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Estimating and mapping the availability of earth resource for light earth building using a soil geodatabase in Brittany (France)

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18 **Abstract**

19 Light earth is a natural insulating material composed of earth and vegetal fibres. It can be used to insulate
20 existing and new buildings to reduce energy and resources consumption, and excavated earth generation
21 by the construction sector.

22 A pedological database is crossed with suitability thresholds in order to evaluate spatially the availability
23 of earth resources. Then, the soil suitability is mapped, and suitable soil amounts metrics are estimated
24 for Brittany territory. A sensitivity analysis is performed to understand the potential variability of the
25 results.

26 Study estimates that 48% of Brittany's soil horizons are suitable for light earth building. Every year, 1.3 Mt
27 of suitable soil are excavated in Brittany. Using only these excavated earths, all existing and new buildings
28 in Brittany could be insulated with light-earth in less than 8 years. This study shows that suitable earth
29 availability is not a limiting factor to develop light earth insulation in Brittany.

30 **Keywords:** earth building, light earth, pedology, soil suitability, material flow analysis

31 **1. Introduction**

32 ***1.1 Buildings insulation: a social and environmental necessity***

33 The building and construction sector is responsible for 36% of final energy consumption and 39% of global
34 CO₂ emissions in 2018 (Global Alliance for Buildings and Construction (GABC) 2019).

35 11% of GHG emissions from the building sector result from the manufacture of modern building materials
36 alone (GABC 2019). In Europe, 67% of the energy consumed by the residential buildings is attributed to
37 the heating of buildings (Brevik et al. 2019).

38 In countries with rapid population growth and strong rural exodus, the construction of new buildings is
39 inevitable and necessary. Therefore, optimizing the energy efficiency (embodied energy and service life
40 energy) of new buildings is an important lever for reducing energy consumption for these countries (GABC
41 2017).

42 On the contrary, population growth is low and building is slowly being renewed in Europe: 65% of the
43 buildings that will exist by 2060 have already been built (GABC 2017). In order to reduce the energy
44 consumption of the building sector in an efficient way, it is ecologically interesting to improve the energy
45 efficiency of existing buildings (Oury et Parissin-Fabert 2019). In addition, new construction consumes 40
46 times more materials than renovation, and 80 times more in collective housing (ADEME 2019a).
47 Renovation also leads to less soil artificialization (French Ministry of Agriculture, 2020).

48 ***1.2 Use of local natural materials for insulation***

49 The use of local materials can reduce the embodied energy of the building sector by a factor of 2 and GHG
50 emissions related to transportation by 4.5 (Morel et al., 2001; UNEP DTIE IETC, 2003).

51 Depending on local socio-economic conditions, the use of local materials and vernacular building
52 techniques also allows for easier access to construction materials, the development of sustainable local
53 industries and the creation of jobs that cannot be relocated (Hamard, 2017; Khoso, 2014; Sameh, 2014).

54 Raw earth construction is the use of earth that has not been stabilized with non-biodegradable binders as
55 a building material. It has the potential to decrease the GHG emissions compared with conventional
56 materials. For example, cob building can reduce 75-82% of such emissions compared with concrete
57 masonry block building (Lola Ben-Alon et al., 2019). At the end of life of the building, the resource can:

58 1) return to the surrounding environment. The eventual bio-based additives such as vegetal fibres or
59 granulates are 100% biodegradable when they are not supplemented with non-biodegradable materials
60 (Holzhueter and Itonaga, 2017).

61 2) be reused infinitely for raw earth building (Morel and Charef, 2019; Van Damme and Houben, 2018).

62 Using earth or bio-based materials would therefore reduce construction waste, which today constitutes
63 50% of the mass of waste in the European Union (Llatas, 2011).

64 The use of natural materials from local and sustainable sources requires adapting, within each territory,
65 to the resources available locally. While the production of bio-based materials for construction may
66 compete with other uses, some are considered as "residues", "co-products" or "by-products" of agriculture
67 (Valbuena et al., 2015). A good example of this is the hemp shiv, which is derived from the hemp stem. Its
68 use in hemp concretes or in light earth could support the development and durability of the hemp sector

69 and therefore its introduction in crop rotations. Indeed, hemp cultivation often has a positive impact on
70 soil properties and requires few inputs (Finnan and Styles, 2013; Struik et al., 2000; Zegada-Lizarazu and
71 Monti, 2011).

72 Assuming that natural material insulation can have adequate insulation performances (see 1.3), it is
73 potentially an efficient solution to insulate existing buildings and therefore reduce energy consumption in
74 the building sector.

75 Currently, the use of natural or recycled materials for insulation is not very widespread: in 2011, mineral
76 wools and plastics represented 93% of the world market share of insulation materials (Asdrubali et al.,
77 2015). However, the current trend is upward: over the period 2015-2050, the total consumption of bio-
78 based insulation products would vary from 2.4 to 7 Mt and that of wood from 1.5 to 3.5 Mt, according to
79 different scenarios (French Ministry of Agriculture, 2020).

80 Approximately 1 to 10 mm of soil is formed every 100 years in temperate climates (Egli et al., 2014).
81 Therefore, this material cannot be considered a renewable resource at human time scale. Besides,
82 European soils are already facing many anthropogenic threats such as water erosion, soil capping and
83 sealing due to the high urbanization rate and extensive contamination of the soils (FAO, 2015). The use of
84 soil as a construction material raises the question of its sustainable management. Yet, till date, soil scientist
85 have paid little attention to earthen building materials (Brevik et al., 2019).

86 In most cases, extensively building with raw earth should not threaten soil resource availability. However,
87 particular cases such as the excavation of fertile surface soils should be avoided. Indeed, it can lead to a
88 degradation of the agricultural or ecological potential of the soil, and abuses have already been identified
89 by the scientific community (Biswas et al., 2018; Hashemi et al., 2015).

90 On the other hand, excavated soil is available in large quantities, 2.8 million tons per year in Brittany
91 (Hamard et al., 2018), often in close proximity to the construction site. The valorisation of this resource is
92 interesting since it has no other function today and is considered as a waste of the construction industry.
93 Using excavated soil for earth construction would reduce the environmental and economic cost of earth
94 collection and transportation (Marrero et al., 2017).

95 *1.3 Technical references for earth-hemp insulation*

96 Raw earth building is often little or not considered in French construction standards (Harries et al., 1996;
97 Jiménez Delgado and Guerrero, 2007), and has been the subject of few research programs compared to
98 the most commonly used materials (metal, cement, wood) (Ciancio and Jaquin, 2011; Morel and Charef,
99 2019).

100 The French code of practice for light earth (Confédération de la Construction en Terre Crue (CCTC), 2018)
101 defines light earth as a building material that is:

- 102 - non-load-bearing
- 103 - composed of an earth slip (earth at liquid state) matrix coating vegetable or mineral aggregates
- 104 - implemented in various ways: compacted in a temporary or lost formwork, manually applied with a
105 trowel or by mechanized spraying, or implemented after drying.

106 Generally, it has a dry density ranging from 200 to 1200 kg/m³. However, our study focuses on light-earth
107 for insulation purpose, which narrows the density range to 200-500 kg/m³.

108 Earth-hemp concrete, or earth-hemp, refers to a light earth material whose aggregate is hemp shiv. It
109 combines the insulation performance of hemp shiv to the thermal inertia and hygroscopic exchange
110 capacity of raw earth (Cagnon et al., 2014; Soudani et al., 2016). These performances are similar to lime-
111 hemp concretes and are attractive for renovation and construction in temperate or hot climates (Volhard
112 and Reisenberger, 2016). However, the Life Cycle Assessment (LCA) of hemp-lime concrete shows that the
113 production of lime results in significant GHG emissions (Pretot et al., 2014; Sagastume Gutiérrez et al.,
114 2012; Shan et al., 2016). Using earth as a binder in plant-based concretes eliminates the need for lime, and
115 ultimately reduces the embodied energy of the insulation system by a factor of 20 and GHG emissions by
116 a factor of 5 (Vinceslas et al., 2019). It also limits the impact and cost of end-of-life management, and
117 decreases the price of the material by a factor of 1.5, while maintaining similar physical performance
118 (thermal conductivity, compressive strength) (Vinceslas et al., 2019).

