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3D Printing: An Emerging Opportunity for Soil Science

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ABSTRACT

The soil, at the interface between geosphere, biosphere, and atmosphere, is a particularly challenging object to study. The ecological and environmental impacts of soil functioning encourage soil scientists to exploit new technologies to generate new data or develop new research protocols. Among these technologies, 3D printing is a promising technology for improving the understanding of soils. The general principle of 3D printing is to build parts by adding materials layer by layer following a three-dimensional solid model. The 3D printing technology makes it possible to produce almost any geometrically complex shape or feature in a wide range of materials. Its interest lies in its ability to produce customized objects easily and rapidly in an endlessly reproducible 3D-arrangement. A large number of techniques and materials are available, which differ in their principles, advantages, and shortcomings.

In this article, we present the main challenges and opportunities of using 3D printing in soil science. To this end, we present a review of the literature from 2000 to 2019 to identify and understand recent applications of 3D printing in this field. We first describe applications such

25 as the manufacturing of agricultural equipment and laboratory devices in soil science, the
26 development of new construction materials, or the geotechnical characterization of soil as a
27 construction base. However, none of these applications requires replication of the soil
28 functional properties as opposed to applications that would be dedicated to improving the
29 understanding of soil functioning. We detail here the challenges and opportunities of building
30 soil models that reproduce its physical, chemical, biological properties, and its dynamics in
31 contact with living organisms.

32 Despite the remarkable and rapid progress made in the development of 3D printing in recent
33 years, this technology is still underused in the field of soil science. In particular, very few
34 applications focus on the functioning of the soil itself as an ecological compartment. Indeed,
35 several technical limitations have still to be overcome. 3D printed objects must be
36 biocompatible, chemically and mechanically stable, and must be spatially resolved on the
37 microscale. Many efforts are being made by the 3D printing community to push these
38 boundaries. This paves the way for the wider use of 3D printing in soil science. In the near
39 future, the availability of additive manufactured soil models, with strict and controlled
40 composition and structure, will provide researchers with an irreplaceable opportunity to
41 conduct reproducible experiments and better understand soil functioning factors.

42 **KEYWORDS.** 3D Printing; Additive Manufacturing; Soil functions; Soil structure; Artificial
43 soil

44 1. INTRODUCTION

45 Soils are a key environmental compartment providing many products, which derive mainly
46 from their agricultural use, and other services useful to human well-being (Commission of the
47 European Communities, 2006). Different soil properties, such as their physical structure, their
48 composition in soil organic matter (SOM), minerals, plant and micro-organisms, and their

49 spatial arrangement, determine soil health. Healthy soils can deliver tangible economic and
50 environmental benefits to farmers, businesses, and human communities (FAO, 2015). They
51 have the capacity to respond to agricultural intervention and support for generations both the
52 optimal biomass production and the provision of other ecosystem services (Kibblewhite et al.,
53 2008).

54 Soil is a complex system in terms of geometry and materials, which leads to high spatial
55 variations of soil structure and composition from the microscopic scale to the field, regional,
56 and global extents. This spatial diversity and variability depend on land use, soil management,
57 agricultural practices, as well as soil types and climate. Soil diversity is a key factor
58 influencing ecological processes and soil functioning. Because of this high variability, it is
59 difficult to understand individual soil type functioning and to compare the functions and
60 services offered by different soils. To address these challenges, soil scientists need to reach
61 out to other scientific disciplines (Keesstra et al., 2016), looking for innovative approaches
62 and solutions (Hu and Jiang, 2017). In this sense, 3D printing is a promising tool in soil
63 science due to its capability to rapidly produce complex, endlessly replicable, and
64 customizable geometrical structures, in a wide range of controlled materials (Behm et al.,
65 2018).

66 Three-dimensional (3D) printing, also known as additive manufacturing, is defined as the
67 process of joining materials to make objects layer upon layer from 3D model data (Bikas et
68 al., 2016). At its beginning in the 1980s, the first applications were prototyping, but in the
69 following decades, the manufacturing technologies and materials transformed, and new fields
70 of application appeared (Leutenecker-Twelsiek et al., 2016). Today, a large number of
71 technologies have been developed for 3D printing, which differs in the way layers are
72 deposited to create parts, changing the operating principle and the used material.

73 3D printing is driving major innovations in many areas, including aeronautics, medicine
74 (Bartolo et al., 2012; Chia and Wu, 2015; Kang et al., 2016; Rengier et al., 2010),
75 manufacturing and engineering (Doubrovski et al., 2011; Leutenecker-Twelsiek et al., 2016;
76 Postiglione et al., 2015; Shahrubudin et al., 2019; Sossou et al., 2018; Yao et al., 2017; Zhang
77 et al., 2016), art (Séquin, 2015; Balletti et al., 2017; Mitterberger and Derme, 2019; Derme
78 and Mitterberger, 2020), education (Kostakis et al., 2015; Wood et al., 2017), building
79 (Ahmed et al., 2016; Duballet et al., 2017), food (Godoi et al., 2016; Sun et al., 2015;
80 Vancauwenberghe et al., 2017), and especially in customized production (Asadollahi-Yazdi et
81 al., 2016). Nevertheless, soil science is a recent field of application of 3D printing and further
82 development and application should impact the way researchers study soils within their
83 ecosystems (Hu and Jiang, 2017). The development of 3D-printed objects adapted to the soil
84 science field should facilitate, for example, the comparison of pedoclimatic conditions and
85 support research for the understanding of soil functioning.

86 This paper focuses on the past and future achievements associated with 3D printing
87 manufacturing use in soil science. First, we described the currently available 3D printing
88 techniques and performed a bibliometric study of the studies, which used any of these
89 techniques for soil-related purposes. Then, we identified the added value of 3D printing
90 technologies for the investigated processes and functions and the possible constraints they
91 generate. Finally, we explored the opportunities and challenges arising from the deployment
92 of 3D printing in soil research to evaluate to what extent it meets the needs of soil science
93 challenges and to encourage soil scientists to seize this new exciting and vast area of research.

94 2. OVERVIEW OF 3D PRINTING TECHNIQUES

95 Producing an object with 3D printing necessitates the use of a specific technology, applied to
96 a material or materials, using different energy sources. In the following sections, the

97 combination of a specific technology, material, and energy source will be referred to as 3D
98 printing « method ». Each method has its advantages and drawbacks in economic, technical,
99 and environmental terms (Asadollahi-Yazdi et al., 2018; Ford and Despeisse, 2016). Table 1
100 summarizes the different processes, technologies, and materials, as well as their
101 characteristics, strengths, and limitations.

