova Z., Lilly A., McBratney A., Mckenzie N., 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., Smith S., Sulaeman Y., Vintila R., Viscarra Rossel R., Wilson P., Gan-Lin Zhang, Swerts M., van Oorts K., Karklins A., Liu Feng, Navarro A.R.I., 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., Alavipanah S.K., 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. Soil legacy data rescue via GlobalSoilMap and other international and national initiatives, *GeoRes J.*, 2017b, V. 14, pp. 1-19.
8. Arrouays D., Savin I., Leenaars J.G.B., McBratney A.B. *GlobalSoilMap. Digital Soil Mapping from Country to Globe*, 1st ed. CRC Press Taylor & Francis Group, 2018, 173 p.

9. Ballabio C., Panagos P., Montanarella L. Mapping topsoil physical properties at European scale using the LUCAS database, *Geoderma*, 2016, V. 261, pp. 110-123.
10. Bishop T.F.A., McBratney A.B., Laslett G.M. Modelling soil attribute depth functions with equal-area quadratic smoothing splines, *Geoderma*, 1999, V. 91, pp. 27-45.
11. Caubet M., Román Dobarco M., Arrouays D., Minasny B., Saby N. Merging country, continental and global predictions of soil texture: Lessons from ensemble modelling in France, *Geoderma*, 2019, V. 337, pp. 99-110.
12. Chagas Cd.S., Saraiva H., Koenow Pinheiro K., de Carvalho Junior W., dos Anjos, L.H.C., Bhering, S.B. Data mining methods applied to map soil units on tropical hillslopes in Rio de Janeiro, Brazil, *Geoderma Regional*, 2017, V. 9, pp. 47-55.
13. Chartin C., Stevens A., Goidts E., Krüger I, Carnol M., van Wesemael B. Mapping Soil Organic Carbon stocks and estimating uncertainties at the regional scale following a legacy sampling strategy (Southern Belgium, Wallonia), *Geoderma Regional*, 2017, V. 9, pp. 73-86.
14. Chen S., Arrouays D. Soil carbon stocks are underestimated in mountainous regions, *Geoderma*, 2018. V. 320, pp. 146-148.
15. Chen S., Richer-de-Forges A.C., Saby N.P.A., Martin M.P., Walter C., Arrouays D. Building a pedotransfer function for soil bulk density on regional dataset and testing its validity over a larger area, *Geoderma*, 2018a, V. 312, pp. 52-63.
16. Chen S., Martin M., Saby N., Walter C., Angers D., Arrouays D. Fine resolution map of top- and subsoil carbon sequestration potential in France, *Science of the Total Environment*, 2018b, V. 630, pp. 389-400.
17. Delmas M., Saby N.P.A., Arrouays D., Dupas R., Lemercier B., Pellerin S., Gascuel-Odoux C. Explaining and mapping total phosphorous content in French topsoils, *Soil Use and Management*, 2015, V. 31(2), pp. 259-269.
18. Gardi C., Yigini Y. Continuous mapping of soil pH using digital soil mapping approach in Europe, *Eurasian J. Soil Sci.*, 2012, V. 1(2), pp. 64-68.
19. Gomez C., Lagacherie, P., Coulouma, G., Regional predictions of eight common soil properties and their spatial structures from hyperspectral Vis–NIR data, *Geoderma*, 2012, V. 189–190, pp. 176–185.
20. Gomez C., Adeline K., Bacha S., Driessen B., Gorretta N., Lagacherie P., Roger J.M., Briottet X. Sensitivity of clay content prediction to spectral configuration of VNIR/SWIR imaging data, from multispectral to hyperspectral scenarios. *Remote Sensing of Environment*, 2018, 204, pp. 18-30.
21. Grundy M.J., Viscarra Rossel R.A., Searle R.D., Wilson P.L., Chen C., Gregory L.J. Soil and Landscape Grid of Australia, *Soil Research*, 2015, V. 53, pp. 835–844.