119 *1.4 Paper objectives*

120 In a context where raw earth building techniques are flourishing in the building sector, understanding
121 where and how earthen construction can be developed while preserving the soil resource is essential. The
122 evaluation of soil suitability for light earth building, and the quantification of the locally available resource
123 is a way to better understand the eventual impacts of the development of light-earth building on the local
124 soil resource availability for other uses. Furthermore, it is an interesting way to evaluate the reuse
125 potential of excavated earth in order to include raw earth construction in a circular economy approach
126 (Kirchherr et al., 2017).

127 From Vincelas (2019) insights on earth suitability for light earth building and expert craftsmen advices
128 (see 2.5.3), and from Hamard et al. (2018) method on how to use a pedological database to estimate
129 suitable soil availability for cob building (see 2.6), this work presents a method to evaluate local soil
130 resource availability for light earth building. A pedological database (DoneSol3 Brittany) is crossed with
131 earth suitability thresholds. Earth suitability is considered as dependant on multiple building steps, that
132 represent on-field easiness of implementation as much as final mechanical performance of the material.
133 The methodology is applied to Brittany (France), but may be applicable to any other territory disposing of
134 an adequate soil map database.

135 **2. Methods**

136 *2.1 Soils of Armorican Massif*

137 This study covers the territory of Brittany region, located in the Armorican Massif geological domain. In
138 this 27,040 km² area, the local pedological database is the Regional Pedological Referential of Brittany
139 (Lemerrier et al., 2015). Generally, geological formations strongly impact on the pedogenesis of the
140 overlying soils and especially in the Armorican Massif. The dominant soil mechanisms in the Armorican
141 Massif are browning and clay leaching (Berthier et al., 2009; Jamagne et al., 2011).

142 *2.2 Soil database structure*

143 DoneSol3 (InfoSol, 2021) is the French national database structuring and regrouping the point and surface
144 data of the pedological studies of the Pedological Regional Referential (RRP) (Lemerrier et al., 2017).

145 The surface data of DoneSol are derived from the synthesis of point and landscape observations by the
146 soil-mapper. The expert defines Soil Type Units (STUs) (“pedon” equivalent), which are vertically divided
147 into layers (“horizon” equivalent). On this territory, Vincent et al. (2018) carried out a predictive map of

148 STUs using DoneSol data and soil landscape relationships. The resulting 50 m raster predicted the
149 occurrence of a STU accurately up to 72.3% of the cases.

150 **2.3 Earth parameters terminology**

151 Earth is the constituent material of soil; where the properties of interest and study methods vary according
152 to the discipline. In geotechnics, attention is often focused on the nature and particle size of soil
153 constituents (LCPC, 2000). In pedology, the analysis of constituents is one of the main dimensions of study,
154 but also their organization at different scales, and the variability of these two parameters in time and space
155 (Jamagne et al., 2011). Following the example of (Vinceslas, 2019), the word "soil" will be used here to
156 indicate the complete soil profile in place (the "solum"). The word "horizon" will be used to describe a
157 pedological horizon, i.e. a volume of soil in place with properties quite homogenous and generally
158 delimited by a horizontal discontinuity. The word "earth" will be used to qualify any earth resource,
159 including extracted soil resource.

160 In order to study soil's particle size distribution, the soil particles are grouped according to the particle size
161 fractions. The limits of these fractions vary according to disciplines and national and international
162 standards. In this article, we will use the size fractions commonly used by soil scientist in France, in
163 particular those used in the DoneSol3 database. The 2000 μm sieve fraction, commonly referred to as the
164 "fine fraction", is separated from the 2000 μm sieve non-passing fraction, commonly referred to as the
165 "coarse fraction". The coarse fraction is called " $F_{2000/D}$ " and is measured as a % of the initial mass of earth.
166 The fine fraction is divided into 3 size fractions, each of which is measured in g.kg^{-1} of the fine fraction:

- 167 - the 0 to 2 μm size fraction ($F_{0/2}$), commonly termed "clays";
- 168 - the 2 to 50 μm size fraction ($F_{2/50}$), commonly termed "silts";
- 169 - the 50 to 2000 μm size fraction ($F_{50/2000}$), commonly termed "sands".

170 $F_{0/2}$ is often referred to as "clays" or "clay fraction", because $F_{0/2}$ often gathers the majority of clay minerals.
171 This creates ambiguity with mineralogical clays (Mitchell and Soga, 2005). Indeed, the particle size
172 definition of "clays" differs from the mineralogical definition (Peinemann et al., 2000). On one hand
173 because non-clay particles (quartz) are present in $F_{0/2}$ (Vinceslas, 2019), and on the other hand because
174 $F_{2/50}$ and $F_{50/2000}$ contain clays, either in aggregate form or in mantle on other particles (Brady and Weil,
175 1984; Curtin and Smillie, 1976; Peinemann et al., 2000). In this article, the term clay will therefore refer
176 only to mineralogical clays.

177 **2.4 Earth suitability for earth-hemp building**

178 **2.4.1 Earth suitability**

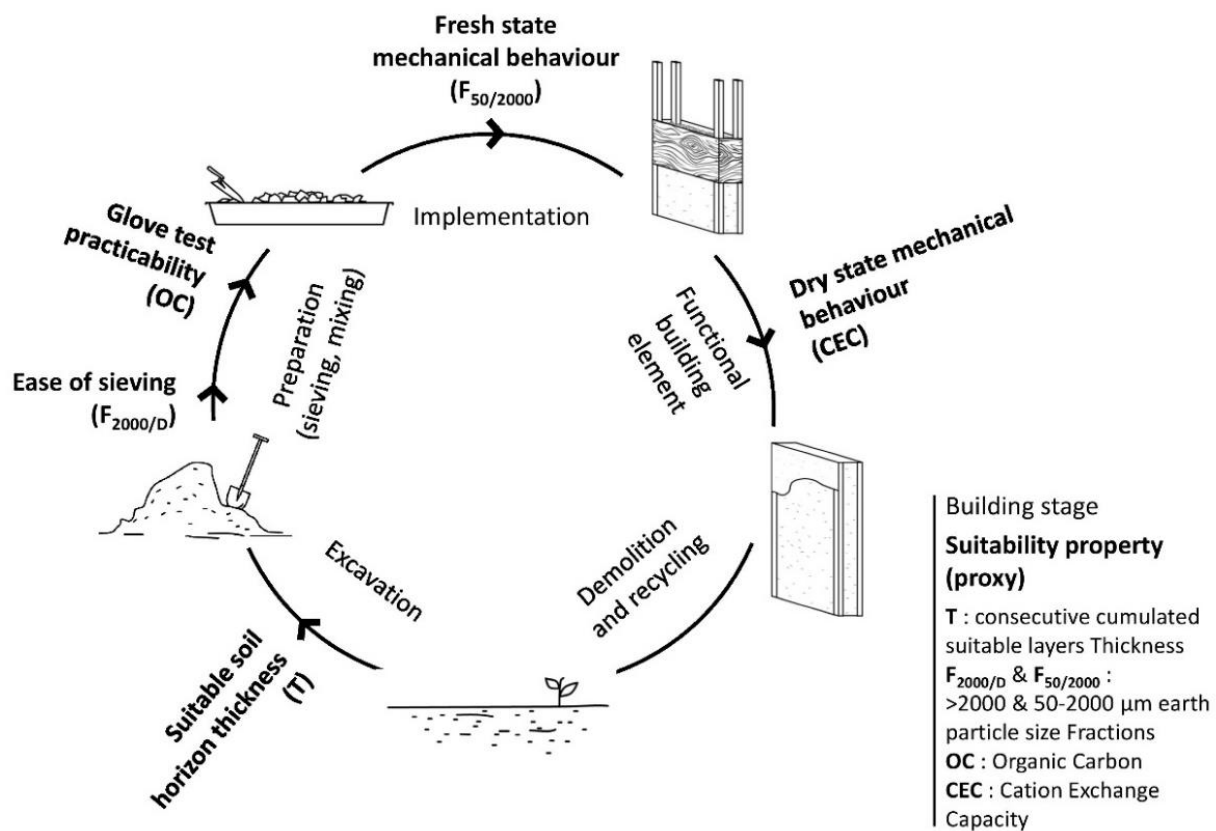
179 A *suitable* earth material for a raw earth building technique can be defined as an earth whose properties
180 (composition, mechanical properties, etc.) enables the earthen building element to reach the desired
181 *building performance*. The scientific community considers the *functional building element* performances
182 (Figure 1) such as its mechanical strength parameters or sometimes hygrothermal performances when
183 dealing with earth suitability for raw earth building. However, when masons evaluate an earth material
184 suitability, they also consider its suitability for other stages of the building process, including its excavation,
185 preparation and implementation. Indeed, these stages also introduce constraints on the composition or
186 mechanical properties of the earth material, that often depend on the building techniques employed or
187 mechanization intensity.