102 2.1. PROCESSES AND TECHNOLOGIES

103 According to ASTM International standards, 3D printing technologies are classified into
104 seven process categories (Gao et al., 2015). The first category of processes, material
105 extrusion, is based on the construction of the object by material extrusion through a nozzle. It
106 comprises the use of melted plastics (fused deposition modeling - FDM) or gel-like materials
107 followed in general by a drying step (direct ink writing - DIW). In a second group, called
108 directed energy deposition, metals are melted using different high-energy sources, i.e. lasers
109 for Laser Engineered Net Shaping - LENS, or electron beams for Electron Beam Welding -
110 EBW technologies. In the third category of processes, called material jetting, droplets of a
111 liquid (photopolymer or wax) are deposited and then hardened with UV-light, in technologies
112 like polyjet or inkjet printing (MJM). In the fourth group, called powder bed fusion, the object
113 is built by sintering or melting powdered materials thanks to a high-energy source, such as a
114 laser, as in Selective Laser Sintering (SLS) and Selective Laser Melting (SLM) or an electron
115 beam, as in Electron Beam Melting (EBM). In the fifth category, VAT polymerization, the
116 solidification of a liquid material occurs through polymerization of plastic or resin using a
117 light source, for example, lasers in the case of stereolithography technology (SLA). In the
118 sixth group, binder jetting, the conformation of the object is achieved through binding with
119 chemicals in what is called indirect inkjet printing or 3DP technologies. In the last category of
120 processes, sheet lamination, the object is built by cutting and assembling solid materials
121 through compaction (laminated object manufacturing, LOM). Some of the aforementioned

122 technologies need a post-processing step, such as drying or polishing. The main
123 considerations for choosing the appropriate technology are, in general terms, speed, cost of
124 the printed prototype, as well as cost and spatial resolution range of the available materials
125 (Bikas et al., 2016).

126 In addition to the seven process categories described above, bioprinting appears a
127 supplementary group of 3D printing techniques based on the deposition of biomaterials (like
128 DIW, MJM, and SLA), either encapsulating cells or loaded with cells later on, at the
129 micrometer scale, to form subtle structures comparable to living tissues (Derakhshanfar et al.,
130 2018). It has recently been extensively developed in medical science for printing functional
131 solid organs according to the manufacturing-specific production capability.

132 2.2. MATERIALS

133 Each 3D printing technology can be implemented with a specific material, adapted to the
134 desired application (third column in Table 1). Different types of printable materials are
135 available: plastics - divided in thermally stable plastics (e.g. epoxy, polyesters, silicone-based
136 materials) and those modifiable by temperature (e.g. polyamide, polyethylene, polypropylene
137 or polylactic acid, PLA); silicon-based materials (clay, ceramics, glass, etc.); metals and
138 others, such as graphene-based and biomaterials (Thompson et al., 2016). This last group of
139 materials is gaining considerable attention due to the rising interest in a “bio-based society”
140 (Dai et al., 2019; Håkansson et al., 2016). Some applications (medicine, ecology, etc.) require
141 biocompatible materials, which is not the case for most existing materials in 3D printing.
142 Increasing concern with environmental issues associated with the use of fossil-based
143 resources can also impact the choice of more sustainable (Dai et al., 2019; Xu et al., 2018).
144 Biomaterials can be implemented with different technologies, such as direct ink writing,
145 inkjet, stereolithography, or laser-assisted bioprinting.

146 Many natural polymers (cellulose, lignin, pectin, alginates) can be used to build the
147 biocompatible supports that receive the living cells. Recent developments such as multi-
148 material printing using different hydrogels together and combining different printing
149 technologies are some of the most important technological advances that can help to develop
150 the applications of bioprinting in tissue engineering (Dai et al., 2019).

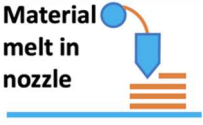

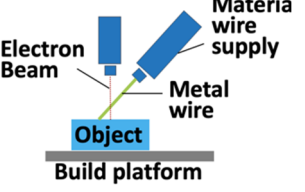
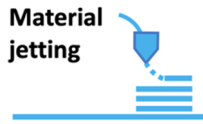
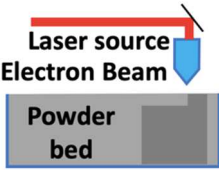
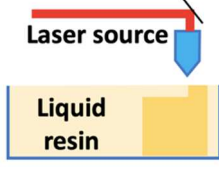
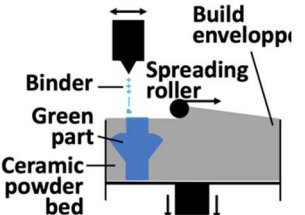
151 Besides bioprinting applications requiring biocompatible materials, cellulosic materials are
152 the most common bio-based materials in many other applications (Liu et al., 2019). Indeed,
153 cellulose and its derivatives are sustainable, almost inexhaustible, and biodegradable
154 polymeric raw materials that meet the rising demand for environmentally friendly products
155 (Dai et al., 2019; Klemm et al., 2005).

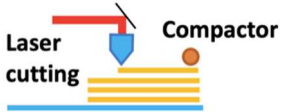
156 This group of materials includes cellulose ethers/esters, microcrystalline cellulose, nano
157 cellulose, etc. In soils, cellulose plays a significant role, as it is the principal component of
158 plants. They are a good alternative to plastic-derived materials since they provide most of the
159 mechanical properties required for materials used in 3D printing technologies (Li et al., 2018).

160 In various 3D printing methods, cellulose and its derivatives are used as substrates, building
161 blocks, viscosity modifiers, binders, excipients, plasticizers, matrices, fillers, and reinforcing
162 agents (Dai et al., 2019). There is also a big potential for cellulosic materials to be the
163 precursors for smart cost-effective materials, which could be assembled in a controlled way to
164 respond to external stimuli, such as temperature, light or other environmental factors, and thus
165 evolve – in what is called 4D printing (André, 2017; Mulakkal et al., 2016).

166

167 **Table 1.** Classification of 3D printing processes (Asadollahi-Yazdi et al., 2016; Bikas et al.,
 168 2016; Gao et al., 2015; Li et al., 2015; Thompson et al., 2016). Some illustrations are
 169 reprinted in part with permission from Bikas et al. Copyright © 2015, Springer Nature
 170 (Creative Commons CC BY).