22. Grunwald S., Thompson J.A., Boettinger J.L. Digital soil mapping and modeling at continental scales: Finding solutions for global issues, *Soil Sci. Soc. Am. J.*, 2011, V. 75, pp. 1201–1213.
23. Guerrero E., Pérez A. Arroyo C., Equihua J. Guevara M. Building a national framework for pedometric mapping: soil depth as an example for Mexico, 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*, Oxon: Taylor & Francis, CRC press, 2014, pp. 103-108.
24. Hartemink A.E., McBratney A.B. A soil science renaissance, *Geoderma*, 2008, V. 148, pp. 123–129.
25. Hengl T., Heuvelink G.B.M., Kempen B., Leenaars J.G.B., Walsh M.G., Shepherd K., Sila A., MacMillan R.A., Mendes de Jesus J., Tamene L., Tondoh J.E. Mapping soil properties of Africa at 250 m resolution: Random Forests significantly improve current predictions 2015, *PLoS ONE*, 2015. V. 10(6), pp. e0125814.
26. 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-Marschallinge, B., Guevara M.A., Vargas R., MacMillan R.A., Batjes N.H., Leenaars J.G.B., Ribeiro E., Wheeler I., Mantel S., Kempen B. SoilGrids250m: global gridded soil information based on Machine Learning, *PLoS ONE*, 2017, V. 12(2), pp. e0169748.
27. Hengl T, Mendes 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., Ruiperez Gonzalez M. SoilGrids1km -Global Soil Information Based on Automated Mapping, *PLoS ONE*, 2014, V. 9(8), pp. e105992.
28. ISRIC. Soil property maps of Africa at 1 km, 2013, 1 p.
29. Lacoste M., Mulder V.L., Richer-de-Forges A.C., Martin M.P., Arrouays D. Evaluating large-extent spatial modelling approaches: a case study for soil depth for France, *Geoderma Regional*, 2016, V. 7, pp. 137-152.
30. Lagacherie P., Arrouays D., Bourennane H., Gomez C., Martin M., Saby N. How far can the uncertainty on a Digital Soil Map be known?: a numerical experiment using pseudo values of clay content obtained from Vis-SWIR Hyperspectral imagery, *Geoderma*, 2019, available online 28 September 2018, in press.
31. Lagacherie P., McBratney A.B., Voltz M. Digital Soil Mapping: An Introductory Perspective, *Developments in Soil Science*, 2006, V. 31, 658 p.
32. Lelyk G.W., MacMillan R.A., Smith S., Daneshfar B. Spatial disaggregation of soil map polygons to estimate continuous soil property values at a resolution of 90 m for a pilot area in Manitoba, Canada. In: Arrouays D., McKenzie N.J., Hempel J.W., Richer de Forges A.C., McBratney A.B. (editors). GlobalSoilMap. *Basis of the global soil information system*, Taylor & Francis, CRC press, 2014, pp. 201-207.