188 **Suitability properties** can thus be identified throughout the life cycle of earth material in raw earth
 189 building. As earth in raw earth building techniques is 100% reusable (Morel and Charef, 2019; Van Damme
 190 and Houben, 2018), we can consider the earth material's life cycle along earth building process as circular.

191 For each *suitability property*, we define a **suitability criterion**, which is a threshold above/under which the
 192 material is considered suitable for the corresponding building stage.

193 Earth suitability for light earth building is not significantly impacted by the type of vegetal aggregate/fiber
 194 used (Vinceslas, 2019) or by the implementation method. This study focuses on earth-hemp implemented
 195 in a formwork, however the results are likely applicable to other light clay mixes with similar aggregates,
 196 such as linen or reed, or to other implementation techniques, such as projected earth-hemp.

197 Five *suitability properties* have been identified along with earth-hemp building process. They are
 198 summarized in Figure 1.



199
 200 *Figure 1 : Distribution of suitability properties along the life cycle of earth in earth-hemp building and*
 201 *corresponding proxies.*

202 **2.4.2 Excavation**

203 An excavation step can be necessary. Although earth can be excavated by hand, nowadays it is usually
 204 excavated by mechanical means. During this step, different soil horizons can be excavated separately. In
 205 this study, we consider that the excavation machines have a limited excavation precision. Therefore, the
 206 cumulated thickness soil of the suitable soil horizons must be greater than this precision.

208 2.4.3 *Ease of sieving*

209 $F_{2000/D}$ earth particles usually do not contribute significantly to the cohesive strength but they increase
210 earth density. In order to maximise the insulation property of the material, a sufficiently low density must
211 be obtained. To this end, the earth can be sieved to remove coarse particles (see appendix A, Figure A.1).

212 2.4.4 *Glove test practicability*

213 Earth is mixed with water until it reaches an adequate liquid state. The earth slip is then mixed with hemp
214 shiv in order to distribute and coat the fibers. The homogenization/coating process requires adequate
215 consistency of the earth in its fluid state. In addition, the slip consistency must have an adequate yield
216 stress for the implementation step (see 2.4.5).

217 The "glove" test is currently the most common test for characterizing an earth slip used in light earth (see
218 appendix A, Figure A.2). Craftsmen dip the hand into the slip, remove it, and observe the flow and cohesion
219 of the slip on the hand, the result resembling a glove. Because this is the most effective test carried on
220 field to characterise the adequate consistency of the earth (Vinceslas et al., 2020), the earth material must
221 allow its good execution.

222 2.4.5 *Fresh state mechanical behaviour*

223 The earth-hemp mix is partially compacted in a formwork that will be removed soon to allow the earth
224 mix to dry. Therefore, the compacted mix must be cohesive enough to stick together at fresh state, even
225 when the formwork is removed.

226 Earth slip behaves as a Bingham fluid, i.e. fluid with a yield stress (Vinceslas, 2019). The yield stress
227 represents the threshold at which the earth slip and hemp mixture "slips" along the wall, under its own
228 weight. Thus, the yield stress can be seen as the capacity of a fresh earth-hemp mixture to stick on the
229 wall (Vinceslas, 2019). At this step, the yield stress of the earth slip must be high enough for the compacted
230 mix to stick together when the formwork is removed.

231 2.4.6 *Dry state mechanical behaviour*

232 After drying, the cohesion provided by the earth in the dry earth-hemp mix must be sufficient to support
233 the mass of a coating.

234 **2.5 Suitability properties: an approximation using soil database proxies**

235 2.5.1 *Proxies*

236 **Proxy:** In environmental sciences, when a data is not directly measurable or estimable, we use estimation
237 parameters of this data, called "*proxies*". For example, satellite spectroscopic data is often used as a proxy
238 to estimate organic content and texture of topsoil (Knadel et al., 2013).

239 In this study, we use proxies to approximate earth *suitability properties*. Therefore, a *proxy* is a pedological
240 property of the earth material that 1) is considered representative of one or more *suitability properties*
241 and 2) is available in the DoneSol pedological database.

242 **Proxy threshold:** As a *proxy* approximates a *suitability property*, the *proxy threshold* will approximate the
243 *suitability criterion* i.e. the theoretic limit above/under which the earth material is no longer considered
244 suitable for light earth building.

245 **Proxy threshold variation range:** The *suitability criterion* along earth life cycle in earth-hemp building can
246 vary depending on many parameters, e.g. implementation method, type of earth, building performances
247 objectives, etc. This leads to a wide possible range of proxy thresholds values. In order to quantify an earth
248 material suitability for earth-hemp building, at this stage, we reduce this variability to one predetermined
249 *proxy threshold* for each suitability property. In order to consider the impact of the variability of the
250 proxies' thresholds, the model will be submitted to a sensitivity analysis. The thresholds will be allowed to
251 vary inside an interval (*proxy threshold variation range*) using a Monte Carlo analysis (see 2.6 part. 3). The
252 intervals are defined by knowledge from expert masons and from literature, and represent a realistic
253 variation range of the *proxy thresholds* in real conditions.

254 2.5.2 Proxy threshold concealment

255 As explained in Rojat et al. (2020), when earth suitability *proxies thresholds* are proposed in the literature,
256 they fail to give full account of the diversity of earth employed for construction. This can be explained by
257 the variability of the materials or techniques employed by present or past masons, mason's ability to adapt
258 their practices to the earth material behaviour, and the complexity of earth suitability prediction for raw
259 earth building.

260 Examples of abuse in the use of suitability thresholds have already been recorded. The grading envelopes
261 published in Houben & Guillaud (2006) are used by several designers and control offices to define
262 suitability criteria imposed in specific technical specifications in France, despite the authors' warning
263 (Luquain, 2021).

264 Thus, in order to avoid potential abuses in the use of the thresholds used in this study, they will not appear
265 explicitly in the article's body. They will be replaced by an artefact: "[proxy name]unit" (ex: [F_{2000/D}]). They
266 will be available on simple request to the authors. However, the *proxy thresholds variation ranges* will be
267 left explicit.

268 The proxies' thresholds and their variation ranges for every suitability criterion are explained below. They
269 are summarized in Table 1.

270 2.5.3 Sources of the data

271 The proxy thresholds and proxy thresholds' variation ranges for light earth suitability have been obtained
272 from two sources. For T, OC, CEC, F_{50/2000}, Vincelas (2019) thesis data, based on 6 earth samples collected
273 in the Armorican Massif, has provided us with hypothetical thresholds, that were validated by expert
274 masons. For F_{2000/D}, expert masons provided us with theoretical thresholds based on their field
275 observations.

276 2.5.4 Excavation (T)

277 Soil horizons suitable for earth-hemp building must be accessible and must be separated easily from other
278 non-suitable soil horizons. Therefore, the cumulated suitable horizons thickness must be thick enough to
279 be excavated separately from others.

280 The proxy used, *consecutive suitable layers cumulated Thickness* (T) is calculated from the database (see
281 2.6). The *proxy threshold variation range* goes from 10 cm (manual excavation) to 60 cm (biggest mechanic
282 diggers).

283 2.5.5 *Ease of sieving ($F_{2000/D}$)*

284 As mechanical sieving is not common on light earth building sites, suitable earth should be easy to sieve
285 manually (see 2.4.3). The *proxy* $F_{2000/D}$ will be used to approximate the ease of sieving. It must be low
286 enough for manual sieving to be practicable.

287 The *proxy threshold variation range* is defined according to experts and goes from 5% (where a sieving
288 process becomes necessary), to 30% if a mechanized sieving is performed.