Process category	Technology	Material type	Example materials	Strengths/ Downsides	Process schematic
Material Extrusion	Fused Deposition Modeling (FDM)	Thermoplastic polymers	Polyamide, Acrylonitrile Butadiene Styrene, Polylactic Acid	Inexpensive extrusion machine Multi-material printing Limited part resolution Poor surface finish	
	Direct Ink Writing (DIW)	Aqueous slurries and dispersions	Cellulose-based hydrogels	Ideal for biomaterials Maintaining structural integrity during drying	
Direct Energy Deposition	Electron Beam Welding (EBW) Laser Engineered Net Shaping (LENS)	Molten metal powder	Steel Titanium Alloys, Cobalt Chromium	Repair of damaged/ worn parts Functionality graded material printing Require post-processing machine	
Material Jetting	Polyjet/Inkjet Printing (MJM)	Thermally stable or unstable plastics	Photopolymers Wax	Multi-material printing High surface finish Low strength material	
Powder Bed Fusion	Selective Laser Sintering (SLS)	Polyamides / Polymers	Nylon, Polystyrene	High accuracy and details	
	Selective Laser Melting (SLM)	Atomized metal powder, Ceramic powder	Steel, Titanium alloys, Cobalt chromium, Alumina, Zirconia	Fully dense parts	
	Electron Beam Melting (EBM)			High specific strength and stiffness Powder handling and recycling Support and structure	
Vat Photopolymerization	Stereolithography (SLA)	Photopolymers Ceramics	Epoxies and acrylates, Alumina, Zirconia	High building speed Good resolution Over-curing scanned line shape High cost for supplies and materials	
Binder Jetting	Indirect Inkjet Printing (3DP)	Polymer powder Ceramics	Plaster Resin	Full-color object printing Wide material selection High porosities on finishing parts Require infiltration during post-processing	

Sheet Lamination	Laminated Object Manufacturing (LOM)	Thermoplastics polymers Wood Metals Ceramics	Polyamide, Acrylonitrile Butadiene Styrene, paper, metallic sheet, ceramic materials	High surface finish Low material, machine, and process cost De-cubing issues	
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171

172 3. METHODOLOGY: USING 3D PRINTING IN SOIL SCIENCE

173 To investigate the state of the art of 3D printing use for soil science research purposes, a
 174 survey was conducted on Scopus, using the keywords "3D Printing", "Additive
 175 Manufacturing" and "soil" or "agriculture" for the title and the abstract. Indeed, for some
 176 applications of 3D printing in soil science concerning agriculture, the keyword "soil" does
 177 appear neither in the title nor in the abstract. The final search equation was:

178 *TITLE-ABS (((3d OR 3-d OR (three-dimensional)) PRE/0 print*) OR (additive PRE/0*
 179 *manufactur*)) AND (soil OR agricult* OR agro*))*

180 The selected sources (original articles, review and books) were analyzed with VOSviewer
 181 (<https://www.vosviewer.com>), a software tool for constructing and visualizing bibliometric
 182 networks. These networks can focus on journals, researchers, or individual publications, and
 183 can be built based on citation, bibliographic coupling, co-citation, as well as co-authorship
 184 relations. Moreover, this tool offers text mining functionality useful to construct and visualize
 185 co-occurrence networks of important terms extracted from a scientific literature body.

186 3.1. SELECTION AND CLASSIFICATION OF REFERENCES

187 The objective of the bibliometric search was to identify the scientific questions in which 3D
 188 printing is used in soil science. Further analysis of the references was thus conducted to check
 189 whether the 3D printing was used for scientific purposes specific to soil science or as a more
 190 generic tool, not dedicated to this scientific field, but only distantly related to soil. Each of the
 191 papers was thus screened to define if the 3D printing approach specifically helped to answer a

192 scientific question linked to soil functioning or not. The references were then classified
193 according to the soil functions that they addressed using six soil functions, as defined by Lal
194 et al. 2018 (Lal et al., 2018).

195 1) Producing plant biomass, ensuring food, fodder, and renewable energy, which are the
196 basis of human and animal life.

197 2) Cycling and storing water, nutrients, contaminants, and carbon.

198 3) Protecting and maintaining soil biodiversity, which is the largest reservoir of
199 biodiversity on Earth.

200 4) Providing a basis for the development of technical infrastructures, such as houses,
201 industrial environments, roads, and other facilities.

202 5) Providing sources of mineral raw materials, such as clay, sand, gravel, and others.

203 6) Supporting natural and cultural heritage and, as such, constitutes a historical memory
204 of humans and its environment.

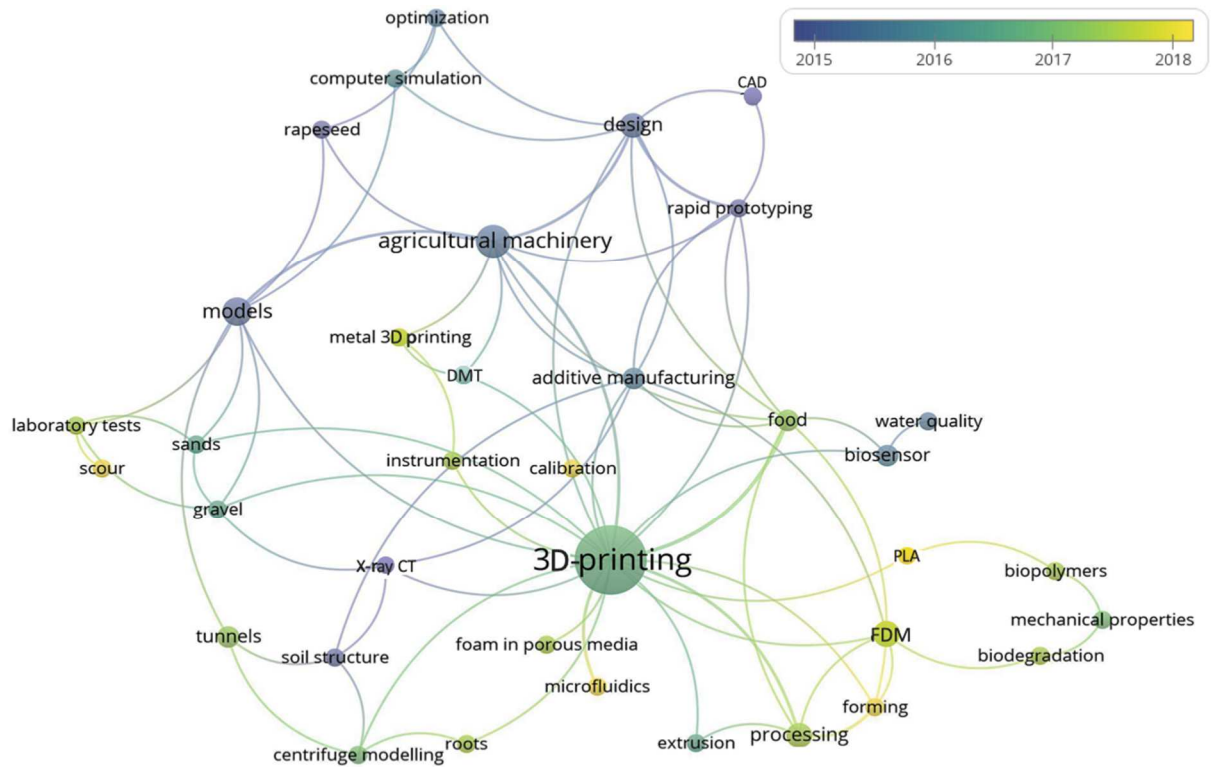
205 The first three ecological functions of soils are strongly related to the content and properties
206 of soil organic matter (SOM), and its relationships with inorganic components. These three
207 functions are strongly dependent on the chemical quality of the plant input and the functional
208 diversity of the decomposer communities, which are strong drivers of the kinetics of plant
209 litter (Dignac et al., 2017; Nguyen Tu et al., 2017; Schmidt et al., 2011). They are also
210 strongly dependent on the stability of the organo-mineral associations and their spatial
211 organization at the microscopic scale. The functions 4, 5, and 6 are technical, social, and
212 economic functions, which are important for humans, and their managed and natural
213 environments. They refer to a macroscopic consideration of soils. Soil functions 4 and 5 seal
214 and/or excavate the soil, which loses their ecological properties defined as the functions 1, 2
215 and 3 (soil capacity for biomass production, filtering, cycling and maintenance of
216 biodiversity).