33. Leenaars J.G.B. *Africa Soil Profiles Database, Version 1.0*. A compilation of georeferenced and standardized legacy soil profile data for Sub-Saharan Africa (with dataset). ISRIC Report 2012/03. Africa Soil Information Service (AfSIS) project. ISRIC - World Soil Information, Wageningen, 2012.
34. 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. Mapping rootable depth and root zone plant-available water holding capacity of the soil of sub-Saharan Africa, *Geoderma*, 2018, V. 324, pp.18-36.
35. Mansuy N., Thiffault E., Paré D., Bernier P., Guindon L., Villemaire P., Poirier V., Beaudoin A. Digital mapping of soil properties in Canadian managed forests at 250 m of resolution using the k-nearest neighbor method, *Geoderma*, 2014, V. 235–236, pp. 59-73.
36. Marchant B.P., Saby N.P.A., Arrouays D. A survey of topsoil arsenic and mercury concentrations across France, *Chemosphere*, 2017, V. 181, pp. 635-644.
37. Marchant B.P., Villanneau E.J. Saby N.P.A., Arrouays D., Rawlins B.G. Quantifying and mapping topsoil inorganic carbon concentrations and stocks: approaches tested in France, *Soil Use and Management*, 2015, V. 31(1), pp. 29-38.
38. Martelet G., Drufin S., Tourlière B., Saby N.P.A., Perrin J., DeParis J., Prognon J.F., Jolivet C., Ratié C., Arrouays D. Regional regolith parameters prediction using the proxy of airborne gamma ray spectrometry, *Vadose Zone Journal*, 2013, V.12(4), pp. 25-39.
39. Martin M.P., Orton T.G., Lacarce E., Meersmans J., Saby N.P.A., Paroissien J.B., Jolivet C., Boulonne L., Arrouays D. Evaluation of modelling approaches for predicting the spatial distribution of soil organic carbon stocks at the national scale, *Geoderma*, 2014, V. 223, pp. 97-107.
40. McBratney A.B., Field D.J., Koch A. The dimensions of soil security, *Geoderma*, 2014, V. 213, pp.203–213.
41. McBratney A.B., Mendonça Santos M.L., Minasny B. On digital soil mapping, *Geoderma*, 2003, V. 117(1-2), pp. 3–52.
42. Minasny B., Hartemink A.E. Predicting soil properties in the tropics, *Earth-Science Reviews*, 2011, V. 106, No. 1–2, pp. 52-62.
43. Minasny B., McBratney A.B. Digital soil mapping: A brief history and some lessons, *Geoderma*, 2016, V. 264, Part B, pp. 301-311.
44. 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.L., Taboada M., Espinosa-Victoria D., AlShankiti A., AlaviPanah S.K., Elsheikh E.A.E., Hempel J., Camps Arbestain M., Nachtergaele F., Vargas R.. World's soils are under threat, *Soil*, 2016, No. 2, pp. 79-82.

45. Mulder VL, Lacoste M, Richer de Forges AC, Martin MP, Arrouays D. National versus global modelling the 3D distribution of soil organic carbon in mainland France, *Geoderma*, 2016a, V. 263, pp.13-34.
46. Mulder V.L., Lacoste M., Richer de Forges A.C., Arrouays D. GlobalSoilMap France: High-resolution spatial modelling the soils of France up to two meter depth, *Sci. Tot. Env*, 2016b, V. 573, pp. 1352-1369.
47. Nauman T.W., Thompson J.A., Odgers N.P., Libohova Z. Fuzzy disaggregation of conventional soil maps using database knowledge extraction to produce soil property maps, In: *Digital Soil Assessments and Beyond: 5th Global Workshop on Digital Soil Mapping*. CRC Press/Balkema, 2012, pp. 203-208.
48. Odgers N.P., McBratney A.B., Minasny B., Sun W., Clifford D. DSMART: An algorithm to spatially disaggregate soil map units. *In: GlobalSoilMap: basis of the global spatial soil information system. Arrouays, D; McKenzie, N; Hempel, J; Richer-de-Forges, AC; McBratney, A. (Eds).* CRC Press, Taylor & Francis, London, 2014, p. 261-266.
49. Orton T.G., Saby N.P.A., Arrouays D., Jolivet C.C., Villanneau E., Marchant B.P., Caria G., Barriuso E., Bispo A., Briand O. Spatial distribution of lindane concentrations in topsoil across France, *Sci. Tot. Env.*, 2013, V. 443, pp. 338-350.
50. Richer-de-Forges A.C., Saby N.P.A., Mulder V.L., Laroche B., Arrouays D. Probability mapping of iron pan presence in sandy podzols in South-West France, using digital soil mapping, *Geoderma Regional*, 2017, V. 9, pp. 39-46.
51. Román Dobarco M., Arrouays D., Lagacherie P., Ciampalini P., Saby N. Prediction of topsoil texture for Region Centre (France) applying model ensemble methods, *Geoderma*, 2017, V. 292, pp. 67-77.
52. Román Dobarco M., Cousin I., Le Bas C., Martin M.P., Pedotransfer functions for predicting available water capacity in French soils, their applicability domain and associated uncertainty, *Geoderma*, 2019, V. 336, pp. 81–95.
53. Rossiter D.G. Past, present & future of information technology in pedometrics, *Geoderma*, 2018, V. 324, pp. 131-137.
54. 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.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. Digital soil map of the world, *Science*, 2009, V.325(5941), pp. 680–681.
55. Santra P., Mahesh Kumar M., Panwar,N. 2017. Digital soil mapping of sand content in arid western India through geostatistical approaches, *Geoderma Regional*, 2017, V. 9, pp. 56-72.
56. Sulaeman Y, Minasny B., McBratney A.B., Sarwani M., and Sutandi A. Harmonizing legacy soil data for digital soil mapping in Indonesia, *Geoderma*, 2013, V. 192, pp. 77-85.
57. Toth G., Jones A., Montanarella L. The LUCAS topsoil database and derived information on the regional variability of cropland topsoil properties in the