289 2.5.6 *Glove test practicability (OC)*

290 Vincelas (2019) noticed experimentally that a high soil organic matters content can perturbate the glove
291 test used on field to characterise the adequate consistency of the earth (see 2.4.4). In addition, masons
292 using local earth are trained to identify earths that are poor in soil organic matters (CCTC 2018). Therefore,
293 a maximum limit of soil organic matters content in the earth is set in this study.

294 Organic Carbon (OC) content is used as a *proxy* for the presence of soil organic matters, via the van
295 Bemmelen coefficient (1.724) (Baize, 2016), which allows one to switch between the two (Eq. 1).

296 Eq. 1 :
$$\text{Soil Organic Matters (g.kg}^{-1}\text{)} = \text{Organic Carbon (g.kg}^{-1}\text{)} \times 1.724$$

297 In the experiments of Vincelas (2019), the richest earth in soil organic matters that did not perturbate the
298 glove test had an OC content of [OC] g.kg⁻¹. Above, there is a risk that the soil organic matters content
299 perturbates this field test.

300 The *proxy threshold variation range* goes from 33.0 g.kg⁻¹ corresponding to the second higher OC content
301 of Vincelas (2019) samples that did not perturbate the test, to 63.1 g.kg⁻¹ which corresponds to the OC
302 content of the earth material disturbing the glove test in the experiment.

303 2.5.7 *Fresh state mechanical behaviour ($F_{50/2000}$)*

304 The earth slip yield stress must be high enough for the earth-hemp mix particles to stick together when
305 the shutter is removed (see 2.4.5). The relationship between yield stress and water content is affected by
306 the composition of the mixture, including clay content, nature of the clays, and particle size (Bolleni, 2019;
307 Nguyen et al., 2018; Vincelas et al., 2020). At equivalent water content, the dominant parameter of the
308 liquid state behaviour is the specific surface area of the particles, which is maximized by increasing $F_{0/2}$ and
309 $F_{2/50}$, i.e. reducing $F_{50/2000}$ (Bolleni, 2019; Coventry, 2004; Vincelas, 2019). Therefore, $F_{50/2000}$ is used as a
310 proxy of the earth slip cohesion at fresh state.

311 The *proxy threshold* and *proxy threshold variation range* [308 g.kg⁻¹ to 829 g.kg⁻¹] are defined according to
312 the results of Vincelas (2019). The *proxy threshold* used is in adequation with Brouard (2018)
313 experimental results. Above this proxy threshold, the earth material is considered not cohesive enough.

314 2.5.8 *Dry state mechanical behaviour (CEC)*

315 The cohesion provided by the earth must be sufficient for the dry earth-hemp material to support the
316 mass of a coating. The mechanical parameters of raw earth materials depend primarily on the phenomena

317 of electronic cohesion and suction. These two types of electronic interactions vary depending on the type
 318 and amount of clay (Curtin and Smillie, 1976; Meimaroglou and Mouzakis, 2019; Weil and Brady, 2016).
 319 Clay bonding capacity is provided by the combined action of clay specific surface area and electrical
 320 charge (Meimaroglou and Mouzakis, 2019). Cation Exchange Capacity (CEC) is the amount of positive
 321 electronic charges in the form of cations that can replace present cations or be retained by negative
 322 charges, in an earth material (Coventry, 2004; Mitchell and Soga, 2005). In non-organic earths these
 323 charges originate mainly from clays (Ersahin et al., 2006; Farrar and Coleman, 1967; Hamard et al., 2018;
 324 Hepper et al., 2006; Weil and Brady, 2016). CEC is therefore a good indicator of the potential for electronic
 325 interactions in an earth material (Coventry, 2004; Meimaroglou and Mouzakis, 2019), and therefore in an
 326 earth building material (Hamard et al., 2018; Vincelas, 2019). In this study, the proxy CEC is used to
 327 approximate the mechanical strength of the dry light-earth material.

328 The *proxy threshold* and the *proxy threshold variation range* [3.9 g.kg⁻¹ to 6.6 g.kg⁻¹] are defined according
 329 to the results of Vincelas (2019).

Building stage stage of earth material life cycle	Suitability property earth material property impacting suitability	Suitability criterion criterion of success of the suitability property	Proxy Soil property used to approximate the suitability property	Abb.	Unit	Threshold estimated value for the most common building methods	Threshold variation range realistic threshold variation range	Source
Excavation	Suitable soil horizons thickness	Thickness is enough to satisfy excavation precision	Consecutive suitable layers cumulated Thickness	T	cm	> [T]	10 - 60	Expert
Sieving	Ease of sieving	Manual sieving is practicable	"coarse elements" size Fraction volumetric percentage	F _{2000/D}	%	< [F _{2000/D}]	5 - 30	Expert
Preparation	Glove test practicability	The glove test is not perturbed	Organic Carbon content	OC	g.kg ⁻¹	< [OC]	33.0 - 63.1	Vincelas (2019)
Implementation	Fresh state mechanical behavior	Light earth material is self- standing	"sand" size Fraction	F _{50/2000}	g.kg ⁻¹	< [F _{50/2000}]	308 - 829	Vincelas (2019), Brouard (2018)
Coating	Dry state mechanical behavior	The wall can support a plaster	Cation Exchange Capacity	CEC	cmol*.kg ⁻¹	> [CEC]	3.9 - 6.6	Vincelas (2019)

330

331 *Table 1 : Suitability parameters and associated suitability criteria, corresponding proxies, proxy*
 332 *thresholds and proxy thresholds variation range.*

333 2.6 Data processing

334 The calculation method is based on the methodology proposed by Hamard et al. (2018) where a
 335 pedological database is used to estimate suitable soil availability for cob building. It was encoded in Python
 336 for reproducibility purposes and to run a Monte Carlo sensitivity analysis, and it was modified to fit the
 337 predictive STU raster map produced by Vincent et al. (2018) and light earth suitability thresholds.

338 2.6.1 Part. 1: Calculation of volume and % of suitable earth

339 STU and STU layers properties were extracted from DoneSol database (see appendix B, Figure B.1). For
 340 each layer, the parameters were compared to the *proxies' thresholds*, and assumed as suitable or not
 341 suitable. Then the consecutive suitable layers of every STU were compared to the *cumulated Thickness*
 342 threshold (T). If the layer satisfies T threshold, it is assumed as *suitable*. The sum of all *suitable layers'*
 343 thickness of the STU is calculated and called *suitable thickness*. The total thickness of the STU is also
 344 calculated.

345 From the predicted STU raster map, STU surface is quantified and extracted. STU total soil volume and STU
 346 suitable soil volume were obtained by multiplying respectively STU total thickness and STU suitable
 347 thickness by STU surface.

348 Finally, all STU total volumes and STU suitable volumes were summed in order to obtain a *total soil volume*
 349 and *suitable soil volume* over Brittany territory. The *Suitable Soil Percentage (SSP)* was calculated after the
 350 *suitable soil volume % of the total soil volume*.

351 **2.6.2 Part. 2: Sensitivity analysis on the proxies' thresholds**

352 In order to consider the impact of the variability of the proxies' thresholds on these soils' suitability, the
 353 model is submitted to a Monte Carlo sensitivity analysis. The Pearson correlation coefficients between the
 354 4 input proxies were calculated from the data extracted from the DoneSol3 database (*Table 2*).

355

	CEC	OC	F _{2000/D}
F _{50/2000}	-0.27	-0.17	0.32
CEC		0.51	-0.19
OC			-0.11

356 *Table 2 : DoneSol3 database input proxies Pearson correlation coefficient.*

357 Overall, the input proxies are not closely correlated, allowing the input thresholds to be submitted to a
 358 Monte Carlo sensitivity analysis. The *proxy thresholds* were randomly selected inside the *proxy threshold*
 359 *variation range*, that is to say on the whole realistic range of possible values. Exception is made for T, as it
 360 is not directly available in the database. However, to be able to evaluate its variability, T varied randomly
 361 on 3 fixed values: the two *proxy threshold variation range* values (10cm, 60cm) and the proxy threshold
 362 value ([T]cm).

363 Then, each set of 4 input proxies and T proxy was used to run the model. The Suitable Soil Percentage (SSP)
 364 was calculated. This process was repeated 10 000 times. The results are plotted on (Figure 3).

365 Smoothing curves were plotted in order to be able to compare the impact of the different proxies'
 366 threshold choices on the SSP. For each proxy, one smoothing curve was plotted for every T value.