217 4. RESULTS

218 4.1. OVERALL ANALYSIS

219 A total of 163 articles emerged from the literature survey conducted in July 2019 over the
220 2000–2019 publication period. These references were analyzed to create a bibliometric
221 network based on author keywords, keeping only those that appeared at least twice, as it can
222 be observed in Figure 1. A total of 36 keywords were considered. In this figure, the size of
223 each circle representing a keyword is proportional to the number of articles in which the
224 keyword appears. Additionally, the temporal evolution of the occurrence of keywords is
225 represented by a color scale (from dark blue for 2000 to yellow for 2019).

226 Unsurprisingly, being a search keyword of the database search equation, “3D printing” and
227 “Additive Manufacturing” appeared as the most cited keywords (32 and 3 occurrences,
228 respectively). The next most-cited keywords are “agricultural machinery” (7 occurrences),
229 “models” (5 occurrences), “design” (4 occurrences), “food” (3 occurrences), “processing” (3
230 occurrences) and “rapid prototyping” (3 occurrences). This means that in the past twenty
231 years agricultural machinery was the most frequent application of 3D printing in the domains
232 explored by our bibliometric equation. The circles’ color shows that the initial predominance
233 (in the 2010s) of applications of 3D printing technologies for the manufacture of agricultural
234 equipment has recently shifted to research topics such as biopolymers, biodegradation (of
235 printed materials) and microfluidics (i.e. fluid circulation in the soil matrix at the microscale).



236

237 **Figure 1.** Visualization of keywords by average publication year. The size of each circle is
 238 proportional to the number of articles in which the keyword appears, and the color of the
 239 circle refers to the average year of publication (from purple for 2015 to yellow for 2018).
 240 CAD: Computer Aided Design; FDM: Fused Deposition Modeling; PLA: Polylactic acid; X-
 241 ray CT: X-ray computed tomography; DMT: Direct Metal Tooling

242 4.2. ANALYSIS OF A SELECTION OF ARTICLES ADDRESSING SPECIFIC SOIL
 243 FUNCTIONS

244 Since soil functions are relevant entries for interdisciplinary studies on ecosystem services
 245 (Keesstra et al., 2016), each article was associated with the soil function it addresses. The
 246 articles that did not relate to any soil function were discarded. In the end, we identified 41
 247 articles, which are related to one or more soil functions. The selected articles are presented in
 248 Table 2, showing the 3D printing technologies and materials they implement (as described in
 249 Table 1) and the soil function they address.

250 It is important to note that some of the articles (5%) did not or only partially describe the
 251 implemented 3D printing method (technology and material), showing that the researchers
 252 used the printers and the materials available in their laboratories without analyzing or
 253 identifying the most appropriate 3D printing method for their purposes.

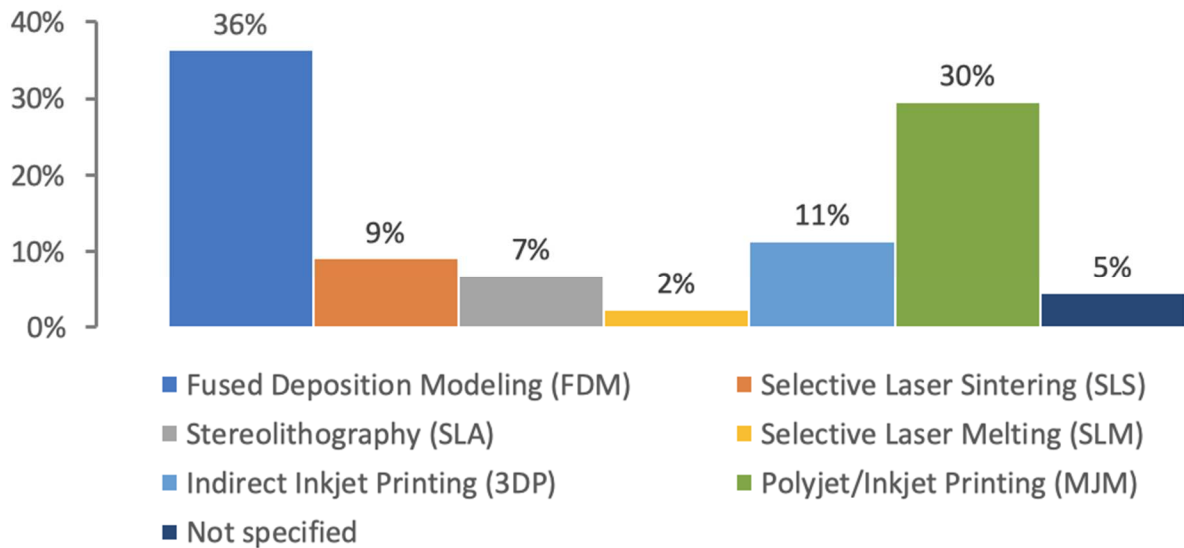
254 **Table 2.** Bibliometric survey selection of 41 articles that address a soil function. The articles
 255 are classified in alphabetical order by the first author and associated with the 3D printing
 256 technology and material they use, as well as the concerned soil function (1: biomass
 257 production, 2: cycling water and nutrients, 3: biodiversity, 4: basis for infrastructure, 5: source
 258 of raw material, and 6: natural and cultural heritage).