European Union, *Environmental Monitoring and Assessment*, 2013, V. 185(9), pp.7409-7425.
58. Vaudour E., Gilliot J.M., Bel L., Lefevre J., Chehdi K. Regional prediction of soil organic carbon content over temperate croplands using visible near-infrared airborne hyperspectral imagery and synchronous field spectra, *International Journal of applied earth observation and geoinformation*, 2016, V. 49, pp. 24-38.
59. Vaysse K., Lagacherie P. Using quantile regression forest to estimate uncertainty of digital soil mapping products, *Geoderma*, 2017, V. 291, pp. 55-64.
60. Viscarra Rossel R., Chen C., Grundy M., Searle R., Clifford D., Campbell P. The Australian three-dimensional soil grid: Australia's contribution to the GlobalSoilMap project, *Soil Research*, 2015, V. 53, No. 8, pp. 845–64.
61. Villanneau E.J., Saby N.P.A., Orton T.G., Jolivet C.C., Boulonne L., Caria G., Barriuso E., Bispo A., Briand O., Arrouays D. First evidence of large-scale PAH trends in French soils, *Environmental Chemistry Letters*, 2013, V. 11(1), pp. 99-104.
62. Vincent S., Lemercier B., Berthier L., Walter C. Spatial disaggregation of complex Soil Map Units at the regional scale based on soil-landscape relationships, *Geoderma*, 2016, V. 311, pp. 130-142.
63. Young Hong S., Minasny B, Hwa Han K., Kim Y., Lee K. Predicting and mapping soil available water capacity in Korea, *Peer J.*, 2013, PubMed 23646290.
64. Zaouche M., Bel L., Vaudour E., Geostatistical mapping of topsoil organic carbon and uncertainty assessment in Western Paris croplands (France), *Geoderma Regional*, 2017, V. 10, pp. 126–137.

Ссылки для цитирования

Arrouays D., Richer-de-Forges A.C., McBratney A.B., Hartemink A.E., Minasny B., Savin I., Grundy M., Leenaars J.G.B., Poggio L., Roudier P., Libohova Z., McKenzie N.J., van den Bosch H., Kempen B., Mulder V.L., Lacoste M., Chen S., Saby N.PA., Martin M.P., Román Dobarco M., Cousin I., Loiseau T., Lehmann S., Caubet M., Lemercier B., Walter C., Vaudour E., Gomez C., Martelet G., Krasilnikov P, Lagacherie P The GlobalSoilMap project: past, present, future, and national examples from France // Бюл. Почв. ин-та им. В.В. Докучаева. 2018. Вып. 95. С. 3-22. doi: 10.19047/0136-1694-2018-95-3-22

For citation:

Arrouays D., Richer-de-Forges A.C., McBratney A.B., Hartemink A.E., Minasny B., Savin I., Grundy M., Leenaars J.G.B., Poggio L., Roudier P., Libohova Z., McKenzie N.J., van den Bosch H., Kempen B., Mulder V.L., Lacoste M., Chen S., Saby N.PA., Martin M.P., Román Dobarco M., Cousin I., Loiseau T., Lehmann S., Caubet M., Lemercier B., Walter C., Vaudour E., Gomez C., Martelet G., Krasilnikov P, Lagacherie P The GlobalSoilMap project: past, present, future, and national examples from France, Dokuchaev Soil Bulletin, 2018, V. 95, pp. 3-22. doi:10.19047/0136-1694-2018-95-3-22