367 For every input proxy, the difference between the maximum and minimum value of the T=[T]cm
 368 smoothing curve was calculated and plotted as a red broken line.

369 **2.6.3 Part. 3: Mapping Brittany's soils suitability**

370 STU suitable thickness was assigned to each raster pixel of the STU map proposed by Vincent et al. (2018)
 371 (Figure 4a.).

372 An estimation of the earth mass required for earth-hemp insulation of all dwellings on the territory of
 373 Brittany was carried out (see Verron 2021). The estimated mass was allocated to every municipality by
 374 population proportion (Figure 4b.).

375 Using municipality vector map (DREAL Bretagne & IGN-F 2020), STUs surface proportion was calculated
 376 for every municipality. Municipality suitable earth mass was then deduced, by increasing the estimated

377 volume by a factor of 1.3, the commonly used density of soils value. The municipality Resource Availability
378 Ratio (RAR) was then calculated (Eq. 2).

379 Eq. 2:
$$RAR = \frac{\text{needed earth mass for light earth insulation}}{\text{existing earth resource}}$$

380 “Non-accessible soils” were defined when DoneSol non-accessible soils cover more than 50% of
381 municipality surface.

382 **2.7 Processing tools**

383 Data format and analysis were processed through Microsoft Access 2018, Spyder 4.1.4 (Python 3.8.3 64-
384 bit), QGIS 3.10.0 (2020) with GRASS 7.8.3, running on Windows 10. The model was tested on DoneSol3
385 Bretagne database. In an effort to make this work replicable, reproducible and reusable as proposed by
386 Cohen-Boulakia et al. (2017), the complete data workflow and the high-resolution figures of this work have
387 been published (Verron, 2021). They can be consulted freely by all or even reproduced provided getting
388 the rights to access DoneSol database by the owners (Grolleau et al., 2004).

389 **3. Results**

390 **3.1 DoneSol3 data statistics**

391 The distribution of the database layers cumulated volume according to the 4 input *proxies thresholds*
392 values allows to visualize the commonly found values for these soil properties in Brittany’s soils (Figure 2).
393 Additionally, it allows the reader to locate the *proxy thresholds variation range* along the values
394 distribution. Indeed, for CEC, $F_{50/2000}$ and $F_{2000/D}$, the variation range covers approximately 50% of the
395 volume of the soil horizons. Therefore, we expect a high sensitivity of the model to the variation of these
396 proxies’ thresholds.

397 **3.2 Sensitivity Analysis**

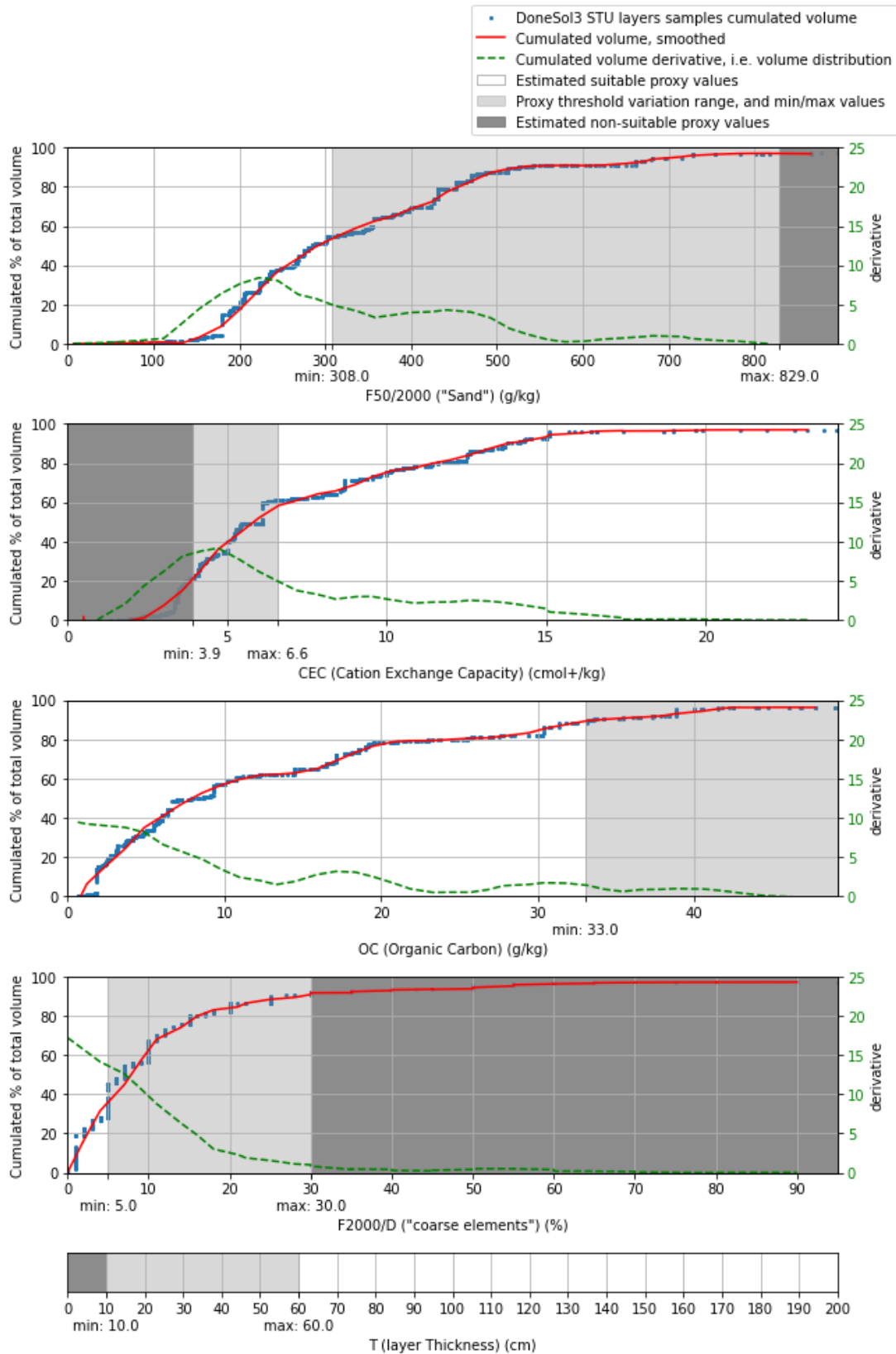
398 The suitability increases with the proxy when the threshold is a maximum, and decreases when it is a
399 minimum (Figure 3).

400 T and CEC are the proxies having the highest impact on the Soil Suitability Percentage (SSP), with a variation
401 of 24 and 30% respectively inside their *proxy threshold variation range*. However, T proxy variation was
402 not calculated exactly in the same way as the other input proxies (see 2.6.2). Therefore, comparison with
403 the other SSP variation results is only illustrative.

404 $F_{50/2000}$ and $F_{2000/D}$ have an SSP variation of 16 and 12%, whereas OC only 5%. This was expected, as the
405 thresholds variation range covered only 10% of the volume distribution curve (see 3.1).