Authors	3D printing technology	Materials ¹	Soil functions
Bacher et al. (2015)	SLS PolyJet (MJM) FDM SLA	Alumide (M) and Polyamide (P) Resin (P) Acrylonitrile Butadiene Styrene (P) Prime Gray resin (P)	2
Bagrov et al. (2017)	SLS	Silica glass nanopowder (S)	5
Borecki et al. (2016)	FDM	Not mentioned (N)	2
Ceccanti et al. (2010)	Binder Jetting (3DP)	Glass-rich basaltic ashes (S)	5
Cesaretti et al. (2014)	Binder Jetting (3DP)	Metallic oxide (M)	5
Chang et al. (2016)	FDM	Acrylonitrile Butadiene Styrene (P)	1
Chow et al. (2017)	SLS	Martian soil simulant (O)	5
Cocovi-Solberg et al. (2019)	SLA	Photopolymer clear resin (P)	2
Dal Ferro and Morari (2015)	MJM	Visijet Crystal EX 200 (P)	2
Farooqui and Kishk (2018)	FDM	Acrylonitrile Butadiene Styrene (P)	2
Gao et al. (2018)	FDM	Acrylonitrile Butadiene Styrene (P)	1
Hanaor et al. (2015)	MJM	Fullcure 720 resin (P)	4
Iubin and Zakrevskaya (2018)	Not specified	Not mentioned (N)	5
Li et al. (2016)	FDM	Acrylonitrile Butadiene Styrene (P) PLA (P)	2
Liang et al. (2018, 2017, 2014)	FDM	Acrylonitrile Butadiene Styrene (P)	4
Lim and Chan, 2017)	FDM	Acrylonitrile Butadiene Styrene (P)	4
Mahabadi et al., 2018)	FDM	Acrylonitrile Butadiene Styrene (P) PLA (P)	2

Matsumura et al., 2017)	MJM	Cured resin (P)	4
Meijer et al. (2018)	FDM	Acrylonitrile Butadiene Styrene (P)	4
Mishra et al. (2018)	MJM	Resin Fullcure 720 (P)	4
Mondini et al. (2008)	MJM	Plastic (P)	4
Osei-Bonsu et al. (2018, 2017)	Polyjet (MJM)	Liquid resin (P) Acrylic-based material (P)	2
Otten et al. (2012)	SLS	Nylon 12 powder (P)	1,2,3
Ozelim and Cavalcante (2019)	SLS	Polyamide (P)	2
Pua et al. (2018)	Binder jetting (3DP)	Kaolin & Bentonite (S)	4,5
Rangel et al. (2013)	FDM	Plastic (P)	1
Ritter et al. (2016; 2017a,b; 2018a,b)	Polyjet (MJM)	3DP material (P) Visijet PXL powder & binder (P)	4
Shen et al. (2017, 2016)	Binder jetting (3DP)	Stainless steel and bronze (M) Not mentioned (N)	4
Su et al. (2017)	SLA	Formlabs Clear Resin (P)	4
Suescun-Florez et al. (2013)	FDM	Plastic (P)	2,4
Sylvain et al. (2016)	FDM	Plastic (P)	4
Tiasas et al. (2017)	Not specified	Not mentioned (N)	1,2
Zhang (2018)	FDM	Acrylonitrile Butadiene Styrene (P)	4

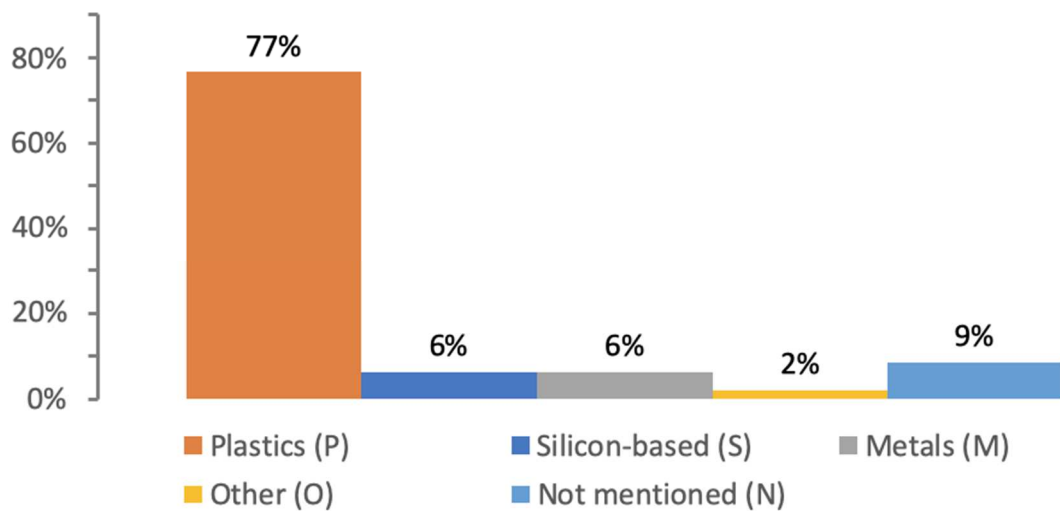
259 1 The material classification is Plastics (P), Metal-based (M), silicon-based (S), others (O)
260 and not mentioned (N), according to the information provided by the paper authors

261 Among 3D printing technologies, Fused Deposition Modeling and Polyjet/Inkjet Printing are
262 the most commonly used technologies in the soil science domain, accounting for about two-
263 thirds of the articles, as shown in Figure 2. In terms of materials (Figure 3), plastics are the
264 most commonly used (77%), maybe because these types of materials are used to develop the
265 most well-known 3D printing technologies (FDM, SLA, and MJM). To the best of our
266 knowledge, there is no utilization of biobased materials for applications dedicated to the
267 investigation of soil functions.



268

269 **Figure 2.** 3D printing technology used in the 41 selected articles related to soil functions.

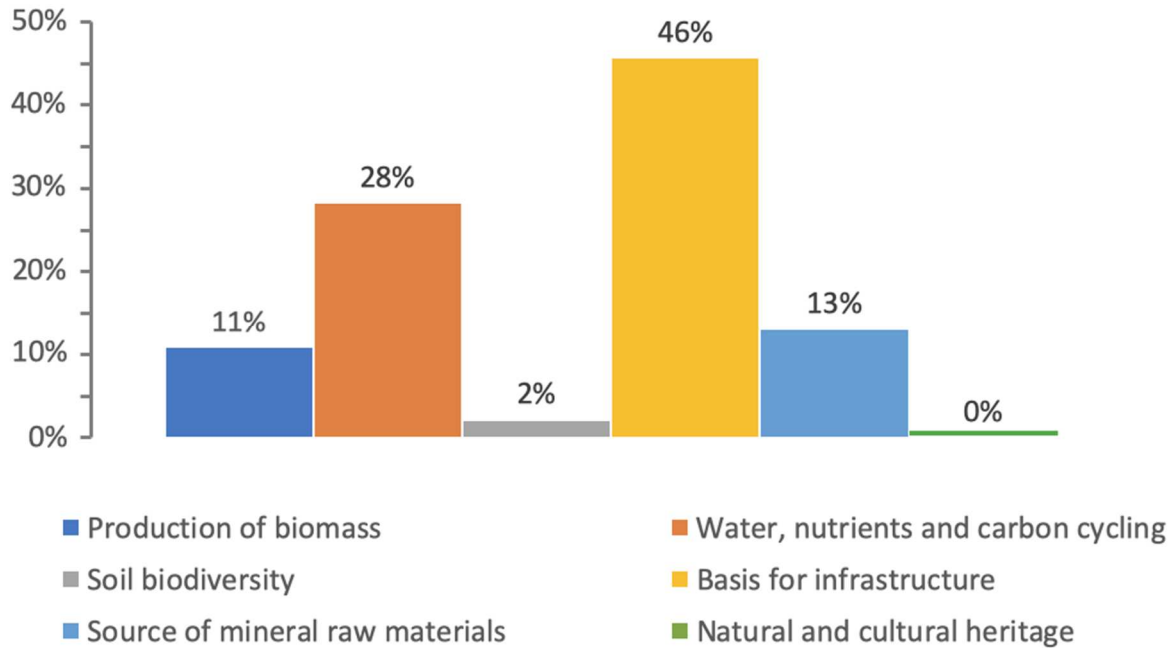


270

271 **Figure 3.** Materials used in the 41 selected articles related to soil functions.

272 In Figure 4, the 41 selected articles were further analyzed and classified according to the soil
 273 function they address. Most of the articles could be related to function 4 (soils as a basis for
 274 infrastructure) or 2 (soils for cycling and storing water, nutrients, and carbon), accounting for
 275 46 and 28% of the articles, respectively. Nevertheless, the articles were not investigating
 276 element cycling itself but addressed methodological issues that must first be resolved.
 277 Function 5, for which soil is considered as a source of mineral raw materials, such as clay,
 278 sand, and gravel, is the subject of 13% of the articles, while functions 1 (production of

279 biomass) and 3 (soil biodiversity) are addressed in only 11 and 2% of the articles,
 280 respectively. None of the selected articles was related to function 6 (natural and cultural
 281 heritage).



282

283 **Figure 4.** Soil functions addressed in the 41 selected articles related to soil science.

284 Some of the 41 articles made use of 3D printing for manufacturing equipment and devices
 285 used in soil-related activities (related to soil functions 1, 2, and 4). 3D printing appears in
 286 these articles as a flexible and easy-to-use prototyping technique for custom manufacturing
 287 of agricultural equipment (related to soil function 1 of biomass production). In this field, 3D
 288 printing allows adapting the tools to particular land or crop situations, as reviewed by (Javaid
 289 and Haleem, 2019) or to design innovative biomimetic tools such as the corn stubble harvester
 290 imitating the morphology of the nymph fore claws proposed by (Chang et al., 2016).

291 3D printing is also used in the field of soil science to build sensors for the study of soil
 292 properties, generally concerning the second soil function (element cycling). In many
 293 situations, 3D printing is presented as the simplest and cheapest, if not the only, way to obtain
 294 an object to be used in the construction of the desired device, in preference to the more

295 expensive and complex conventional tool-machinery (Rangel et al., 2013). Such 3D-printed
296 devices are, for example, an instrumented dilatometer for measuring soil disturbance during
297 penetration (Shen et al., 2017, 2016), a permeameter (Rangel et al., 2013), or various housings
298 for sensors monitoring soil properties (Borecki et al., 2016; Cocovi-Solberg et al., 2019;
299 Farooqui and Kishk, 2018; Li et al., 2016; Sylvain et al., 2016; Tiausas et al., 2017). 3D
300 printing is also used for prototyping innovative biomimetic probes, such as those imitating
301 root growth. These probes, which imitate the root morphology, can move in the soil with a
302 high penetration efficiency and a limited energy consumption typical of growing roots
303 (Mishra et al., 2018; Mondini et al., 2008).

304 In the field of civil engineering and architecture (function 4), 3D printing is increasingly used
305 to rapidly produce two types of customizable objects: either small-scale building models used
306 to test building resistance to soil perturbations or objects devoted to soil stabilization. In the
307 first group of studies, small scale houses are produced with 3D printing and placed on the soil
308 to evaluate house stability, depending on their characteristics (i.e. position, length, and facade
309 openings). Different constraints that affect building stability can be tested, such as soil
310 tunneling below 3D printed buildings (Ritter et al., 2016; Ritter et al., 2017a,b; Ritter et al.,
311 2018a,b), or water erosion (Suescun-Florez et al., 2013). The second group of geomechanical
312 applications consists of building 3D-printed objects dedicated to the improvement of soil
313 mechanical properties (Lim and Chan, 2017). For example, the stability of a vegetated slope
314 was investigated by equipping a soil profile with a model plant root system produced with
315 plastic material (ABS, Acrylonitrile Butadiene Styrene) and submitting it to mechanical tests
316 (Liang et al., 2018, 2017; Meijer et al., 2018).

317 Soils have also been used as a cheap, easily available, and sustainable source of raw material
318 for 3D printing in alternative to fossil resources (Iubin and Zakrevskaya, 2018). Printing with
319 soil was mostly achieved with the binder jetting technology in applications related to

320 architecture and art. It was combined with binding agents to enhance the chemical and
321 structural properties of the printed structure (Mitterberger and Derme, 2019; Derme and
322 Mitterberger, 2020). None of these applications required replication of soil characteristics.
323 Furthermore, one of the disadvantages of using soil as a material is its heterogeneity and the
324 resulting lack of control over the composition of the printed object. 3D printing has also been
325 successfully tested with exotic materials such as Moon or Mars regoliths, to prepare habitat
326 building in the event of establishment outside the Earth, using 3D printing technologies
327 adapted to the specific conditions in outer space (Bagrov et al., 2017; Ceccanti et al., 2010;
328 Cesaretti et al., 2014; Chow et al., 2017).