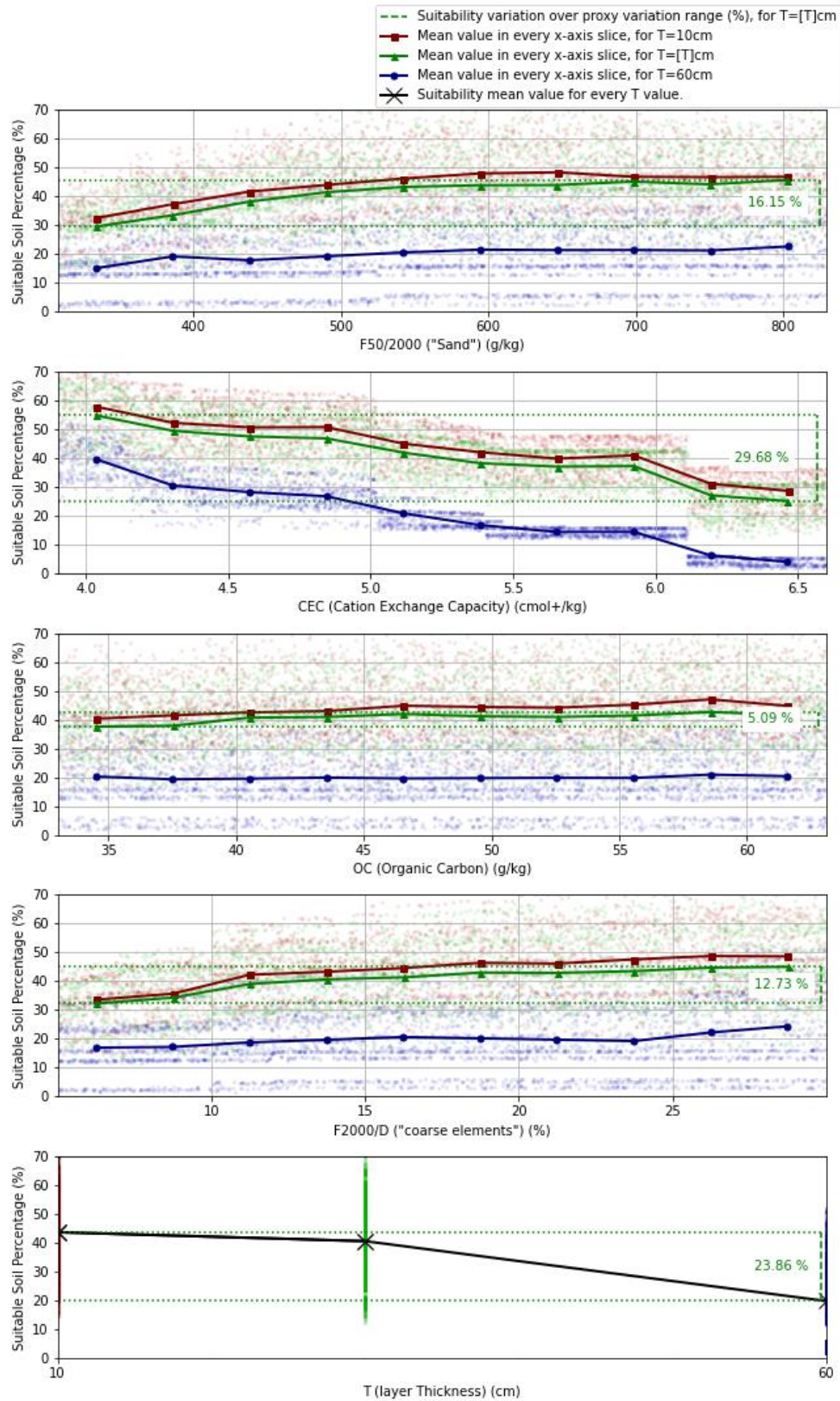
406 **3.3 Suitable soil volume and percentage**

407 The estimated total soil volume in Brittany is more than 27 558 000 000 m³. The estimated total volume
408 of suitable soil for earth-hemp building is more than 13 277 000 000 m³ (17.3 Bt). Therefore, the Suitable
409 Soil Percentage (SSP) is 48%. If the “coarse elements” ($F_{2000/D}$) volume is deduced from the suitable volume,
410 to represent the earth actually available after sieving, the suitable earth volume goes down to 12 636
411 347 046 m³ which represents 46% of the total soil volume.

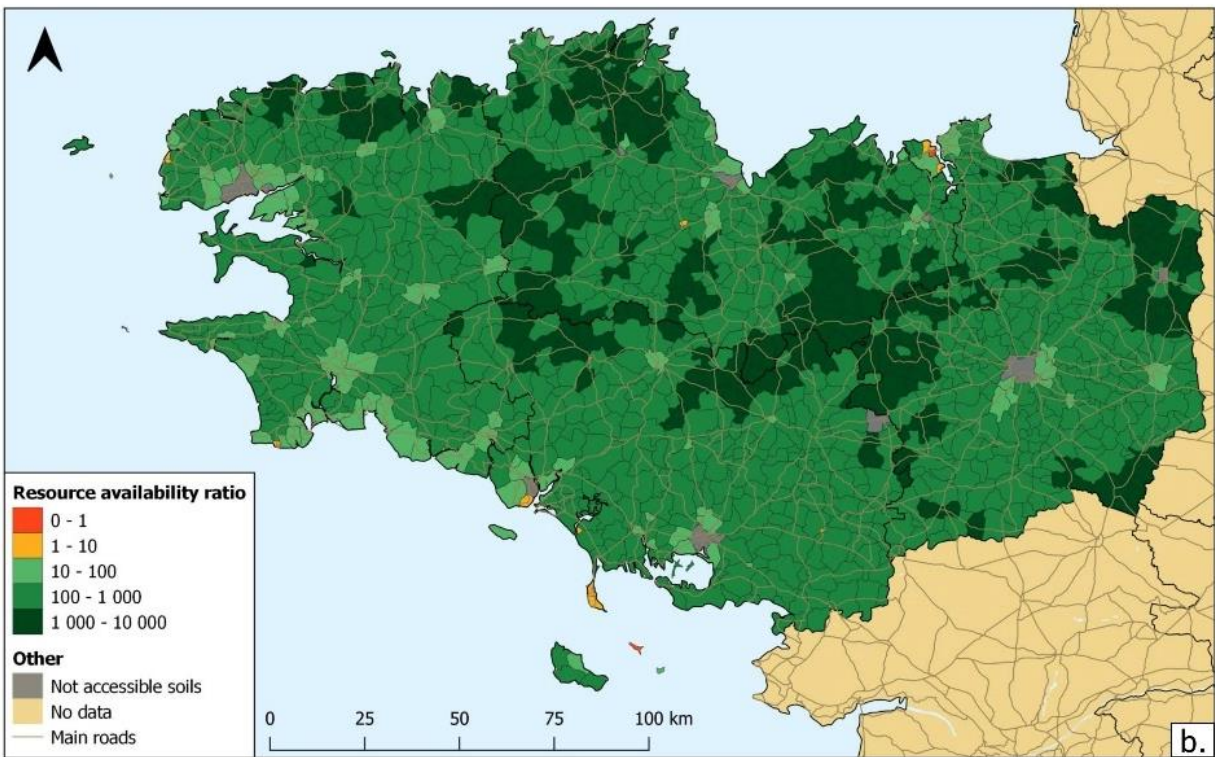
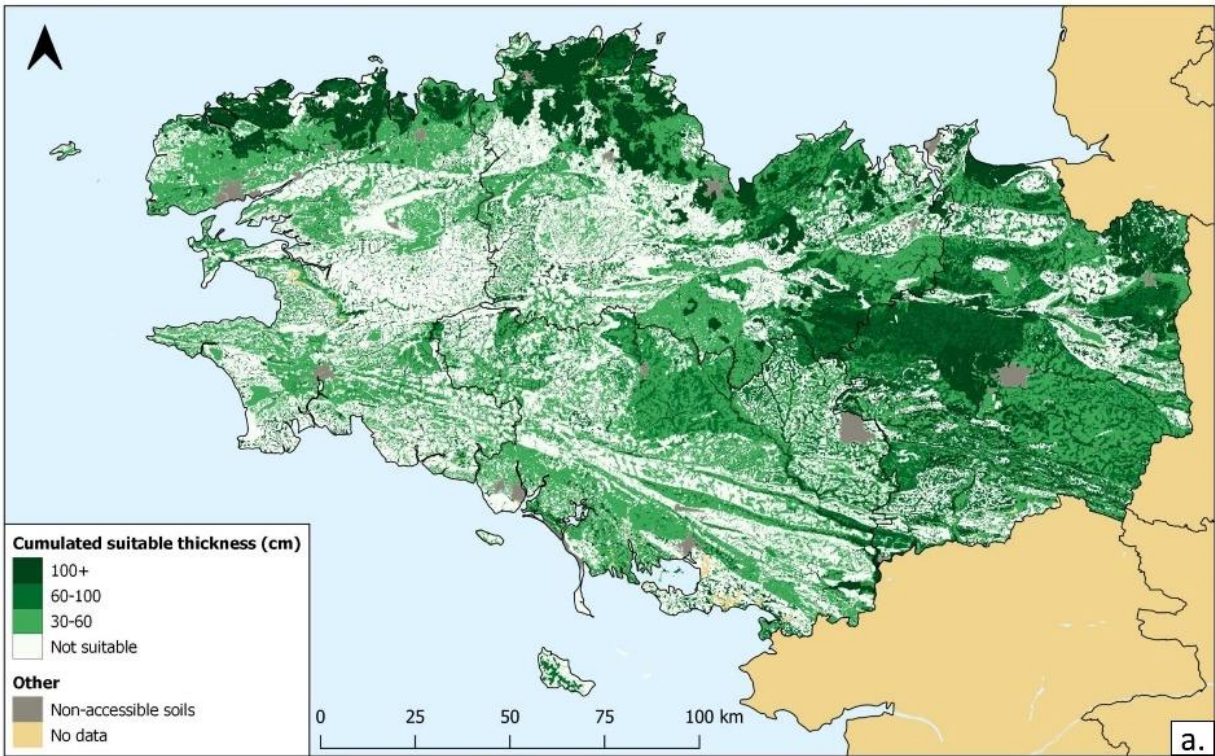


412
 413
 414

Figure 2 : Comparison of the cumulated distribution of DoneSol3 layer volume and its derivative (earth volume repartition), with proxy threshold variation range.