329 Finally, a group of articles is dedicated to the printing of soil models, reproducing physical,
330 chemical, and biological behavior and soil evolution dynamics. This topic raises many
331 opportunities and challenges for research in soil science that are discussed in the following
332 section.

333 5. DISCUSSION: OPPORTUNITIES AND CHALLENGES OF 3D PRINTING IN 334 SOIL SCIENCE

335 5.1. PRINTING TECHNOLOGIES TO PRODUCE PHYSICAL ANALOGS OF SOIL 336 (RELATED TO SOIL FUNCTIONS 5, 2 AND 3)

337 3D printing is increasingly used to produce analogs of granular soil particles or soil profile for
338 geotechnical tests, as an alternative to numerical simulations or laboratory (Hanaor et al.,
339 2015; Matsumura et al., 2017; Su et al., 2017). Numerical simulations are indeed prohibitively
340 expensive or are carried out with highly simplified particle shapes without a real
341 understanding of the reliability of the simulation being achieved. On the other side,
342 geotechnical laboratory tests are limited due to the unavoidable structural variation in the
343 granular assemblages of the specimens. By contrast, 3D printers using resin polymers can

344 generate individual particles of repeatable shapes or assemblages of bonded particles whose
345 particle shapes, sizes, and arrangements match those of natural samples. Besides, the
346 construction of 3D-printed objects is less time-consuming than that of numerical or hand-
347 made models. However, the representativeness of their mechanical response has still to be
348 tested and compared to the results of numerical or geotechnical simulations. In particular,
349 current investigations are focused on the influence of both materials (powder, adhesive,
350 binding agents) and technology on the micro- and macro scale mechanical behavior of the 3D
351 printed specimens (Matsumura et al., 2017; Su et al., 2017).

352 3D printing also offers a great potential for investigating how the 3D pore arrangement
353 regulates fluid circulation and biological activity in soil (e.g. root or fungal mycelium growth,
354 movements of microbes, or soluble substances), properties respectively related to soil
355 functions 2 and 3. The main challenge of 3D printing techniques for the construction of soil
356 models is their ability to print objects exhibiting a customized 3D-arrangement of the pore
357 system or to reproduce the physical properties of soil at an adequate resolution. 3D printers
358 using Selective Laser Sintering (SLS) technology (Table 1) can reproduce the imaged
359 porosity and the macro-pore shapes corresponding to the resolution of X-ray computed
360 tomography images (Dal Ferro and Morari, 2015; Bacher et al., 2015). Investigations are
361 conducted to test how various properties of the printed porous media impact fluid motion
362 (Osei-Bonsu et al., 2018, 2017). The major caution point for SLS printing of soil analogs is
363 the incomplete removal of powder residues that may remain inside the printed object despite
364 the immersion of the sample in acetone (Ozelim and Cavalcante, 2019). Pore clogging indeed
365 would decrease the resulting porosity and limit pore connectivity, affecting fluid flow (Dal
366 Ferro and Morari, 2015). Pore clogging due to residual powder can be avoided by using a
367 liquid printing material as in stereolithography (Bacher et al., 2015). A second critical
368 challenge for investigation of soil functions 2 and 3 with 3D-printed soil models is the

369 limitation of most 3D printing technologies in terms of the minimum wall thickness,
370 minimum buildable details, and maximum dimensions of the model (Ozelim and Cavalcante,
371 2019). These limitations have direct impacts on the accuracy of the reproduced microporosity
372 (arrangement of pores at the micromillimeter scale), which strongly controls elements cycling.
373 Current 3D printing technologies can only control pore diameter down to 60 micrometers
374 (Kadkhoda-Ahmadi et al., 2019). Smaller pores occur but are not intentional: they are those
375 imposed by the selected 3D printing method.

376 Research efforts are also focused on finding the 3D printing method, i.e. the combination of
377 material and technology, which could reproduce the hydraulic properties and wettability of
378 soil. On the material side, hydrophobicity must be carefully considered. (Mahabadi et al.,
379 2018) dismissed stereolithography technology because corresponding materials were too
380 hydrophobic for reproducing soil hydrological properties. By contrast, Bacher et al. (2015)
381 showed that stereolithography with Prime Gray, a plastic material, provided a good accuracy
382 and an unclogged macropore system with a relatively high hydrophobicity (contact angle
383 65°). Fused Filament Modeling (FDM) technique with Nylon, a plastic with a low
384 hydrophobicity (contact angle 40°), also allowed modeling the wetting behavior and hydraulic
385 conductivity of a natural soil sample (Mahabadi et al., 2018).

386 In alternative to studies optimizing the technology and materials to produce soil physical
387 analogs, demonstrated the ability of the 3D printing technology based on material extrusion to
388 print real soil material, without additives or expensive energy sources (Pua et al., 2018). Also,
389 they successfully built composite objects reproducing soil three-dimensional heterogeneity
390 using several contrasted soil materials. Their technical device must still be improved, as voids
391 were observed at the interface between two types of soil materials, possibly by subjecting the
392 printed object to vacuum.

393 5.2. PRINTING SOIL AS A SUPPORT FOR LIFE: BIOCOMPATIBILITY (RELATED
394 TO SOIL FUNCTIONS 1, 2 AND 3)

395 The pore connectivity and the porosity of 3D printed soil models discussed above govern the
396 specific interactions between different living organisms, between organisms and their
397 resources. Another essential property of the soil analog for modeling of soil functions 1, 2,
398 and 3 is its biocompatibility. Biocompatibility first implies that the printed material should not
399 be toxic for living organisms (plant seeds and roots; macro, mesofauna, or microorganisms).
400 Besides, 3D-printed objects used as physical habitat should deliver living resources (water,
401 organic matter, nutrients) to guarantee organism viability and growth. The plastic materials
402 commonly available for 3D printing technologies do not meet these requirements. Often toxic,
403 they are hydrophobic and water repellent, which is prohibitive for supporting life.