415
 416 *Figure 3 : Monte Carlo sensitivity analysis results. The 10 000 model run results were plotted as*
 417 *transparent coloured dots in the background.*



418
419
420

Figure 4 : Predictive mapping of Brittany (France) soils: a. suitable thickness; b. suitable soil resource for light earth building, relatively to estimated needs for the municipalities

421 **3.4 Soil suitability mapping**

422 The thickest suitable soils for earth-hemp building (Figure 4a.) are located in a zone starting along the
423 north-eastern coast of Brittany and expanding to the east to reach Rennes city. This trend follows
424 particularly suitable soils: Cambisols, Luvic Cambisols and Luvisols developed from deep aeolian silts
425 deposits (Jamagne et al., 2011), rich in $F_{0/2}$ and $F_{2/50}$, and poor in coarse elements. The municipality
426 Resource Availability Ratio (RAR) ranges from 0 to 6802 (Figure 4b.). Almost all municipalities show a ratio
427 above 10, predicting an abundant resource. The RAR decreases with municipalities' population, and
428 increases with soil suitability. The RAR is logically lower near major cities, where the population is high,
429 hence the potential need is high. However, there is still a significant amount of locally available material.
430 Conversely, it is higher in the centre of Brittany, where the inhabitant density is the lowest, and in the
431 northern part of Brittany, where deep suitable soils are found. Distances to suitable soils

432 The maximum acceptable transport distance of the earth resource varies and depends on many criteria
433 (economical, ecological or practical). Experts estimate that today's maximum distance is between 30 and
434 50 km. The soil suitability map (Figure 4a.) shows that 99,5% of Brittany territory is at less than 1 km of a
435 suitable soil resource for earth-hemp building. The further point from a suitable resource is located 2,3 km
436 away from a suitable soil. Thus, earth resource for earth-hemp can be considered a very local resource in
437 Brittany.

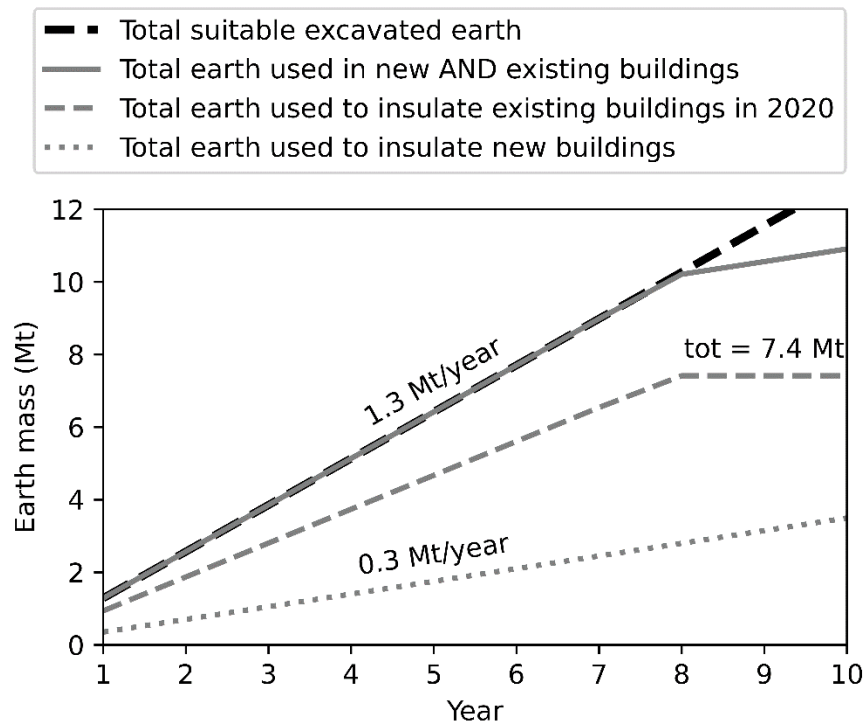
438 **4. Discussion**

439 **4.1 Availability of total soil resource**

440 According to the model, 46% of the total soil volume in Brittany could be used for light earth building.
441 Considering that the mass of annually excavated earth is 2.8 Mt (Hamard et al., 2018), 1.3 Mt should then
442 be suitable for light earth building. The broken line on Figure 5 represents this mass, cumulated over the
443 years.

444 To put these findings into context, the mass of earth required to insulate all buildings in Brittany that need
445 insulation with light earth is estimated. Data from the French government is used to estimate the amount
446 of earth material required per house, the number of houses that must be insulated, and the number of
447 houses built each year (CGDD, 2014; INSEE, 2020, 2017). The details of the calculation can be found in the
448 metadata (Verron, 2021). The total mass of earth required to insulate all building that need insulation in
449 Brittany with light earth is estimated to be 7.4 Mt. This corresponds to less than 6 years of suitable
450 excavated earth. In addition, to insulate every new building with a light earth, the estimated requirement
451 is 0.3 Mt annually, which is less than 1/4th of annually suitable excavated earth.

452 A scenario where the reuse of suitable excavated earth in light earth building is maximised would consist
453 in insulating all new buildings with light earth using 0.3 Mt/year of suitable earth, and using the 1 Mt/year
454 left to insulate existing buildings (Figure 5). In this scenario, it would take only 8 years to finish the
455 insulation of all existing buildings that require insulation (in 2020). In reality, other materials are used for
456 insulation, therefore the requirement is considerably lower and the stream of excavated earth should
457 meet light earth building earth needs in most of the contexts.



458
 459 *Figure 5: Scenario maximising the reuse of suitable excavated earth in light earth building in a period of*
 460 *10 years. Estimations of volumes extracted, and used to insulate new and existing buildings. Building*
 461 *requirements estimated from French government data (CGDD, 2014; INSEE, 2020, 2017), see Verron*
 462 *(2021).*

463 Due to the different benefits of earth material and driven demand for sustainable constructions, there is
 464 a growing interest in this material for construction (Walker et al., 2005). Even if the earth resource seems
 465 abundant in total, the soil is also a support for other human and non-human uses. All soils should be
 466 preserved as high-value and essential ecosystems for human and non-human well-being. Furthermore,
 467 reusing excavated earth in light earth insulation does not mean that the excavation operations don't have
 468 to be reduced, or that this insulating solution is the most ecologically efficient for every building project.
 469 A complete analysis of the positive and negative externalities should always be performed before using a
 470 building material, for example conducting life cycle assessment.

471 **4.2 Thresholds sensitivity**

472 The Monte Carlo sensitivity analysis shows that the Soil Suitability Percentage (SSP) is particularly sensitive
 473 to the *Cation Exchange Capacity* (CEC) and the *consecutive layers cumulated suitable Thickness* (T) proxies'
 474 thresholds.

475 As discussed in 2.4.2, T is greatly dependent on the building context and on the excavation precision. The
 476 sensitivity to T is high, but we can notice that soil suitability remains stable for T values between
 477 approximately 10 and 30 cm. This would mean that it probably won't increase soil suitability to use
 478 excavation means more precise than 30 cm. The reason may be that the majority of Soil Type Unit (STU)
 479 layers are thicker than 20 cm, and that the thinner layers correspond to O (organic) and A (mixed organic
 480 and non-organic) horizons (AFES 2008) which are often already evicted from suitability by the OC

481 threshold. The actual precisions of the common mechanic diggers being around 15 to 30 cm, this
482 parameter is probably not the most impacting on soil suitability.