404 Various biocompatible polymers have recently received tremendous attention as promising
405 alternative bioinks for 3D printing technologies. For example, pectin, a heterogeneous
406 polysaccharide present in the plant cells, has been recently reported as a suitable hydrocolloid
407 used to develop new materials for tissue engineering (Cernencu et al., 2019), and food
408 applications (Vancauwenberghe et al., 2018). Alginate biopolymers are also of high interest
409 because they can entrap water and their chemical structure can be modified and implemented
410 with specific nutrients (Gopinathan and Noh, 2018; Liu et al., 2019). Biopolymers, such as
411 bovine serum albumin (BSA) or gelatine are also being used in particular for lab-on-a-chip
412 applications (Alekklett et al., 2018). In lab-on-chip applications, the desired pattern of the chip
413 is sometimes obtained with synthetic biocompatible polymers, for example, a PDMS silicone
414 exposed to UV light (Alekklett et al., 2018). Some biopolymers, such as BSA, can also be
415 directly cross-linked with pulsed laser light into a biocompatible hydrogel exhibiting the
416 desired shape (Connell et al., 2012, 2010). They can be mixed with gelatine and specific
417 bacterial communities before chemical cross-linking with pulsed laser light with a

418 photosensitizing molecule (methylene blue or Rose Bengal) (Connell et al., 2013). Some
419 applications interestingly use transparent materials enabling visual and spectroscopic control
420 of soil functioning (Downie et al., 2012). Even if they physically reproduce soil pore
421 geometry and properties at fine scales (Alekklett et al., 2018), lab-on-a-chip systems cannot be
422 considered as replication of soils, since they do not reproduce the spatial arrangement of these
423 microscopic habitats. However, they could inspire soil science developments in terms of
424 biocompatible materials.

425 To improve the spatial representation of the complex soil system, the 3D printing process
426 should also allow the addition at precise locations of specific components, such as nutrients
427 enriched biopolymers or viable organisms, as it was successfully achieved by several
428 (Ringeisen et al., 2015; Taidi et al., 2016).

429 5.3. PRINTING A SOIL THAT RESPECTS THE DYNAMICS OF SOIL PROPERTIES 430 (RELATED TO SOIL FUNCTIONS 1, 2, 3 AND 5)

431 Soil is a living system. Its physicochemical properties are constantly evolving under the
432 action of biotic agents (microbes, micro, and mesofauna, plant roots, etc.), related to soil
433 biodiversity or of abiotic processes (solubilization, redox reactions, adsorption, compaction,
434 freezing, etc.) related to pedo-climatic conditions. The use of multi-material printing, mainly
435 using MJM, and also bio-printing technologies (Lopes et al., 2018), allows the development
436 of shape-morphing objects that respond to external changes, such as humidity, light or touch
437 (Sydney Gladman et al., 2016). This so-called 4D printing technology uses self-assembly
438 programmable materials to build objects that are no longer simply static and dead but rather
439 transformable (Pua et al., 2018). This technology has already been applied in tissue
440 engineering, biomedical devices, and soft robotics (Velasco-Hogan et al., 2018). Such

441 approaches are promising for reaching a better representation of the complex and dynamic
442 soil matrix.

443 On the other side, to be used in soil science experiments with living organisms, 3D-printed
444 objects should not exhibit artefactual dynamics. They must have the ability to self-retain their
445 3D printed macro and micro-structure, as real soil does when subjected to physical and
446 chemical constraints favorable to organism growth or generated by the organism activity. For
447 example, it may be necessary to autoclave the object at high pressure to optimize the growth
448 of specific microorganisms and prevent the development of competing bacteria or fungi.
449 During plant growth or incubation experiments using the printed object, water may circulate
450 in the object pores. Root and microorganism's activity may generate protons and acidify
451 material surfaces. For example, the printed soil block must be resistant to biotic stress due to
452 fungal growth, as shown by Otten et al. (2012) To meet these requirements, the materials or
453 combination of materials used to produce the object shall have a wide range of thermal
454 compatibility, sufficient rigidity to prevent collapse due to physical disturbances (e.g. through
455 high cross-linking capacity) and surfaces with buffering properties.

456 6. CONCLUSIONS

457 The present article evidences that 3D printing has emerged as a revolutionary technology,
458 promising to push the boundaries of experimental research. It advantageously allows the fast
459 and inexpensive production of endlessly replicable identical and customizable objects, for
460 conducting experiments. Soil science, like many other fields, has already started to explore
461 the research opportunities opened up by various 3D printing technologies. Most of the
462 applications appearing in our bibliometric survey concern soil functions 4, and 5, in which the
463 soil is considered either as a source of raw materials or as the basis for the development of
464 technical infrastructures. These applications refer to the fields of civil engineering or

465 architecture more than soil science since they do not take into account the functioning of the
466 soil itself but simply consider soil either as a source of raw materials or as the basis for the
467 development of technical infrastructures.

468 The use of 3D printing in soil science, for research issues related to carbon and nutrient
469 cycling and storage (function 2), which impact biomass production (function 1) and
470 biodiversity (function 3) is a new research opportunity. The under-representation of
471 applications addressing these functions in the bibliometric survey may be explained in the
472 first place by the limited user group that is currently involved in the development and use of
473 3D printing in soil science. The emphasis on the potentialities of this technique that we
474 provide in this article will hopefully enlarge this potential user group. It can be particularly
475 attractive for researchers developing participatory research projects by producing identical,
476 reproducible samples with strict and controlled composition and structure or for those looking
477 for tools and indicators to provide stakeholders with an assessment of soil health and/or
478 ecosystem services.

479 If the deployment of 3D-printing in soil science is still limited, it is also because of the
480 technical limitations that we analysed here. One of the main limitations is the difficulty of
481 adequately representing the soil porous network with 3D printing. Indeed, soil functioning is
482 strongly related to the spatial arrangement of soil pores and of soil constituents, the
483 accessibility of resources, and the circulation or growth of living organisms in the soil pore
484 network. In addition to the classical criteria of cost and availability of 3D-printing material
485 and process, we have identified three specific constraints that need to be considered and
486 improved to use 3D printing to build realistic soil models for use in soil science: (i) finding
487 suitable biocompatible material (depending on the scientific question, any natural
488 biomaterials, especially those derived from plants, could be of interest), (ii) choosing a 3D
489 printing technology whose spatial resolution is adapted to the experiment it is dedicated

490 (down to the submicrometric scale) and (iii) implementing the 3D printing method that
491 produces chemically and mechanically stable objects, when brought into contact with living
492 organisms.

493 We are confident that all technical limitations will be overcome in the next years through
494 enhanced dialogue between disciplines and in-depth scientific reflection on the objectives and
495 outputs of the applications. Soil scientists have to precisely define the technical specifications
496 related to their study and work closely with 3D printing developers to meet them. To meet the
497 specifications of soil scientists, 3D printing developers may recommend the use of materials
498 and techniques already available or must implement new research programs. This dialogue
499 will contribute significantly to the progress of 3D printing technologies and materials and will
500 also benefit other application areas of 3D printing, such as food processing or the agriculture
501 of the future on Earth but also on the Moon or Mars in the context of the conquest of space.

502

503

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