483 CEC is an interesting proxy for raw earth building techniques properties, as it indicates clay bonding
484 capacity, which is the combined action of clay specific surface area and electronical charge (Hamard et al.,
485 2018; Meimaroglou and Mouzakis, 2019). This parameter is sensitive in the suitability model, notably
486 because the defined threshold is located on a peak of the earth volume distribution curve. As it is a key
487 parameter of earth suitability, there is a need for more investigation on the link between CEC and earth
488 properties for earth building.

489 In this study, Organic Carbon (OC) threshold variation impacts the suitable soil volume percentage by only
490 5%. But as organic matter content is generally higher in the surface layers of soil (Girard et al., 2017), it
491 could be more impacting depending on field excavation conditions, as it forces to dig deeper to extract the
492 resource.

493 **4.3 Model limitations**

494 All of the numerical modelling choices can be accessed and questioned as the complete data workflow of
495 this study is available in the metadata of the article (Verron, 2021). The suitability calculation model has
496 been designed with the objective of underestimating the potential resource when an adequate estimation
497 process was not possible. This open-source numerical model is flexible and could be reused for future
498 estimations and mapping of soil suitability for earth building techniques.

499 We can imagine that all of the *suitability criteria* used to limit earth suitability for light earth building in
500 this model could be more or less overcome in different building conditions: by the discovery or rediscovery
501 of new building techniques, by technology, with highly mechanized means, or by the addition of natural
502 or artificial additives, etc. Therefore, the model parameters, chosen collaboratively with local masons,
503 represent a realistic possibility of parameters actually used on field along the earth material life cycle in
504 light earth building, rather than absolute thresholds that must be satisfied.

505 The spatialized pedological data employed in this study, like any map, does not accurately depict reality.
506 The results of this model highly depend on the accuracy of this data. Because this accuracy was not
507 assessed in our study, it remains a possible source of inaccuracies.

508 The results of this study have been obtained by considering the 5 previously defined suitability criteria. In
509 real field conditions, the earth resource choice must consider other criteria such as private property,
510 natural or anthropic physical or chemical contaminations of the soil, and other technical accessibility
511 parameters of the resource. Indeed, some studies record urban chemical contamination to around 10% of
512 urban soils (Ferreira et al., 2019). As the major part of the excavated earth comes from urban areas, it
513 could impact significantly the suitability results. Yet, as the available amounts are considerably bigger than
514 the estimated needs, it is probable that this study conclusions about earth availability for light-earth
515 insulation would remain similar.

516 Furthermore, the maps precision does preclude their use at field scale for resource prospection, or to
517 validate earth suitability for an earth-hemp building project. On field, the mason's expertise and manual
518 tests are the only reliable source of information concerning an earth material suitability for earth building.

519 **5. Conclusion**

520 Soil suitability was estimated using 5 proxies based on previous research and experts' advices. Using
521 spatialized pedological data in Brittany (France), suitable soils for light earth building were quantified and
522 mapped.

523 The abundance of excavated earth, and the potentially low resource selectivity and quantity that is
524 required for light earth indicates that the availability of the earth resource should not be an obstacle to
525 develop light earth building in Brittany.

526 According to our estimations, 48% of the total soil volume in Brittany could technically be used for light
527 earth building, which corresponds to 17 Bt. Furthermore, using only the annually excavated earth of the
528 construction sector, all existing and new buildings could be insulated with light earth in less than 8 years.
529 It was also found that, suitable earth for light earth building can be found locally almost anywhere in
530 Brittany. Indeed, 99.5% of Brittany territory is at less than 1 km of a suitable soil resource, the farthest
531 point being 2,3 km away.

532 Cation Exchange Capacity (CEC) is a parameter that has a high influence on the model results. It is notably
533 because a great fraction of Brittany's soils has CEC values close to realistic CEC thresholds. Little
534 information is available about the potential impacts of CEC on light earth building, and particularly its
535 interaction with clays and soil organic matters. Therefore, more research is needed to understand CEC and
536 soil organic matters impact on the properties of earth building materials.

537 The model parameters, chosen collaboratively with local masons, represent a realistic possibility of
538 parameters actually used on field along the earth material life cycle in earth-hemp building, rather than
539 absolute thresholds that must be satisfied. On field, the mason's expertise and manual tests are the only
540 reliable source of information concerning earth suitability. Furthermore, the accuracy of the model
541 depends on the spatialized pedological data used. Therefore, the model thresholds and the mapping
542 accuracy are not operational field data and cannot be used as references for earth selection for earth-
543 hemp or other light earth building techniques.

544 However, this model is an innovative way to raise awareness on the availability of earth resource for light
545 earth building. For example, it could help territorial institutions to understand the development potential
546 for sustainable building techniques on their territory. This open-source model could be reused to
547 investigate other raw earth building techniques resource availability in other territories.

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750 9. Appendices

751 9.1 Appendix A : building steps illustrations.



752
753 *Figure A.1: Manual dry sieving prior to an earth-hemp formwork. On this building site, the sieve mesh size*
754 *was close to 1 cm, illustrating the variability of sieving objectives on field. Liquid state sieving is also a*
755 *common practice.*

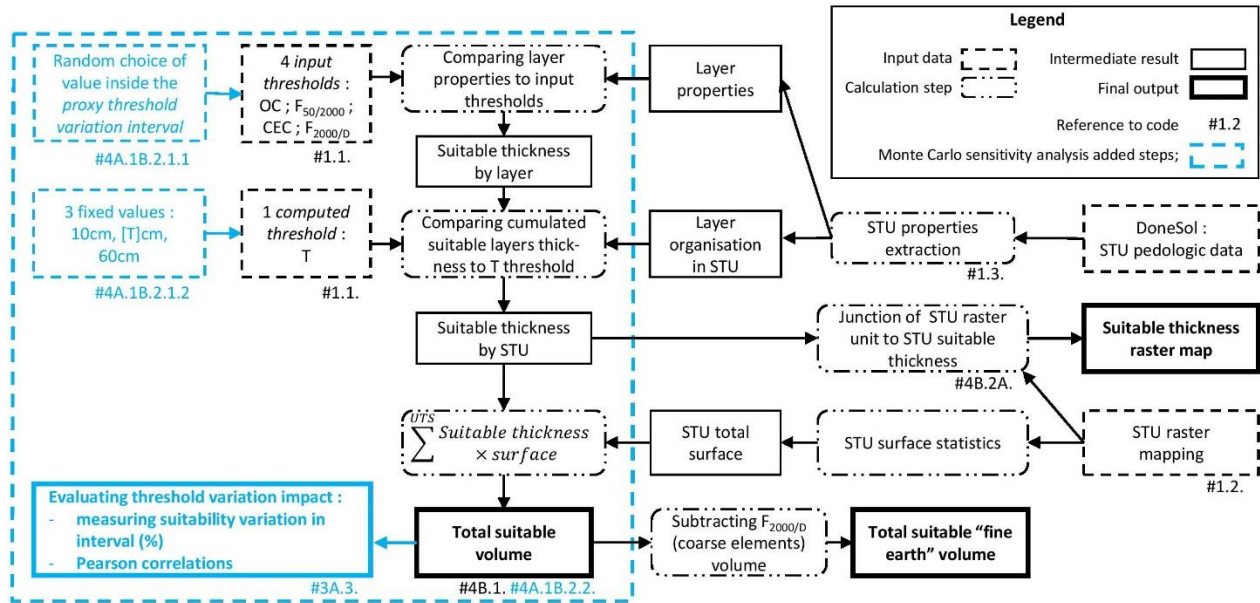
756



757
758 *Figure A.2: Glove test carried out on site. a) the earth slip is too fluid, the hand appears through;*
759 *formulation of the earth slip is correct when it forms a perfect glove on the hand, without transparency of*

760 the latter; c) the slip is too greasy when the fingers are webbed and the glove too thick. From Vincelas
 761 (2019).

762 **9.2 Appendix B : Numerical model**



763
 764 **Figure B.1: Numerical model used for Brittany's soils suitability analysis and steps added for the 10 000**
 765 **occurrences of the Monte Carlo sensitivity analysis.**

766